Modelling Agricultural Energy at Neolithic Çatalhöyük

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ABSTRACT

The Neolithic Agricultural Revolution brought new ensembles of activities, behaviours, and technologies permitting cultivation, increases in production, and changes in nutrition, workload, mobility, and population growth. The Neolithic also evoked substantial changes in energy flows associated with human communities and their wider environments. Thus, the primary concern of this thesis is to understand the energy flows accompanying agricultural actors in the past, using the case study of Neolithic Çatalhöyük, Turkey.

Many recognise the importance of an “agricultural labour trap” and that energy plays a role in population growth, yet none have understood or quantified the energetic dependencies of agriculture, its processes, and population growth within an archaeological context. All agricultural systems are constructed as energy feedback systems that aid population growth and enforce a reliance upon agriculture. This thesis analyses the development of these sparsely studied energy flows, feedbacks, and dependencies, which I have termed the *agricultural energy feedback system*. The methodology created and enacted here proves the existence of this system during the Neolithic and delivers a methodology to quantify and assess past energy systems.

The findings within this thesis are:

(1) Agriculture, as a system, comes with the caveat that its processes become increasingly dependent on one another’s success to produce an energetic surplus; high yielding crops are more efficient at providing this surplus.

(2) Agriculture’s efficiency and cost initially improve with population growth. However, this efficiency and cost plateau when additional land clearance is needed in a time of high population growth rate, depending on the yield and how much of the diet is dependent on agriculture. Once costs and efficiency no longer improve, agriculture’s threshold is reached and the system must be made to be more efficient to keep relying upon agriculture.

(3) Tillage, harvesting, land clearance, crop processing and storage are energetically demanding, thus, are crucial to agricultural systems' success.

These findings enhance conclusions about what encourages population growth, facilitates an increasing reliance on agriculture, why agriculture requires additional land and explains limits to growth during the Neolithic.

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1 CHAPTER 1: INTRODUCTION

Archaeologists agree that the Neolithic Revolution was a fundamental turning point for humans. The Neolithic came with a new ensemble of human activities, behaviours, and technologies that, alongside cereal cultivation, led to unprecedented population growth, increases in production, and changes in nutrition, workload, mobility, and social interaction (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Rindos, 1980, Shennan, 2007, Shennan, 2018, Shennan, Downey et al., 2013, Smith, 1995).

Archaeologists have studied these crucial changes through the lens of people, animals, materials, crops, and the landscape in which these changes occurred. However, this new agricultural way of living and the surplus production that came with it can also be thought of in terms of changes to the temporality of the human-environment energy system. While the energy flows associated with hunting and gathering are primarily linked to seasonal changes in solar energy; agriculture has seasonal energy cycles along with much longer-term energy investments in land preparation and maintenance. Thus, the concern of this thesis is understanding the energy flows that accompany agricultural actors. This thesis considers the processes of energy extraction by which the adoption of agriculture took place, the cumulative energy effects of past agricultural processes and seeks to understand and discuss the relationship between energy, settlement growth, and subsistence pathways. Investigating the Neolithic from an energy point of view allows for a new, exciting perspective on this pivotal turning point in humanity's history and provides an opportunity to quantify the impact of agriculture and measure yearly cumulative lock-ins and feedbacks.

Within agricultural systems are certain energy feedbacks and dependencies which both aid in population growth and effectively enforce a reliance upon agriculture. Such energy feedbacks and dependencies can only be distinguished by analysing the energy flows associated with agriculture and population growth. This thesis analyses the development of these flows, feedbacks, and dependencies, which I have termed the *agricultural energy feedback system* (see Figure 1), at Neolithic Çatalhöyük. Referring to Figure 1, on the one hand, agriculture provides a surplus of energy to societies which aids in population growth. On the other hand, as agriculture provides this excess energy, societies become increasingly reliant upon agriculture due to a combination of becoming increasingly more invested (i.e., dedicating more energy) in agricultural processes to sustain agricultural activity and the growing population. Further, agriculture's energetic cost and efficiency *improve* when more people participate in agriculture, which reinforces a reliance upon agriculture. However, this improved energy cost and efficiency are only beneficial if agriculture has enough people participating, enough land, and sufficiently high yields. Thus, societies become increasingly reliant upon agriculture due to a combination of receiving and maintaining an energy surplus, investing more energy into agricultural processes, and the improved energetic cost and efficiency that comes with a growing population. With a growing population, however, comes the need for more energetic resources to sustain both the growing population and agriculture, including more land. This efficiency and cost change throughout its occupation depending on these factors and is not limitless. Çatalhöyük's threshold for population growth, which is influenced by domestic cereal reliance and yield (land) was 2000-3000 people. Once this threshold was reached, Çatalhöyük's agricultural system must be made to be more efficient to keep relying upon agriculture and sustaining itself. Some of the unintended consequences of sustaining agriculture and improving efficiency include permanent changes to the environment and changes in diet and nutrition, material culture, technology, animal relationships, and even ritual practise. Additionally, agriculture's processes in themselves are dependent upon one another's success. If one agricultural process fails, the entire agricultural system, and the subsequent energy flows of which it is a part, break down. Agriculture is only successful when its processes are successful; a society maintains this success by inputting energy into agriculture's processes. These complicated mechanisms together develop a cycle of energy feedback and dependency: the agricultural energy feedback system.

The implications for this are significant. One of the fundamental questions surrounding archaeological discourse and the Neolithic is the spread of agriculture and its relationship to population growth. Stephen Shennan, for example, takes a Darwinian approach to understanding the Neolithic and the spread of agriculture (Shennan, 2007, Shennan, 2018, Shennan, Downey et al., 2013). Shennan argues that the spread of agriculture is due to the fact it maximises reproductive success (Shennan, 2007, Shennan, 2018). Shennan argues this colonisation model explains the "boom and bust" populational patterns witnessed in parts of southwest Asia and Europe correlating with the spread of agriculture (Shennan, 2007, Shennan, 2018, Shennan, Downey et al., 2013). In enabling this successful reproduction, agriculture subsequently forced populations to grow rapidly, i.e. "booms" (Shennan, 2018: 1-3, 21-22, Shennan, Downey et al., 2013). As populations dedicated more investment to agriculture, they became constrained to this lifeway and thus were more vulnerable to disasters (e.g. disease, crop failures, environmental changes), thus causing "busts" to occur (Shennan, 2018). However, because agriculture is "portable," in other words, domestic plants can be grown in other places, this creates more opportunities for population growth and expansion, thus people colonised environments through agriculture (Shennan, 2018). With agricultural expansion came a new way of life, sets of social practices, beliefs, and technologies which were essentially passed on to children and others they encountered (Shennan, 2018: 77). Similarly, David Rindos (1980) argues that agriculture is inherently based upon environmental manipulation (1980: 752). By concentrating resources in a single area, Rindos argues, agriculture increases risk to diseases, insects, or environmental catastrophes which decreases crop yield (Rindos, 1980). Decreases in crop yield results in instability, and forces populations to relocate to different areas, bringing along with them agriculture and the lifeways, customs, information, and technologies that come with it (Rindos, 1980: 753). Agricultural inherently causes environmental instability, facilitating its spread, and, allows populations to carry on their subsistence patterns in new areas, and the cycle continues (Rindos, 1980: 753).

Both Shennan and Rindos attempt to understand the dynamics of the Neolithic, especially the spread of agriculture. The agricultural energy feedback system posited and modelled in this thesis provides a mechanism that allows us to explain both Shennan's and Rindos' theories on the spread of agriculture. In other words, this thesis provides a mechanism for expansion during the Neolithic, a mechanism that can only be teased out by taking an energetic approach to agriculture in the past. Energy extraction and humanity's relationship with energy plays a fundamental role in both societal growth and development as well as understanding the spread of agriculture during the Neolithic. Archaeology *can* and needs to model and better understand the relationship between energy and societal growth, and this thesis provides a methodology to do just this.

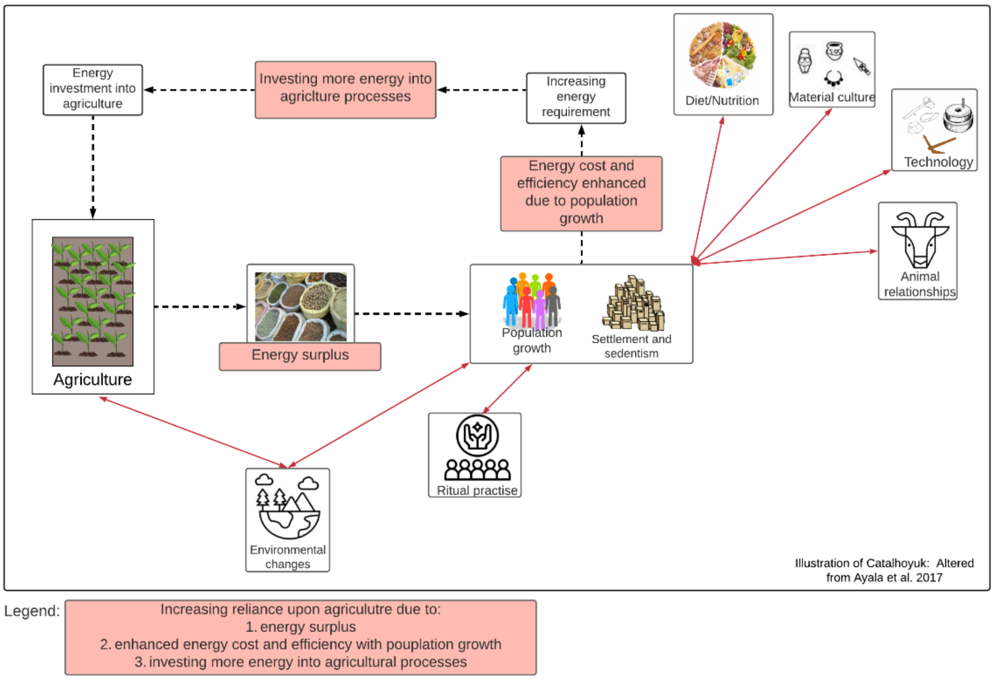


Figure 1 The Agricultural Energy Feedback System: Agriculture provides a surplus of energy to societies. As it provides this surplus energy to societies, agriculture facilitates population growth, however, this also requires more energy to keep the growing population sustained. As this positive feedback cycle occurs, societies become increasingly more invested (i.e., dedicate more energy) to agricultural processes to sustain it while permanently changing the environment. Illustration of Çatalhöyük altered from Ayala et al. 2017 (Ayala, Wainwright et al., 2017)

The genesis of this feedback system builds upon theories of what some have designated as an “agricultural labour trap” (Fuller, Allaby et al., 2010).The recognition of a positive feedback between the adoption of agriculture, surplus energy, and societal development is dealt with below and has been commented upon by many others (Chapter 2; White 1943; Chaisson 2003, 2005, 2011, 2013, 2014a, 2014b, 2015; Smil 2000, 2008, 2013, 2017; Odum and Pinkerton 1955, Odum and Odum 1977, Odum 1977, 2007; Fischer-Kowalski and Haberl 2007, 1997, Fischer-Kowalski et al. 2014, Fischer-Kowalski and Weisz 1999, Lenton and Watson 2011, Lenton et al. 2021; Rappaport 1971; Barrett 2011), and an energetic analysis of Çatalhöyük’s archaeological material is covered in chapters 5 to 6.

The agricultural energy feedback system itself builds upon the work of many within the realm of society energy literature, but especially Fischer-Kowalski and colleagues (2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999), Lenton and co-authors (Lenton and Watson, 2011, Lenton, Kohler et al., 2021), Redman and colleagues resiliency work (Redman, 1999, Redman, 2005, Redman and Kinzig, 2003), Rappaport 1971, Smil (2000, 2008, 2013, 2017), Fuller et al.2010, Barrett (Barrett, 2011, 2013a, 2013b, 2014, 2021, Ion and Barrett, 2016), and optimal foraging theory (Kennett and Winterhalder, 2006, Winterhalder and Smith, 2000). Fischer-Kowalski and colleagues essentially posit the agricultural energy feedback system and investigate agriculture as a form of colonisation or land colonisation (2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999). Lenton and co-authors recognise a positive feedback within agriculture, its processes, and agriculture’s resulting energy surplus, and demand a quantifiable modelling of such feedbacks as an avenue of future research (Lenton and Watson, 2011, Lenton, Kohler et al., 2021). Redman has called for archaeological contributions to resiliency theory and argues that archaeological case studies are evidence of completed adaptive cycles, allowing for a better understanding of the resiliency of human systems (Redman, 2005: 70, Redman and Kinzig, 2003). Moreover, Redman and colleagues' discussions of adaptive cycles as positive feedback systems, in which accumulating a surplus and maintaining efficiency aids in facilitating the emergence of complex society, is directly relevant to this thesis (Redman and Kinzig, 2003). The agricultural energy feedback system posited here is a sort of adaptive cycle. Agriculture allows for a society to accumulate energy and capital, develop new relationships and processes, and as argued by others (Fischer-Kowalski and Haberl, 1997: 64-67, Fischer-Kowalski and Weisz, 1999: 231, Rindos, 1980, Shennan, 2007, Shennan, 2018), colonises the surrounding environment. The energy methodology enacted in this thesis is a step towards empirically modelling and understanding the role energy plays within adaptive systems and resiliency within human systems.

Rappaport's (1971) detailed ethnographic work on agricultural energy inputs utilises human energetics to understand agricultural energy through the lens of ritual practice and implies the existence of a feedback within complex agricultural societies (Rappaport, 1971). Smil highlights the importance of the inputs and outputs of energy systems, the efficiency of humanity's energy systems, and links energy efficiency to societal complexity (Smil, 2000, Smil, 2008, Smil, 2013, Smil, 2017). Fuller et al. 2010 focus specifically upon the labour organisation of threshing and winnowing and argue that these agricultural processes must be further investigated to aid our understanding of domestication, sedentism, and agricultural lifeways, more generally (Fuller, Allaby et al., 2010). Barett argues for an energetic focus on agricultural feedbacks and their relationships to population growth and ecologies and views the Neolithic as a process of changes in managing energy (Barrett, 2011, Barrett, 2013a, Barrett, 2013b, Barrett, 2014, Barrett, 2021, Ion and Barrett, 2016). While they recognise the importance of energy, none have quantified it for past systems based upon archaeological data. However, energy modelling is not a new feat within archaeological discourse, especially with optimal foraging theory approaches, in which energy is the main form of currency (Bird and O'Connell, 2006: 147, Keene, 1983: 140, Kennett and Winterhalder, 2006: 13, 170, Stiner and Kuhn, 2016, Winterhalder and Smith, 2000: 51). Moreover, optimal foraging theory utilises energetic costs and benefits to understand the efficiency of past human decision-making processes (Bird and O'Connell, 2006: 147, Keene, 1983: 140, Kennett and Winterhalder, 2006: 13, 170, Stiner and Kuhn, 2016, Winterhalder and Smith, 2000: 51). I relate the agricultural energy and efficiency to yield, domestic cereal reliance, and population growth and highlight efficiency with respect to increasing agricultural costs and energetic conflicts accruing during times of high population growth rate. This thesis expands upon these works by modelling the energy of a past agricultural system, that of Neolithic Çatalhöyük: it bases its quantifications on archaeological data and demonstrates the existence of an agricultural energy feedback system during the Neolithic.

Çatalhöyük is one of the largest (0.13km^2) Neolithic sites in southwest Asia. It provides evidence of a flourishing early farming settlement and represents the Neolithic Revolution, a critical transition in human history. Archaeological evidence at Çatalhöyük indicates that it was a complex society consisting of community and political organisation, long-distance trade and mobility, increasing symbolic practice, craft specialisation, ritual practice and an organised social structure, making it an archetype of "Neolithization" (Childe, 1951 (1936), Despina and Relaki, 2020 :156, Fowler, Harding et al., 2015, Hodder, 2018, Robinson, Hadjikoumis et al., 2011). Additionally, Çatalhöyük's expert-led excavations, rich archaeological evidence, well-understood stratigraphic sequencing, paleoenvironmental data, covering 1400 years of occupation with no breaks, make it a remarkable case study to explore energy use among early historic communities (Farid, 2014, Hodder, 2014a). Finally, Çatalhöyük and the surrounding region is known to be one of the sources of the western expansion of farming, thus, Çatalhöyük shines a particular light on understanding the spread of agriculture during the Neolithic (Barrett, 2011, Barrett, 2016, Barrett, 2019, Shennan, 2018: 77). Utilising Çatalhöyük as a case study for quantifying, presenting, and assessing past energy systems will provide a valuable perspective on modelling society-energy relationships, bring the desperately needed deep history into energy sustainability models, provide a way to quantify and present energy systems in the past, and help to better understand the relationship between energy, agriculture, and population growth during this crucial time in human history.

To quantify and model Çatalhöyük's agricultural system energetically, this dissertation recalculates Çatalhöyük data through the lens of a modern human energy requirements framework, the 2004 Human Energy Requirements Expert Consultation (henceforth referred to as the HERE consultation). The HERE consultation was created to determine and assess populational energetic needs accurately; it is currently employed and supported by the Food and Agriculture Organisation (FAO), World Health Organisation (WHO), United Nations University (UNU), and utilised by modern human energetics specialists (Durnin and Passmore, 1967, James and Schofield, 1990, Passmore and Durnin, 1955, UNU, 1985, UNU, 2004, Vaz, Karaolis et al., 2005). For this dissertation, the HERE consultation is applied to Çatalhöyük's archaeological data to quantify and establish an agricultural energy baseline, convert agricultural activities into energy equivalents, and thus, quantify, model, and present the Çatalhöyük agricultural system energetically. This energy-systems method and analysis provides a bridge for the aforementioned energy understanding gap in archaeology and demonstrates that quantifying and assessing past energy systems using archaeology, its data, and methods *is* possible and imperative.

Before presenting an energetic analysis of Çatalhöyük, first, we must understand how academic disciplines comprehend the relationship between agriculture, population growth, and energy. Most human energy systems, sustainability, and global climate change research have focused their analyses on the last 150 to 200 years and suggest that prior to the Western "industrial revolution", human energy systems were in harmony with the environment and any impact these systems might have had was local and trivial (Hudson, 2012, Lane, 2015, Mann, Bradley et al., 1999, Pétursdóttir, 2017, Steffen, Broadgate et al., 2015). Worse, these narratives argue that it is only very recently that our "unsustainable" energy systems emerged and detrimentally affected the Earth system. From an archaeological perspective, this is erroneous. Past communities' impacts were not just local or trivial. There is substantial evidence from around the world indicating that, before the industrial revolution, human activity thousands of years ago affected the environment over the long-term (e.g., Hillman 2015, Simmons 2001, Pompeani 2019) (Lane, 2015 :5, Ruddiman, 2013).

Our modern understandings of energy systems and "sustainability" within the global climate change community lack a quantitative measure of the energy interactions of societies in the past. Further, the development of the agricultural feedback system is missing from both archaeological and modern sustainability and global climate change research narratives, methods, and analyses. Therefore, the focus of chapter **0** is to demonstrate how modern energy analyses lack energy quantifications of the past in their models, why this is a problem, and why an archaeological approach to human energy systems is required. Further, how archaeology has dealt with human energy systems in the past will also be addressed. Omitting energy systems of the past impedes a transdisciplinary, holistic approach to understanding today's energy sustainability problems (Hudson, 2012, Malm and Hornborg, 2014, Steffen, Broadgate et al., 2015). The current climate change crisis affects every aspect of Earth, and thus humanity, in ways that no single discipline can tackle alone (Hudson, 2012). The need to fully understand and recognise our relationship with nature and energy requires studying the world through an interdisciplinary lens, which includes archaeological narratives, analyses, and data (Hudson, 2012). Energy and sustainability are enduring problems for humanity, and analyses of current conditions would benefit from such an analysis of the past.

Chapter 3 presents Çatalhöyük as a case study to understand Çatalhöyük itself: its local and regional environment, the lifeways, and temporal changes occurring throughout its occupation. Section 3.1. provides a background of Çatalhöyük in relation to broader Neolithic trends, primarily focusing on the Agricultural Revolution. Section 3.2 presents Çatalhöyük's environment, regionally and locally. Following this, Section 3.3 presents the evidence for subsistence, health, population, material, and overall temporal changes at Çatalhöyük during its occupation. Section 3.4 summarises the results of the analysis of Çatalhöyük which demonstrates that the agricultural energy feedback system occurred in the Neolithic at Çatalhöyük. Overall, this chapter seeks to establish, using Çatalhöyük's archaeological data, that the agricultural energy feedback system was indeed occurring at Neolithic Çatalhöyük.

Chapter 4 focuses on establishing and presenting an energy baseline that can energetically model the Çatalhöyük agricultural system. This chapter sets out a methodology demonstrating the application of a modern human energy requirements framework, the 2004 HERE consultation, to Çatalhöyük's archaeological data, to establish this energetic baseline and convert agricultural activities into energy. In other words, the energetic baseline in this thesis is the minimum energy requirement for Çatalhöyük's agricultural system, including the amount of land required to support Çatalhöyük's agricultural system and the human energy requirements to support its agriculture and its processes. Establishing an energetic baseline and converting agricultural activities into energy equivalents are fundamental steps toward modelling and presenting the energy of Çatalhöyük's agricultural system. Specifically, sections 4.1 to 4.3 describe the HERE consultation, how it was applied to Çatalhöyük archaeological data, and how agricultural activities can be converted into energy equivalents. It also presents Çatalhöyük's nutritional energy requirements, which are fundamental to determining agricultural production activities. Section 4.4 explains the importance of accurate time estimates for the duration of activities in quantifying energy, and briefly describes the ethnographic and experimental archaeological data used for said time estimates. For this analysis, Çatalhöyük's agricultural system at hand is assumed to be a 25%-75% reliance upon the four most common domestic cereals identified at Çatalhöyük: free-threshing wheat, emmer, einkorn, and barley (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Charles, Doherty et al., 2014). Section 4.5 provides concluding remarks on energy conversions and for the chapter.

The bulk of the dissertation, chapters 5 and 6, focus specifically on presenting the baseline energy requirements of the Çatalhöyük agricultural system. Chapter 5 focuses on the relationship between land and energy use and utilises the energy methodology outlined in chapter 4 to quantify how much land was required for Çatalhöyük. Defining the amount of land required to sustain Çatalhöyük (5.2) is crucial for determining the energy of agricultural activities, and thus, the Çatalhöyük agricultural system. Section 5.3 focuses on quantifying the energy of land clearance at Çatalhöyük, section 5.4 focuses on quantifying the energy of land tillage for Çatalhöyük, and section 5.5 focuses on quantifying planting energy at Çatalhöyük as well as seeding rate and storage required. Chapter 6 focuses on harvesting and crop processing. Each subsection within chapters 5 and 6 describes each agricultural activity, how these activities would have occurred at Çatalhöyük utilising archaeological evidence and presents how time allocations were determined using ethnographic and experimental archaeological data.

Chapter 7 amalgamates the energy quantifications made in chapters 5 and 6 to analyse, interpret and investigate agricultural flows at Çatalhöyük to understand the relationship between agriculture, energy, and population growth during the Neolithic. Overall findings within this chapter are, first, that agriculture’s efficiency and cost initially improve with population growth. However, this efficiency and cost plateau when additional land clearance is needed in a time of high population growth rate. It is at this point when agricultural systems require expansion. Second, tillage, harvesting, land clearance, crop processing, and storage are energetically demanding, thus, are crucial to the success of agricultural systems. Third, agriculture, as a system, come with the caveat that its processes are increasingly dependent one another’s success to produce an energetic surplus. Furthermore, high yielding crops are more efficient at providing this surplus than low yielding crops. Section 7.2 focuses on analysing Çatalhöyük’s agricultural energy system, including energy inputs, costs, and efficiency and presents various yield scenarios. Section 7.3 provides a more detailed consideration of the inputs and outputs within Çatalhöyük’s agricultural system. Section 7.4 correlates the models presented (7.2 to 7.3) with Çatalhöyük’s archaeological data to prove that the agricultural energy feedback system was occurring at Çatalhöyük. Section 7.5 focuses upon issues unaddressed by the energy model and focuses on improvements and avenues for future research.

Finally, chapter 8 focuses on discussing and concluding the thesis. Moreover, section 8.1 discusses broader themes, focusing primarily on issues surrounding archaeology and sustainability. Section 8.2 concludes the energy methodology and energy analysis.

Although this thesis focuses on agricultural processes and agricultural energy, the advantage of taking an energetic approach is that *everything* has and uses energy. Energy, therefore, is a valuable currency and allows for quantification and direct comparison. Specifically, within this thesis, energy allows for people, materials, crops, and the landscape to be brought together into one framework. Bringing together material, botanical, and skeletal remains can be challenging for our discipline, yet this thesis provides a way to do so. Further, work focusing on energy can stimulate discussions about implications for archaeological remains and archaeological methods. Routinely collected archaeological data *can* be used to quantify and model energy systems in the past, as demonstrated in this thesis, and thus, can inform and better understand energy systems today.

By utilising energy, it is also possible to energetically model other human, plant, and animal relationships, environmental feedbacks, tool production flows, feasting flows, or, more specifically, to Çatalhöyük for example, clay extraction and use. By quantifying and examining these relationships on the same scale, it is possible not just to model them energetically but it is also possible to better understand the entanglement of these energy flows and identify energetic dependencies or feedbacks. Thus, reframing archaeological data via an energy framework helps provide a valuable perspective on quantifying and modelling society-energy relationships and can potentially help in disentangling the complicated energetic relationships between animals, humans, the local environment, and the broader Earth System.

Finally, this thesis indicates that agriculture is dependent upon energy, and it always has been. Moreover, to be beneficial, agriculture requires social cohesion, population growth, land, and high yields; the agricultural energy feedback system posited here demonstrates and quantifies this energetically. Balancing energy input, energy use, and energy output was a struggle in the Neolithic, just as it is now. Today, our extraction and use of energy sources and resources have radically changed all major earth cycles—water, element, and atmospheric (Ellis, Maslin et al., 2016, Steffen, Broadgate et al., 2015, Waters, Zalasiewicz et al., 2016, Zalasiewicz, Waters et al., 2017). This work indicates how intricate and sensitive agriculture as a system *was* during the Neolithic, and the same issues are prevalent today. Archaeology and sustainability research can and must model and understand how agricultural systems developed, and this thesis provides an avenue forward.

2 CHAPTER 2: A BACKGROUND TO SOCIETY AND ENERGY

2.1 INTRODUCTION

Although some have recognised the existence of an agricultural labour trap within agriculture past and present, archaeology has neither attempted to understand or quantify the agricultural energy feedback system nor has archaeology recognised the energetic dependencies of agriculture and its processes. Further, most energy quantifications of the past are missing or are not based on archaeological data, methods, or analysis. Therefore, before presenting a methodology to quantify past energy systems, this chapter will call attention to the lack of energy quantifications of the past and argue that an archaeological approach to human energy systems is required. To accomplish this, an extensive review of society and energy literature was conducted.

The succeeding subsections of this chapter (2.2 and 2.3) primarily focus on those who try to understand energy's role in the complexity and evolution of society, often via a sustainability lens, i.e., to help formulate a more sustainable future or aid in understanding sustainability issues. Within these bodies of literature, it is often the case that archaeological data and methods are missing and a methodology by which to calculate energy use in the past is non-existent. When energy relationships in the past are quantified, they are typically too generalised and are often mistaken assumptions not in accordance with archaeological data or conclusions. As a result of this, energy sustainability analyses are often narrowly focused on the last 150 to 200 years, and it is suggested that prior to the Western "industrial revolution", human energy systems were in harmony with the environment and any impact they might have had was local and trivial (Hudson, 2012, Lane, 2015, Mann, Bradley et al., 1999, Pétursdóttir, 2017, Steffen, Broadgate et al., 2015). Subsection 2.4, however, focuses on the few archaeologists who have theorised about energy or energy feedbacks, especially regarding the relationship between agriculture and energy. Finally, subsection 2.5 focuses on contextualising archaeological modelling in relation to this thesis, specifically focusing on comparing and contrasting agent-based modelling and optimal foraging theory approaches to the model within this thesis. These types of archaeological modelling are particularly suited to help justify the model within this thesis, especially optimal foraging theory and modelling, as energy is its main form of currency and it analyses costs and benefits (Bird and O'Connell, 2006: 147, Keene, 1983: 140, Kennett and Winterhalder, 2006: 13, 170, Stiner and Kuhn, 2016, Winterhalder and Smith, 2000: 51).

The tools archaeology has at its disposal are being neglected, and thus, quantifications and models of past energy systems are missing, or at best, inaccurate; this is problematic on multiple fronts. First, the lack of quantifications of past energy systems does not allow us to incorporate unintended or unanticipated consequences of past human decisions and actions upon the environment (van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). These likely directly relate to the Global Climate Change issues which we have today; we have been accumulating these unanticipated consequences for thousands of years but are not incorporating these timescales or understandings into models or analyses (van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016).

Further, omitting quantifications of past energy systems thus forces us to mistake causes and effects. For example, the "industrial revolution" is considered a cause of Global Climate

Change now, however, it is likely an effect of earlier processes and potential past unintended consequences(van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011). Finally, the lack of past energy systems in today's sustainability and energy analyses, models, and understandings means they fail to incorporate the deep history of human-environmental relationships and humanity's relationship to energy (Malm and Hornborg, 2014, Steffen, Broadgate et al., 2015). We must have a richer, more contextualised understanding of how our unsustainability and the global climate change problem developed. An energy systems framework that includes an archaeological approach to past energy systems is required, as demonstrated throughout this chapter.

2.2 THE EARLY WORKS: LESLIE WHITE

Understanding the relationship between society and energy is not a new academic aim. One of the earliest attempts to understand the relationship between society and energy was Herbert Spencer's *First Principles* (1867). In *First Principles,* Spencer outlines his social progress and energy theories, explicitly arguing that surplus energy was the mechanism behind social growth, complexity, and activity (Spencer, 1867 :219). Essentially, the more energy a society consumed, the more it advanced (Fischer-Kowalski and Weisz, 1999 :225, Rosa, Machlis et al., 1988 :150). The seminal work of Leslie White, *Energy and the Evolution of Culture* (1943)*,* drew from and rekindled Spencer's energy theories. Although the goal of this dissertation chapter is not to outline the historical development of society-energy literature, as this has been well-documented (see Rosa et al. 1988, Fischer-Kowalski and Weisz 1999, Fischer-Kowalski and Haberl 2007, and Smil 2008, Binford 2001, for example), it would be remiss to exclude discussing White's work, as his theories and themes still echo throughout modern society-energy approaches today.

To White, everything from galaxies, stars and molecules, to atoms and cultures could be described in terms of energy; all of these systems were simply different ways of energy organisation (White, 1943 :335). Society itself was a form of energy organization, and culture was the mechanism by which humans controlled and extracted energy from the environment (White, 1943). In *Energy and the Evolution of Culture,* White specifically sought to understand and classify how cultures harness and utilise energy (White, 1943 :355). White is most renowned for his society-energy mathematical equation, $E\,x\,T = P$ (more commonly known as $E\,x\,T = C$) and was based on his "law of cultural evolution" (White, 1943). Focusing on the equation itself, E represented the energy expended per unit time, T represented the technological means of energy expenditure, and P represented the total amount of goods or services in any cultural situation (the status of culture and degree of cultural development) (White, 1943: 336-338). White's equation above represents his law of cultural evolution: "culture develops when the amount of energy harnessed by man per capita per year is increased; or as the efficiency of the technological means of putting this energy to work is increased; or as both factors are simultaneously increased" (White, 1943 :338). From White's perspective, social evolution was the consequence of technological evolution (White, 1943 :347).

White reduced society to an equation to demonstrate that energy and technology are responsible for cultural development; the more energy expended, the more efficient the technology was at expending energy, or both, the more "advanced" the society (Rosa, Machlis et al., 1988). White provides an analogy of a man cutting wood with an axe to elaborate on his energy equation. If someone cuts wood with an axe, assuming the quality of wood and the skill of the person are constant, the amount of wood cut per hour depends on the energy expended from the man during this time; the more energy expended, the more wood the person cuts (White, 1943 :337). Further, the better the axe they use, the more wood cut, especially if they use a more technologically efficient axe; a steel axe would cut more than an iron axe, which cuts more than a stone axe (White, 1943 :337). Similarly, the more efficient the technology a culture or society uses, the more energy they expend, and therefore, the more they “advance”.

Much like other anthropologists during his time, White viewed society as undergoing an evolutionary, unilinear process. White provides an account of societal energy throughout time, albeit generalising cultural development in a racist and ethnocentric way. White’s sequence of history, culture, and energy was as follows:

> “In savagery (wild food economy) the productivity of human labour is low; only a small amount of human need-serving goods and services are produced per unit of human energy. In barbarism (agriculture, animal husbandry), this productivity is greatly increased. And in civilization (fuels, engines) it is still further increased” (White, 1943 :347).

Essentially, societies based on wild resources did not produce much energy; peoples reliant upon wild resources could only utilise and control their own bodily energy for what he designates as “culture building”, as environmental energy (wind, water, fire) is insignificant and did not provide an energy surplus (White, 1943 :340, 347). Regarding quantifying the energy use of systems reliant upon wild resources, White states that the total energy derived from humans, wind, water, and fire was limited and was dependent upon population size (White, 1943). If a community was reliant upon wild resources, the energy at its disposal was simply the energy of the average of the community, which is less than “one man-power” per capita; more specifically, he states, “the amount of energy per capita in the earliest stage of cultural development was very small indeed—perhaps 1/20th horsepower per person” (White, 1943 :340). This energy value is simply inaccurate; it is not based on any archaeological analyses or data, and it is thus a subjective, baseless estimate. I should note that the inaccuracy of this energy value has not been commented upon, which indicates the level of inattention to modelling past energy systems.

Further, White explains that, historically speaking, those reliant upon wild resources “would have remained on the level of savagery indefinitely” had humans not domesticated animals and cultivated plants; culture building would not have been possible had animals and plants not been controlled by people (White, 1943 :341). For White, social progress is very much tied to exploiting and ‘controlling’ the environment; those that are more efficient at doing so prosper.

Focusing more on his analysis of agricultural-based societies, White states that agriculture and domestic animals produce more energy than wild resources because domestication allowed humans to force plants and animals to do work for them (White, 1943 :341-342). Although White does not energetically model or quantify this, he argues that within an economy reliant upon domestic plants and animals, the initial energy return compared to the energy input amplifies itself (White, 1943 :342). He maintains that agriculture increased the amount of energy per person, which allowed for culture building (White, 1943). Culture-building occurred due to the energetic effects from agriculture, which provided a positive feedback:

> “Agriculture transformed a roaming population into a sedentary one. It greatly increased the food supply, which in turn increased the population. As human labour became more productive in agriculture, an increasing

> portion of society became divorced from the task of food-getting and was devoted to other occupations. Thus, society becomes organised into occupational groups: masons, metal workers, jade carvers, weavers, scribes, priests. This has the effect of accelerating progress in the arts, crafts, and sciences (astronomy, mathematics, etc.), since they are not in the hands of specialists, rather than jacks-of-all-trades….Thus, agriculture wrought a profound change in the life-and-culture of man as it had existed in the human-energy stage of development" (White, 1943: 343-344).

Agriculture helped initiate a feedback that effectively allowed for today's industrial society. Agriculture provided excess energy, forced populations to become sedentary, made human labour more productive, caused the division of labour and craft specialisation, allowed for the accumulation of wealth, and therefore, pushed society to progress to "civilisation" today. According to White, this simply could not happen within cultures whose economies rely on wild resources, as agriculture and domestic animals allow for an ample energy supply and wild resources do not. Although White does not energetically model his theories or base any quantifications on archaeological, ethnographic, or historical data, he argues that historical and archaeological evidence indicates this because of the lack of cultural progress before the Neolithic (White, 1943 :342).

White steers us towards the existence of an agricultural energy feedback system; however, his theory on past and present energy use falls short in many ways. First, his descriptions of cultures and food economies are far too generalised. White actively condemned Boasian cultural relativism and was an avid proponent of social evolutionism; therefore, his descriptions and theories regarding the societies he attempts to energetically describe are ethnocentric, racist, and simply erroneous. White clearly does not fully understand the diversity of activities of cultural groups, past or present, even though archaeological and ethnographic literature at the time supported this diversity in lifeways. Second, because White promotes and relies on a deterministic and ethnocentric understanding of cultures, he is also missing out on the complexities of energy within these cultures, society, and agriculture itself. This is a significant downfall of his energy theory because this drives White's bias and focus on social progress and energy output. Because he is so focused on output instead of flows, he may very well be confusing causes and effects. White states that greater energy use is the primary cause of societal changes over time; however, it is more likely that it is the *effect* of ongoing internal mechanisms. White misses these mechanisms because he does not provide an appropriate energy model of the past.

Further, his focus on energy output does not allow him to explore the energy inputs and energy flows throughout the societies he attempts to classify. This, in effect, inhibits him from recognising the agricultural energy feedback system. Similarly, this prevents White from fully understanding past energy relationships and does not allow him to explore how society-energy relationships have developed over time. Finally, White's accounts of the past themselves are incredibly problematic. White's discussions and theories regarding the past are factually baseless, far too generalised, and his quantifications are haphazardly estimated. White oversimplifies humanity's deep past and has no regard for contextualizing past societies geographically, environmentally, technologically, socially, or energetically. Because he oversimplifies and overlooks humanity's deep past, again, he is missing how energy mechanisms such as the agricultural energy feedback system develop through deep time.

Although inherently problematic, White's work did rekindle a focus on society-energy relationships throughout the 20th century (Chaisson, 2003, Rappaport, 1971, Rosa, Machlis et al., 1988). More importantly, White's work provides a perspective on energy that attempts to include culture and cultural use of energy; people have specific ways of extracting energy and often do so through technology (White, 1943). White’s work is also one of the earliest to provide a theory that comes close to the agricultural energy feedback system discussed in chapter one. However, much society-energy literature focused on sustainability does not necessarily break from the Leslie White tradition of energy research, i.e., there is an inherent focus on energy output, overgeneralisation of culture and the past, neglecting archaeological data and methods in energy quantifications, and the lack of modelling the agricultural energy feedback system. Much of this is echoed even in modern society-energy accounts, which is the focus of the subsequent chapter subsection.

2.3 ENERGY IN THE PAST: ATTEMPTS OUTSIDE OF ARCHAEOLOGY

This chapter subsection primarily concentrates on society-energy literature that addresses the relationship between energy, order, and complexity. This review starts with those who focus on comparing life, Earth, and the Universe, and ends on a more focused, individual case-study of a particular human energy system. Most of the literature within this subsection also analyse such relationships in order to aid in better understanding today’s sustainability issues or investigate avenues towards a more sustainable future.

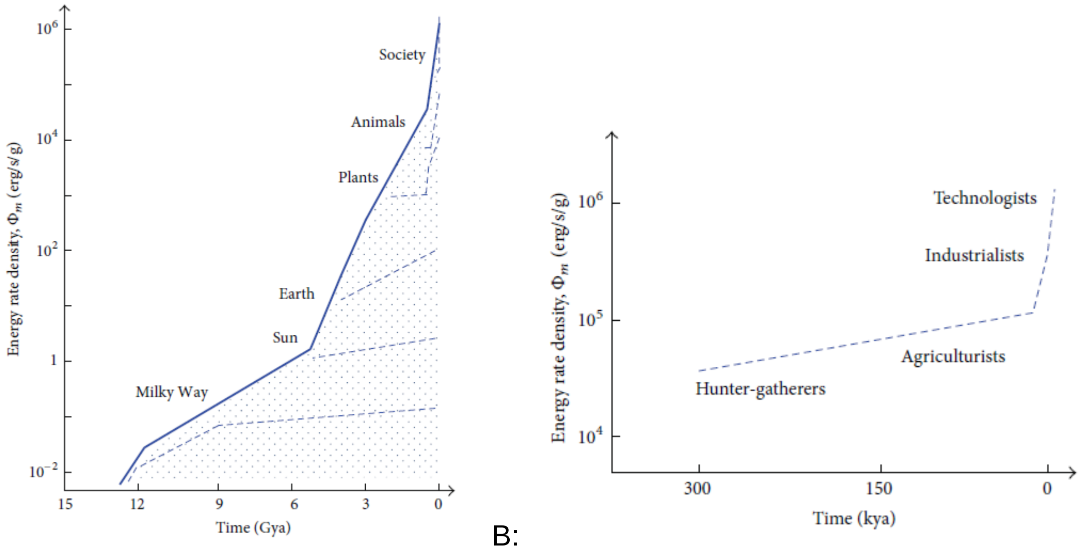
Overall, the literature within this chapter subsection understands energy as the foundation of the complexity and evolution of all systems, whether cosmic, earthly, human, or animal systems. Within this literature, many researchers include or attempt to include past societies and human systems. Quite often, however, human systems and quantifications are often based on sweeping generalisations and assumptions, the past is primitivized, and quantifications of past energy systems are either absent or haphazardly estimated. Because of this, the modelling and development of the agricultural energy feedback system is missing from society-energy research. Thus, many theorists are mistaking causes and effects, and argue that surplus energy output of agriculture is the *cause* of societal development, when it instead results from internal mechanisms surrounding energy feedbacks with agriculture, as a system. Finally, much of this literature does not break from a Leslie White approach to society and energy relationships, in that there is an inherent focus on energy output, overgeneralisation of culture and the past, and overall neglect of archaeological data and methods in energy quantifications.

2.3.1 Big Cosmologic History: Eric Chaisson

The work of Eric Chaisson’s analyses attempt to both include deep history *and* quantify the energy of past societies. Chaisson is a proponent of deep cosmic history, bringing together humanity into a cosmological framework (Chaisson, 2014a, Chaisson, 2014b). Overall, he seeks to create a holistic evolutionary synthesis by modelling and quantifying energy flow in complex systems, from the start of the universe to humankind’s societal systems (Chaisson, 2003, Chaisson, 2005, Chaisson, 2011). Chaisson continuously argues for a focus on energy and theorizes that *energy flow* is the key mechanism of change and order, no matter if the system is physical, biological, or cultural (Chaisson, 2015). Energy flow is the universal and evolutionary driver for all systems (Chaisson, 2013). With regards to human systems, Chaisson recognises that there is a relationship between energy, humans, and societal development over time, stating that “rising energy expenditure per capita has been a hallmark in the origin, development and evolution of humankind … however, none of these early energy-centred cultural theses addressed causality or were in any way quantitative” (Chaisson, 2014b: 26). Chaisson emphasises that energy and humanity have a special relationship, which must be teased out via quantifying energy flows. Thus, Chaisson concedes that a quantitative analysis of energy and society is needed, especially one which includes the past. In this, Chaisson and I agree.

Although Chaisson argues that energy flow and energy can help us understand the evolution of all complex systems, he does not argue that the metric by which to model these systems is a quantification of energy or energy flow per se; instead, he argues that the metric should be a normalized factor known as the energy rate density (Chaisson, 2005, Chaisson, 2011, Chaisson, 2014b). Energy rate density is defined as the total amount of energy passing through a system per unit time and mass, whose units are typically presented in erg/second/gram', one erg being 10^{-7} joules (Chaisson, 2014b). Essentially, energy rate density measures the energy flow rate through a system, normalised with the system's mass (Chaisson, 2011). To Chaisson, what is important is the *rate* at which energy flows through a system, i.e. energy rate density, and therefore, energy rate density can be used to understand complexity because it is responsible for building complexity (Chaisson, 2003, Chaisson, 2011: 28). The higher the energy rate density, the more that system has optimised its energy flows; in other words, the greater the energy rate density, the greater the energy flow density of that system, and thus, the more complex the system (Chaisson, 2003, Chaisson, 2011, Chaisson, 2014b, Chaisson, 2015). By utilising the energy rate density, Chaisson argues that it normalizes all systems in the same way and on the same scale, allowing for an objective comparison of complexity across any system (Chaisson, 2005, Chaisson, 2014b: 4). By quantifying the energy rate density of various systems, it thus is possible and easier to better understand complexity.

Chaisson calculates the energy rate density of many systems, including galaxies, animals, plants, hunter-gatherers, and even early agriculturalists. In terms of energy rate density and complexity, the Milky Way is less complex than the Sun, and the Sun is less complex than the Earth, etcetera; however, society is the most complex system of them all, as it has the highest energy rate density (Figure 2). Similarly, he quantifies the energy rate density of various human groups, past and present, also presented in Figure 2, indicating that hunter-gatherers have a lower energy density rate than agriculturalists, agriculturalists have a lower energy rate density than industrialists, and so forth.



A:

B:

Figure 2: Diagram A from Chaisson 2014, fig. 2., presents the energy rate density for a variety of systems throughout nature, including the Milky Way, plants, animals, and society. Chaisson argues that cultural evolution

is faster than biological evolution which is thus faster than physical evolution. Society is one of the most complex system known, according to energy rate density. Energy rate density units are quantified in erg/second/gram, one erg being 10^{-7} joules. Diagram B from Chaisson 2014, fig. 8, illustrates humanity's per capita energy usage over time; the rise in energy rate density being recently exponential is interpreted, by Chaisson, as society becoming heavily dependent upon energy. Here, energy rate density units are quantified in erg/second/gram, one erg being 10^{-7} joules. Agriculturalist's energy rate density seems to be quantified, based on the work of Vaclav Smil (1994), at roughly 100,000 (10^5) erg/s/g.

Chaisson attempts to quantify energy in the past, although a deeper look into his quantifications indicates that he only models total energy output and greatly generalises and simplifies the past. For example, not only does Chaisson describe hunter-gatherers insensitively as “relatively simple cultures” but his energy rate density quantification is based on a combination of “ancient habitats of extinct forebears [australopithecines] but also by observing mores of modern hunting groups extant in today’s tropical forests,” to surmise that the energy exploitation of hunter-gatherers could have been ~40,000 erg/s/g for archaic Homo sapiens (Chaisson, 2014b:26-27). It is difficult to pinpoint how this was quantified as it is not based on available archaeological data, appropriate ethnographic analysis, or experimental archaeological data, and it generalises all hunter-gatherers to modern hunting groups in the tropics (Chaisson, 2011, Chaisson, 2014b). Although archaeology often utilises ethnographic analogy to aid in our interpretations and conclusions, Chaisson’s attempt at quantifying all hunter-gatherer lifeways by utilising an extremely small sample of present societies and extinct hominids without utilising or drawing from archaeological data, methods, or analysis, is problematic and too generalising.

Similarly, Chaisson’s quantifications of agriculturalists are solely focused on energy output and do not utilise archaeological data to support his quantifications. Chaisson argues,

> “within the onset of agriculture and the use of trained animals ~10kya, the equivalent energy available to individual H.sapiens (assumed here to be a 50kg body) increased energy rate density to 12,000 kcal/day or ~10^5erg/s/g; in turn these would have easily doubled with the invention of advanced farming techniques and invention of metal and pottery manufacturing a few millennia ago” (Chaisson, 2014b: 27).

It is difficult to pinpoint how this agriculturalist energy output and energy rate density were quantified; they are not based on available archaeological data, appropriate ethnographic analysis, or experimental archaeological data. Focusing on his energy output calculation, it is unclear how this was calculated and which crops were included. There is variation with crop domestication across time and geographical space; thus, both energy input and energy output would vary based on the crop. None of this is specified in his model. Similarly, Chaisson assumes a 50-kilogram body standard to normalise agriculturalist energy flow and does not utilise archaeological evidence to utilise this weight value. Bioarchaeological data and methods can aid in quantifying average size of populations and are based on skeletal evidence, yet Chaisson does not use such bioarchaeological data or methodology to support this claim (Elliott, Kurki et al., 2016, Hillson, Larsen et al., 2013, Jeanson, Santos et al., 2017, Larsen, Hillson et al., 2015). Instead, Chaisson does not use archaeological data or methods to substantiate this mass value.

Focusing on the Neolithic Revolution, Chaisson argues that the Neolithic was energy-enhanced due to food production being deliberately managed, which resulted in cities, warriors, regional alliances, and eventually nation-states (Chaisson, 2014b: 27). However, Chaisson does not quantify this “energy-enhancement” of the Neolithic, nor has it ever been quantified or modelled based on archaeological data. He, like White, is missing the mechanisms which helped initiate such fundamental changes. Chaisson focuses on analysing only the energy *output* of past agricultural societies based on quantifications that are, at best, haphazardly estimated. By focusing exclusively on energy output, Chaisson is completely missing the energy *input* required of past and present agricultural societies, how this energy flows throughout the agricultural system, and even agriculture's costs and benefits. Although it may be the case that as societies changed over time, more energy was used, this has not been quantified or modelled using *archaeological* data and analysis, rendering Chaisson's quantifications of the past imprecise. Thus, Chaisson is missing the link and mechanism that may very well connect the agricultural revolution with the advent of cities, warriors, alliances: the agricultural energy feedback system.

Concerning agriculture and population growth, Chaisson describes that agriculture's "greatest achievement was to feed the growing human population", and underlying the cultural advancement of society from the Neolithic revolution to the Industrial Revolution was "greater energy usage per unit mass at every step of the way" (Chaisson, 2014b: 27). Chaisson, like White (1943), reduces "social progress" to greater energy usage. Societal and cultural development cannot be simplified to "more energy = more advanced society;" it is *how* societies utilise this energy and how energy flows within societal systems; thus, societal energy inputs must also be a part of these quantifications. Chaisson's analyses are wholeheartedly missing this; thus, his theories and methodology are missing how energy ties in with the relationships between agriculture, energy, and population growth.

Further, Chaisson argues for the importance of energy flows, yet he completely disregards energy input and how this energy input flows throughout the agricultural societies he discusses. Similar to White (1943), Chaisson seems to be mistaking causes and effects. Again, increased energy output is being interpreted by Chaisson to be the cause of societal complexity; however, it may very well be the result. His lack of modelling energy flows through cultural and agricultural systems forces him to miss the mechanisms potentially causing this. Finally, Chaisson also defines and describes agriculturalists in a blanketed way, even though archaeological and ethnographic literature shows a diverse array of agricultural lifeways. A narrowed-down case study exploring a specific past agricultural lifeway or comparing multiple agricultural lifeways in the past would have been superior to a model based on few baseless generalisations.

Overall, the issues arising from Chaisson's energy quantifications are tied to underutilising archaeological data, methods, and analyses, and more importantly, lacking a methodology to quantify past human energy systems. Albeit somewhat problematic, Chaisson's work helped to emphasise the importance of energy flows. By focusing upon energy flows, Chaisson highlights the advantage in utilising energy to compare all systems along the same scale, and he utilises energy to brings us closer to an understanding that energy use in the past is absolutely linked to the present.

2.3.2 Energy Economics: Vaclav Smil

Vaclav Smil takes an 'energy economics' approach to understand the mechanisms behind complexity and energy. Like Chaisson and White, Smil argues that efficient energy management is the driver of complexity and the reasoning behind the order of all things; the entire biosphere is an assemblage of energy stores and flows, and life maintains itself via the conversions of energy (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). Society is no different from the biosphere, and "civilization" as we know it is the direct result of society's quest for higher energy (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). To Smil, the disastrous effect our societies have had on the Earth System is the direct result of an evolutionary dependence on higher energy flows (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). Moreover, Smil theorises that like all other systems, society evolves and is complex due to higher and more efficient energy inputs (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). To address today's sustainability issues, he argues that what is needed is a systematic, interdisciplinary overview and evolutionary account of energy in natural and societal systems (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). Smil attempts to provide this via quantifying energy in both natural and human systems by highlighting energy input and output, efficiency savings and quantifies the energy balances of various systems, including planetary, photosynthetic, heterotrophic, and human systems (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017). Smil is one of the few grand energy theorists who attempt to quantify energy relationships in humanity's past and even discusses various archaeological sites. However, like White and Chaisson, throughout his work, Smil consistently makes sweeping, simplified generalisations regarding the energy of past societies.

One of the past energy calculations Smil quantifies is the yearly maximum amount of wood consumption for open-fire meat cooking during the Late Palaeolithic (Smil, 2013, Smil, 2017). He quantifies this as 1.5-2.2 Gigajoules per person per year (Smil, 2013, Smil, 2017). He bases this off the following: an average daily food energy intake of 10 megajoules per capita, meat comprising 80% of the diet (8 megajoules), the food energy density of animal carcases as 8 to 10 megajoules per kilogram (he assumes mammoth meat, but if we assume large ungulates the value is lower), various climatic temperatures, meat being cooked at 80C, various cooking efficiency data, an average density of air-dried wood, and an average daily per capita intake of Palaeolithic hunters of 1 kilogram of mammoth meat per day (or 1.5 kilogram of large ungulate meat) (Smil, 2013 :74-76, Smil, 2017 :27). This is a detailed attempt at quantifying the yearly maximum amount of wood consumption during the Late Palaeolithic. Nevertheless, none of the data or assumptions he makes is based on any archaeological data, methods, or analyses. His assumption of meat consisting 80% of the palaeolithic diet and a daily meat intake of 1 to 1.5 kilograms per day is uncorroborated with bioarchaeological, archaeobotanical, zooarchaeological, archaeological or even isotopic data.

Regarding "prehistoric agriculturalists", regrettably, Smil does not provide calculations of agriculture in the past. Instead, Smil makes generalised statements regarding agriculture, e.g., agriculture was more energy-intensive than hunting, gathering, or foraging, and agriculture as a system allowed for a higher net energy return for societies (Smil, 2017 :42-44). Within Smil's analysis, past agricultural energy is taken no further than this. He has no calculations regarding what he deems as "prehistoric agriculturalists" but assumes that the shift to agriculture in the Neolithic would have had the same energy inputs and returns as those of traditional agricultural societies today. When describing "early agriculture," he states that it took the form of shifting cultivation, assumes fallow times, states that all agricultural lifeways are driven by efforts to minimize energy expenditures, and provides a generalised narrative of what early agriculture might have been like, including that all agriculture was slash and burn type agriculture (Smil, 1994, Smil, 2013, Smil, 2017). Although Smil recognises that agriculture has higher human energy inputs, states that it supports higher population densities and provides a more reliable food supply, he does not energetically model any of this. For example, when describing net energy returns of agriculture, he solely relies upon modern horticultural values from a limited number of locales, assuming they are fully representative of all past agricultural societies (Smil, 2017 :44-45). Regarding gender roles in past agricultural societies, he even goes so far as to state that "men did the heavy work while women's labour was dominated by weeding and harvesting"(Smil, 2017 :44). Focusing on animal husbandry, Smil simplifies relationships between animals and humans in the past as simply "prey conservation" (Smil, 2017 :45). However, Smil theorises and attempts to explain and understand the relationship between agriculture, energy, and population growth. Smil is close to recognising the agricultural energy feedback system, specifying the presence of a sort of feedback within *modern*, traditional agriculture:

> "Once established, storage supported sedentation could not be abandoned without returning to lower population densities. The new mode of existence [settled agriculture] precluded frequent mobility and fostered the emergence of new activities and opportunities. Human existence shifted to a fundamentally different way of subsistence, and widespread surplus accumulation became the norm. The process was clearly self-amplifying: the human quest to manipulate an ever-larger share of solar energy flows set the societies on the road toward higher complexity" (Smil, 1994 :22).

Although Smil's arguments do not take us beyond Leslie White's "more energy leads to more complexity" type theories, he does recognise the existence of a feedback within agriculture societies. Smil even states, whilst focusing on modern agricultural societies, that intensive cultivation required more energy and "most of the additional energy inputs had to come from longer hours and harder exertion of human labour. Moreover, intensified food production often had a lower energy benefit/cost ratio than its less intensive predecessors" (Smil, 1994 :22). He states this throughout his work, yet he does not energetically model this. Delving into his discussions of the intensification of agriculture in traditional societies, Smil states

> "the advancing intensification of farming sustained higher population densities, but it also demanded higher energy expenditures, not only for direct farming activities but also for such critical supportive measures as the digging of wells, the building of irrigation canals, roads, and food storage structures, and terracing of fields. In turn, these improvements required more energy to make a large variety of better tools and simple machines" (Smil, 2017 :51).

In essence, although the intensification of agriculture did allow for more population growth, it required significant energy expenditures in all kinds of ways, initiating a sort of energy feedback where agriculture requires more and more energy. Although Smil is getting us towards an agricultural energy feedback system, what he is missing is that this sort of "trap" was not just present in modern agricultural societies or pre-industrial revolution agricultural lifeways, but it has likely been present since the Neolithic. Because Smil has no way to quantify energy in the past and does not have a holistic understanding of human relationships and activities in the past, he is forced to rely upon sweeping, incorrect generalisations. Smil attempts to theorise about the transition to agriculture and the relationship between agriculture, energy, and population growth in the past without actually drawing from archaeology to do so. He misses this because he has not energetically modelled a past agricultural energy system.

Additionally, although Smil does attempt to model modern, traditional agricultural inputs, he neglects to model the input of agricultural processes separately. For instance, regarding labour and energy requirements, he specifies that using an average of net energy costs of traditional farming works well; in other words, looking at total input for agricultural processes instead of modelling them separately, suffices (Smil, 2017 :60-61). Although agricultural processes vary in difficulty, time to complete, and even in the tools required, modelling the labour and energy of agricultural processes separately is unnecessary to Smil (Smil, 2017 :60). In this regard, I wholly disagree. As this thesis demonstrates throughout chapters 4 to 7, agricultural processes are not energetically equal, and it is crucial to understand how agricultural energy flows through agricultural systems; this cannot be completed by focusing solely upon total input. Instead of modelling the energy of agricultural processes separately, Smil makes generalised statements about them, such as “a considerable amount of energy went into crop processing,” and “harvesting was the most time-consuming task” and put clear limits on what families could manage, yet, he does not model any of these (Smil, 2017 : 57, 64).

Focusing on the difference between different crops, Smil recognises differences in the energy inputs and outputs of crops exist; however, he does not model said differences. This is a mistake. As this thesis demonstrates, free-threshing wheats require different energy inputs than hulled wheats, and this is something that cannot be neglected. Further, although Smil does discuss losses and even seeding, recognising that farmers must set aside a portion of every harvest to seed the following year, he does not model or even discuss it concerning storage requirements or agricultural processes’ inherent dependency upon one another and one another’s success. Overall, because Smil does not model agricultural inputs separately, he is missing that agricultural processes require a significant amount of energy to perform, and they are dependent upon one another’s success. If one agricultural process fails, the entire agricultural system and subsequent flows of which it is a part break down. Although his attempt to focus on inputs and outputs is notable, he is missing *how* this energy flows within subsistence lifeways, past and present.

Smil does state and claims to recognise that humanity’s past was varied and diverse geographically, temporally, and culturally and that he does not seek to generalise the past, yet his models do just this. He even goes so far as to state that researchers cannot reconstruct pre-agricultural subsistence (Smil, 2017 :40). Clearly, Smil does not know or understand the tools archaeology has at its disposal; bioarchaeological, archaeobotanical, or experimental archaeological data could aid his models, yet he does not utilise them. Further, because there is no method by which to calculate the energy of subsistence lifeways in the past, he instead must resort to relying upon sweeping generalisations. Thus, Smil’s work is yet another example of past energy quantifications lacking archaeological input. Further, Smil’s work also points out the overall lack of understanding of the variety of activities foraging, hunting, and gathering, either today or in the past. Both present and past hunter-gatherers' social and economic relationships are far more complex and diverse than once assumed (Kelly, 2013, Milner, Conneller et al., 2018:23). He also treats living and traditional agricultural societies as evolutionary relics, something the fields of archaeology and anthropology no longer condone (Kelly, 2013 :26). For example, to further elaborate on foraging energetics in the past, Smil uses 20th-century foraging groups to calculate foraging outputs and explains that this provides “an excellent window on the lives of prehistoric foragers” (Smil, 2017 :34). Overall, because he is missing this archaeological research, knowledge, and methodology to quantify past energy, Smil’s work comes up short in modelling energy use in the past.

Although Smil’s work falls short in several ways, he is one of the only grand energy theorists who associates humanity’s greater energy output as society’s *downfall* and being directly related to our current sustainability issues. Further, his use of energy efficiency and comparing traditional agricultural systems to modern ones has proved pivotal for this thesis. Smil’s comparison and efficiency of energy systems was the foundation for utilising energy efficiency (EROIE- energy return on invested energy; see chapter 7.2, Figure 41) as a way by which to analyse Çatalhöyük’s agricultural energy system. This allows for a comparison of all aspects of energy systems and processes and, if warranted, permits comparing past and modern energy processes.

2.3.3 Ecological Energetics: Howard Odum

Howard T. Odum, renowned ecologist and pioneer of ecological engineering, takes a macroscopic approach to understand the relationship between society, the environment, and energy (Odum, 1973, Odum, 2007, Odum and Odum, 1977). To Odum, nature consists of one energetic system, including microorganisms, plants, animals, human societies, and earth processes, all of which exchange energy flows (Odum, 2007). All systems depend on the flow of energy per unit time (power) to develop, produce, grow, and function; all systems, including human systems, seek to produce a maximum power output (Odum, 2007: 32, Odum and Pinkerton, 1955: 331-332). This maximum power principle, developed first by Lotka (1922), is critical throughout Odum's works (Lotka, 1922a, Lotka, 1922b, Odum, 2007, Odum and Pinkerton, 1955). To achieve maximum power output, systems maximize their energy intake and energy processing efficiency (Odum, 2007: 56-57). This maximum power law controls system growth, production, competition, succession, energy storage, diversity within the system, and system pulsing (Lotka, 1922a, Odum, 2007: 32).

Focusing more on Odum's theories of energy and society, Odum makes it explicitly clear that societies are no different from any other system on Earth (Odum, 1973, Odum, 2007, Odum and Odum, 1977). Odum takes this further and equates complex ecosystems with complex societies: "Nature, civilization and the whole biosphere and Earth and the miniature worlds of ecological microcosms are similar. All use energy sources to produce, consume, recycle, and sustain" (Odum, 2007 :1). Like any other system, society utilises energy and abides by maximum power laws (Odum, 1973, Odum, 2007, Odum and Pinkerton, 1955). Humanity's biological and social evolution are based on the photosynthetic energy of the environments to which people are adapted (Odum, 2007 :177). All societies and societal diversity are based on their environments' energy flows, and cultures and customs were created to aid in maximum energy production of these photosynthetic pathways (Odum, 2007:176, Odum and Odum, 1977:179). In other words, societal diversity depends on ecosystem design and variation, and culture is the mechanism by which societies use to process environmental energy (Odum, 2007 :133). To validate this, Odum analyses various societies from a macroscopic, ecological lens to understand the energy flow requirements of humanity, the systems of which it is a part, and, overall, to utilise knowledge of past energy systems to predict and help plan for a more sustainable future (Odum, 2007, Odum and Odum, 1977).

Although Odum does not explicitly quantify and model past societies' energy, he argues that the energy sources for past societies were only based on various earth cycles and past humans played a minor role in ecosystem energetics (Odum, 2007 :177). In his early work (1977), he argues that the variation of early tribes and civilizations was due to the climatic belts of the earth, seasonal differences in sunlight, rain, and migratory animals, and within his later work (2007), Odum continues to argue for this environmentally deterministic approach (Odum, 2007 :177, Odum and Odum, 1977 :133). To Odum, societies were adapted to the environment, and the environment itself determined all energy flows. To achieve maximum power output, societies maximized their energy intake and energy processing efficiency by adapting to their environment and its variation (Odum, 2007). Although environmentally deterministic, Odum was very influential within archaeological theory, especially within the work of Lewis Binford, who draws heavily from Odum (see 2.4.1).

To better understand how societies achieve maximum power output, Odum separates history into what he designates as "solar" societies and "industrial" societies (Odum, 2007, Odum and Odum, 1977). The former designates those societies based on environmental energy flows (solar, oceanic, and earthly processes) such as hunter-gatherer societies and agrarian societies, and the latter are those based on non-renewable fossil fuels from the industrial revolution onwards (Odum, 2007 :5-6, Odum and Odum, 1977). Unlike solar societies, which are energetically balanced, industrial society today is unsustainably consuming the Earth's resources; by delving into past societies and other types of societies, Odum argues it is possible to plan for a more sustainable energetic future (Odum, 2007 :124). Odum provides an energetic account of many modern solar societies, including those located in environmental locales such as savannas, monsoonal regions, forests, tropical forests, and island atolls, to understand past and potential future societal energetics (Odum, 2007). Instead of utilising archaeological case studies to understand past solar societies, Odum utilises modern agrarian and hunter-gatherer case studies to demonstrate that solar societies did not interfere with energetic ecosystem stability in the past or present.

Focusing on hunter-gatherer societies, he surmises that these societies and the differences in their lifeways represent the ways groups adapted to environmental energy flows (Odum, 2007, Odum and Odum, 1977). Figure 3A demonstrates a hunting, gathering, and gardening society within a complex ecosystem. The bulk of the energy storage is within the complex forest and the diversity of consumers upon which hunting and gathering peoples are reliant; the system itself is balanced (Odum, 2007). Hunter-gatherer societies maximize their power output by allowing complex ecosystems to process energy for them (Odum, 2007). He argues that hunter-gatherer societies helped to control wild species, and the energy per person was as great as it is in urban societies today; however, unlike society today, the hunter-gatherer system was balanced (Odum and Odum, 1977 :136-137).

Similarly, Odum argues that agrarian societies are solar societies that also lived in harmony with the environment: “with people and domestic animals living off the land, there was often a balance of primary production and total respiration (consumption) in the course of the year… the system was balanced as an aquarium is balanced” (Odum, 2007: 6-7). Like hunter-gatherer systems, solar agrarian societies were energetically balanced. However, unlike hunter-gatherer systems, where the energy is stored and processed in the immediate environment, energy processing for agrarian societies is concentrated in agriculture and animals (Odum, 2007). In other words, agricultural systems utilise animals as energy storage *and* as energy processing mechanisms, whereas hunter-gatherer societies utilise the ecosystem itself (Odum, 2007). Because of this, for Odum, agriculture and domestic animals permitted people to channel environmental energy more efficiently, which provided a surplus of energy to society, leading to more activity and a higher societal carrying capacity (Odum, 2007). This allowed for an energy surplus that could not be gained within hunter-gatherer societies (Odum, 2007, Odum and Odum, 1977). However, Odum argues that the caveat to agrarian societies is a decrease in diversity of foodstuffs and, therefore, less protection from epidemics and famines (Odum, 2007, Odum and Odum, 1977). In addition, agriculture forced people to become more dependent on fewer resources, resulting in populational ebbs and flows within societies to balance energy, which is not witnessed in hunter-gatherer societies (Odum, 2007, Odum and Odum, 1977). Relating this to the agricultural energy feedback system posited in this thesis, Odum is getting us toward this; however, he is missing that agriculture within it has mechanisms that effectively force those participating to become more dependent upon agriculture and further investment into its flows.

Odum utilises the example of a “typical sacred cow agroecosystem” reliant upon rice agriculture to demonstrate and compare the energy flow differences between hunter-gatherer and agrarian societies (Odum, 2007). Odum argues that rice agriculture was the most successful ancient system which could support dense populations because it is based on natural energy of monsoonal climates and domestic animals were used as “energy transformers” to plant, fertilize, weed, and as energy storage devices (Odum, 2007 :184). Figure 3B demonstrates Odum’s model, based on Harris (1965) and Brown (1965). The entire system is balanced (solar input= 1.350 Kcal/m2/yr.; energy output= 1.352 Kcal/m2/yr.) and is based on solar energy, but the concentration of energy is distributed through cows within this system, as opposed to a complex forest within Odum’s hunting and gathering system, (Figure

3A) (Brown, 1965, Harris, 1965, Odum, 2007). Unfortunately, there are no quantifications for what Odum describes as hunter-gatherer societies.

Odum argues that the cultural sacredness of cows is directly tied to the fact that they both provide and control energy throughout this particular agroecosystem (Odum, 2007). Cows are essential for enhancing nutrition from different food chains (weeds, rice stores, humans), producing bulls required for agricultural labour, keeping the agricultural system functioning, recycling minerals, and providing milk proteins (Odum, 2007:184-185). Odum bases this on Marvin Harris' (1965, 1966) interpretations of Indian cattle as an essential part of Indian ecosystems; it should be noted that Harris' accounts were based on his "intensive readings" and research and were an attempt to understand the economic and ecological aspects of Hinduism in India throughout the early 20th century (Harris, 1965, Harris, 1966: 51). Odum's "sacred cow agroecosystem" quantifications are as follows: he assumes a population density of 640 people per square mile, 0.1 animals per person, rice yield of 250 kilograms/acre/year, one-third of food calories for cattle are present in faeces, work and faecal fertilization is half of animal metabolism, animal protein intake for India as 6g per person, 2% of food crop is fed to animals, animal metabolism is 8,000 kilocalories per day, and farm work is assumed to be 10% of total worker hours (Odum, 2007 :184).

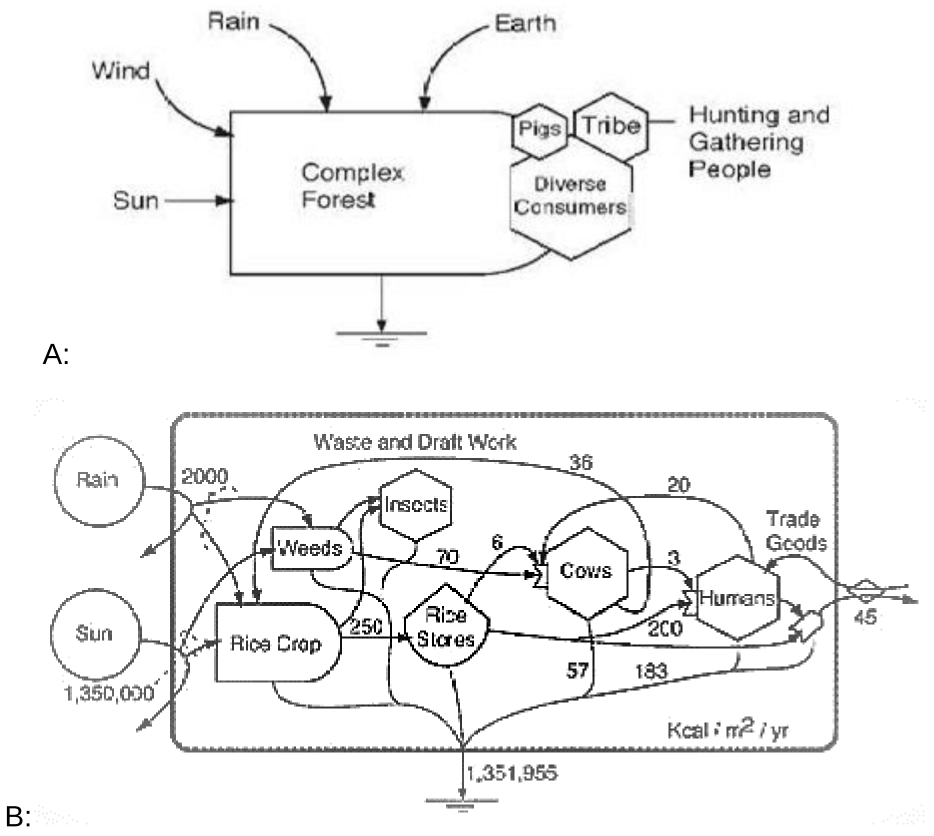


Figure 3: Figure 3A is Odum's (2007: fig. 7.1, pg. 178) diagram representing the energy system within a hunting, gathering, and gardening society in low density within a complex ecosystem. Figure 3B is Odum's (2007: fig. 7.4, pg., 186) energy system diagram of a Sacred cow agroecosystem in India during seasonal monsoonal wet and dry pulses.

Odum's flow of a "typical sacred cow agroecosystem," at best, is an ethnocentric description and highly reductionist. Regarding his energy system diagram of hunter-gatherer societies, Odum, like others, does not understand human societies' cultural diversity or intricacies, and these are missing from his models. Further, there are no quantifications for any hunter-gatherer society, past or present.

Focusing on Odum's agricultural energy quantifications, the calculations seem to be grand assumptions and are not based on empirical data. Odum's population density of 640 people per square mile is based on "tropical dense populations" which is far too vague (Odum, 2007: 184). Here, Odum could have utilised a particular case study and utilised its population density. Odum's assumption that animals are present as 0.1 animals per person is quite simply flawed; no one can have 0.1 animals as animals are whole entities. Again, this does not seem to be, at minimum, supported by any ethnographic or historical data. Grain yields are based on historical crop yields; however, it is unclear where these crop yields are from, what time period they are from, or whether this value is from an average, low, or high yielding scenario. Crop yields vary environmentally and historically; his model would have benefited from utilising quantifications from various crop yield situations. Similarly, the animal protein intake is not based on relevant ethnographic data and is instead generalised data. Regarding animal metabolism quantifications, it is simply unclear from where these derive. Concerning "farm work," it is also ill-defined from where his 10% of work hours dedicated to farming work stems. Further, Odum does not designate what this "farm work" entails. Although there is a plethora of ethnographic, historical, human energetics, and experimental data surrounding the input of agricultural labour (Dietrich, Meister et al., 2019, Gregg, 1988, Halstead, 2014, James and Schofield, 1990, Meurers-Balke and Lüning, 1999, Passmore and Durnin, 1955, Russell, 1988, UNU, 1985, UNU, 2004, Wright, 1994), Odum neither utilises it nor includes this in his models. I argue that this is one of the most crucial mistakes Odum makes. Because he generalises farm work and neglects to model the assortment of activities it entails, he is missing that maximum power output may not be the cause of diversity within social systems but may be a *symptom* of energy flows and energy systems. Moreover, because he does not appropriately model agricultural activities, he is missing the agricultural energy feedback system, which could help strengthen his model regarding population ebbs and flows and their relationships to agriculture.

Related to this, Odum does not have a way to quantify and model human energy input because he is taking such a staunch ecological and macroscopic approach. Because he is inherently focused on the environment and ecology, he is missing the crucial fact that humans also alter and help manipulate the energy flows within energetic systems; the environment does not complete this alone, even within what Odum deems hunter-gatherer systems. Overall, the human aspect is completely missing from his model, and instead, it is environmentally deterministic. Focusing exclusively on environmental energy flows is simply neglecting the relationship between humans and energy. Finally, Odum relies solely upon modern agrarian and hunter-gatherer societies whilst treating them as evolutionary relics.

Many of the issues within Odum's work are likely related to the fact that there is not a methodology by which to quantify energy use in the past. However, Odum's contributions toward understanding energy in the past are still quite significant. First, Odum recognised that cultures indeed play a role in energy flows, past or present. Although he does not explicitly model past energy, he does recognise the merit in energetically understanding past societies. Second, Odum understood that agriculture as an energy system was not as energetically advantageous or sustainable as others have suggested, recognising that agriculture effectively trapped society into depending upon specific energy resources and that it plays a role in population ebbs and flows. Thus, Odum's work brings us closer to the energy mechanisms within the agricultural energy feedback system.

2.3.4 Societal Metabolism: Marina Fischer-Kowalski

Societal metabolism is the theoretical approach that views human societies as metabolic entities and hybrids between the natural, cultural, and the material world (Fischer-Kowalski and Weisz, 1999). Within this approach, all societies are subsets of the biosphere which have a metabolism requiring energy and material inputs from the environment, which are subsequently returned to the environment in various forms; if societies do not meet their material or energetic requirements, they perish or change their form (Fischer-Kowalski and Weisz, 1999: 229). Because societies are viewed as sustaining themselves under specific environmental circumstances via their energy and matter exchanges, socio-metabolic approaches typically focus on modelling and understanding the flows of materials and energy (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Weisz, 1999: 12). Furthermore, material flows and energy aid in a society's development and organisation; thus, it is crucial to investigate these inputs and outputs, flows, and understand how these function and relate to the environment (Fischer-Kowalski and Haberl, 1997). Overall, societal metabolic approaches are pivotal to any analysis of energy, including this thesis.

The work of Marina Fischer-Kowalski takes such a societal-metabolism approach to sustainable development and has proved to be crucial for the foundation of this thesis (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999). Fisher-Kowalski and her co-authors consistently argue that our modern sustainability problems are directly related to our societal metabolism, as societies use resources from the environment and transform these into waste and emissions (Fischer-Kowalski and Haberl, 1997).

For Fischer-Kowalski and co-authors, history provides us with a timeline of how society today became unsustainable, or in their words, "colonised" Earth's system in a potentially irreversible manner (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999). Somewhat similar to Shennan's (2007, 2018) colonisation in chapter 1 and Rindos's (1980) notion of environmental instability, Fischer-Kowalski and colleagues notion of colonisation occurs when natural processes are intentionally and persistently transformed using various interventions (i.e. planting, growing, fertilising, breeding), resulting in unintentional and intentional consequences (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski and Weisz, 1999). In all cases of colonisation, there is a high degree of human organisation of labour and information, in addition to technologies that aid in completing environmental transformations (Fischer-Kowalkski and Haberl, 2007: 18, Fischer-Kowalski and Haberl, 1997: 65, Fischer-Kowalski and Weisz, 1999: 215, 231-236). Once environmental or land colonisation occurs, the systems of which it is a part never revert to their original states (Fischer-Kowalski and Weisz, 1999: 236). Fischer-Kowalski and colleagues suggest that our sustainability issues are linked to such environmental colonisation; to understand our sustainability problems today, we must understand both a society's metabolism, what colonisation practices took place, and know at what point in human societal development colonisation occurred (Fischer-Kowalski and Haberl, 1997). At some point in our history, humanity's societal metabolism became uncontrollable or unsustainable; to understand how this occurred and find solutions to this unsustainability, we must understand the metabolism of societies past and present (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999). By modelling and understanding the energetic exchanges between humanity and nature over time, it is possible to identify which societal metabolisms are sustainable or unsustainable and use them to analyse contemporary society today and form a more sustainable future (Fischer-Kowalski and Haberl, 1997: 62). Thus, most of Fischer-Kowalski's work focuses on modelling quantifying energy use through time, focusing on various subsistence lifeways.

Regarding societal energy, Fischer-Kowalski and colleagues' model societal energy by taking a formulaic approach which is similar to Leslie White's (1943) energy equations. As a reminder, White's (1943) equation was, $E\ x\ T = P$, E representing the energy expended per unit time, T representing the technological means of energy expenditure, and P representing the status of culture and degree of cultural development (White, 1943: 336-338). Fischer-Kowalski et al. draw from an IPAT formula, $I = P \times A \times T$ (Ehrlich and Ehrlich, 1991, Fischer-Kowalski, Krausnmann et al., 2014). This formula is taken from Ehrlich and Ehrlich (1991), who attempted to quantify environmental degradation and the total impact of society, which they argue can be lowered by decreasing P (population), A (affluence a population enjoys), or T (technology) (Ehrlich and Ehrlich, 1991: 58, Fischer-Kowalski, Krausnmann et al., 2014). Fischer-Kowalski et al. 2014 alter this equation slightly and designate that *I* represents environmental impact (e.g. greenhouse gas emissions, biodiversity loss), *A* is metabolic rate, in other words, the average energetic input into the socioeconomic system per person per year, *T* represents technology, and *P* is the human population estimate (Fischer-Kowalski, Krausnmann et al., 2014). With this equation and building from previous work, Fischer-Kowalski and colleagues quantitatively compare the sustainability and metabolic profiles of hunter-gatherer societies, agrarian societies, and industrial societies over the last two millennia to understand how and when humans "dominated" the Earth System (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999).

Fischer-Kowalski and her co-authors focus first on past hunting and gathering subsistence lifeways and argue that their social metabolism can be designated as "passive solar utilisation" (Fischer-Kowalski, Krausnmann et al., 2014, Sieferle, 2003). Passive solar utilisation is when society's energy metabolism depends on solar energy converted into plant biomass with no deliberate intervention in this energy transformation (Fischer-Kowalkski and Haberl, 2007, Sieferle, 2003). In Fischer-Kowalski's terms, past hunter-gather societies do not "colonise" their environment because they do not intentionally or persistently transform natural processes (Fischer-Kowalkski and Haberl, 2007). Focusing more so on their IPAT formula, Fischer-Kowalski and colleagues consistently describe hunter-gatherer energy as only being based upon the food available from ecosystems and fuel for fires (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014). Fischer-Kowalski et al. argue that archaeological evidence indicates the only energy (A) utilised by such groups was food and firewood, therefore, this is all that one needs to consider, although they completely overlook archaeological evidence (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014). Focusing on technology (T), they argue that past hunter-gatherer technological development was, again, only based upon fire and hunting gear, and therefore, the energy used for hunter-gatherer technology per person per year should be considered as static (Fischer-Kowalski, Krausnmann et al., 2014: 11-12). For Fischer-Kowalski and her co-authors, nothing else needs to be considered for hunter-gatherer technology as this lifeway does not allow for an accumulation of belongings, there is little environmental pollution, hunter-gatherers in the past "did not build any durable infrastructures," and therefore, the only sustainability threat they would have caused is overexploitation of resources (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski, Krausnmann et al., 2014: 12). Populationally (P), Fischer-Kowalski do draw from archaeological data, citing genetic and population growth rate data from populations and estimates in Pre-Neolithic Europe, Western Africa, and Southeast Asia (Fischer-Kowalski, Krausnmann et al., 2014: 12, 28). With this data, Fischer-Kowalski and colleagues calculate hunter-gatherer societal metabolism as follows: food (including waste and losses) ranges between 3-4 Gigajoules per person per year, a rough fuel-wood consumption estimation is 6 Gigajoules per person per year, totalling to 11 gigajoules per person per year (Fischer-Kowalski, Krausnmann et al., 2014: 22). The food energy quantifications Fischer-Kowalski utilise are based on the assumption of a mixed diet and the wood needed for fire in a temperate climate (Fischer-Kowalski and Haberl, 1997: 69, Fischer-Kowalski, Krausnmann et al., 2014). Other than this vague description, it is very difficult to identify from where these estimates derive or how this was calculated.

Like others described throughout this chapter, Fischer-Kowalski's descriptions of past hunter-gatherer societies are incredibly generalised and far too simplistic. The only estimations based on archaeological data are population estimates. Overall, it is difficult to pinpoint how their food energy estimates and wood estimates were quantified, as they are not based either on available archaeological data, appropriate ethnographic analysis, or experimental archaeological data, and they generalise all past hunter-gatherers to those in temperate climates. Additionally, the fact that Fischer-Kowalski and colleagues state that hunter-gatherers in the past did not build any infrastructures and had no changes in technology is ludicrous. For example, Göbekli Tepe's inhabitants were sedentary Neolithic hunter-gatherers, with evidence of monumental buildings and richly decorated stone pillars up to 5.5 meters high; its inhabitants even had standardised and efficient grinding tools (Dietrich, Meister et al., 2019). Recent archaeological research (i.e., Mesolithic site of Star Carr) indicates that the Mesolithic period had variations in technology, resources, architecture, patterns of mortuary practice, settlement, mobility, and territoriality; thus, the Mesolithic was quite complex and dynamic (Conneller, 2006, Milner, Conneller et al., 2018, Spikins, 1999, Waddington, 2015). Further, the British Mesolithic period is one in which we witness the initial stages of strategic environmental management such as repeated woodland burning and large-scale carpentry, making it a period on the brink of "'major human transformations" (Simmons, 2001: 50).

Hunter-gatherer subsistence flows are far more complicated than Fischer-Kowalski and her colleagues portray. Take William Kemp's *The Flow of Energy in a Hunting Society* (1971), for example. Kemp sought to understand the patterns of energy flow within an Inuit group on Baffin Island (currently Nunavik) and how this energy flows amongst other social and economic activities (Kemp, 1971: 104). Kemp does allude to utilising this model to understand past energetics; however, he does so to show how hunting and gathering "involves much more than a simple interplay of environment and technology" (Kemp, 1971: 114-115). Although it is an ethnographic approach and primarily focused on modern subsistence and fuel, it is a prime example of how complicated and entangled fuel and subsistence can be within modern hunter-gatherer societies (Figure 4) (Kemp, 1971).

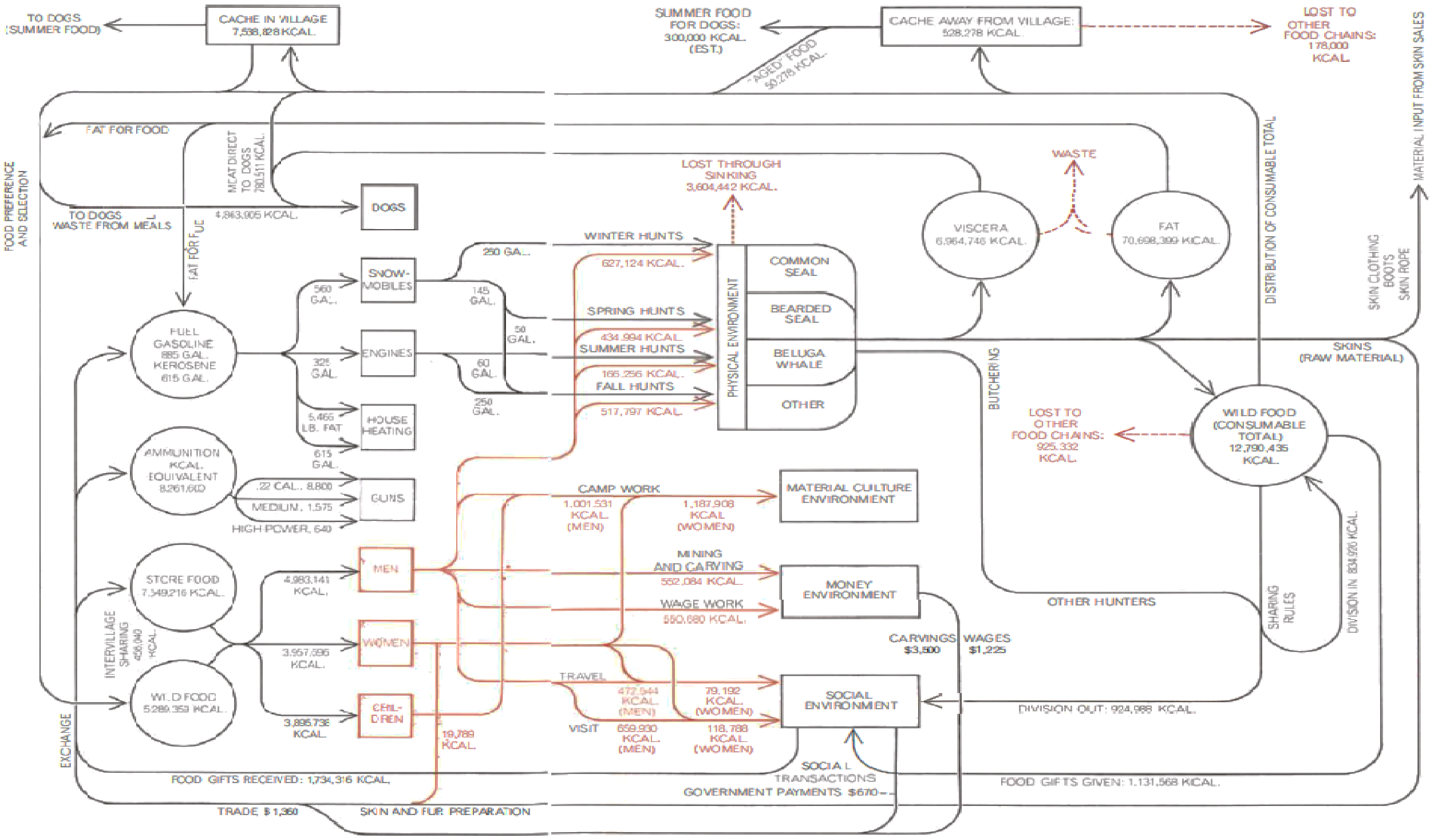


Figure 4: Flow of energy within two hunting households by Kemp (1971), pg. 108 to 109. Kemp recorded the yields and labour inputs during his residence in an Inuit Village on Nunavik (Baffin Island). Energy imports from fuel, ammunition, native game, and imported foodstuffs allowed the hunters and their kin (left, orange) to fuel their dwellings, machines, join seasonal activities (Kemp, 1971: 108-109).

Kemp's study was highly detailed. He observed and recorded all hunting and food preparation activities, food imports, material imports, fuel imports, hunting events, community sharing, methods of transport, economic exchanges, and essentially all aspects of daily life over 54 weeks, including caloric food intake of humans and animals (Kemp, 1971). With his energy flow model, based on the data he recorded, he incorporated social controls surrounding village activities, including technological change, and even accounted for age and gender-based differences between individuals within the households (Kemp, 1971). Kemp even socially contextualises these energy flows, emphasising that social controls direct and mediate energy flows within these two Inuit households (Kemp, 1971). This social contextualisation of energy models is effectively missing from many energy models, yet Kemp includes them.

Within Fischer-Kowalski and her colleagues' work, any attempt at contextualising their energetically modelled societies is wholeheartedly missing. Fischer-Kowalski and colleagues only quantify two energy inputs and severely oversimplify hunter-gatherer subsistence flows. It should come as no surprise that this aspect of their model is, to use their terminology, "less complex" as their agrarian one because they promote and rely upon a generalised, and quite frankly, colonial, and ethnocentric understanding of human lifeways. Thus, they neglect the complexities of energy within these cultures, society, and subsistence practices themselves.

Focusing on their model of agriculturally based societies, Fischer-Kowalski and colleagues argue that, unlike hunter-gatherer societies, societal metabolism of agrarian societies is based upon "active solar utilisation" (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski, Krausnmann et al., 2014, Sieferle, 2003). A society that practises active solar utilisation is one whose energy metabolism depends on the manipulation or intervention of solar energy via biotechnologies or mechanical devices to help provide a higher energy return; in other words, active solar utilisation is one in which the energy system is, in Fischer-Kowalski's terms, "colonised" (Fischer-Kowalkski and Haberl, 2007: 14-15, Fischer-Kowalski, Krausnmann et al., 2014: 11-13). Thus, agriculture is a form of land or environmental colonisation and is a major innovation of agrarian lifeways compared to hunting and gathering (Fischer-Kowalski and Haberl, 1997: 64-67). Once agriculture took place and environments became colonised, their metabolism forever changed, along with many intended and unintended consequences (Fischer-Kowalski and Weisz, 1999: 231). More specifically, Fischer-Kowalski and Haberl argue that with agriculture:

> "A new mode of production was 'invented,' which led to the colonization of parts of the natural environment instead of its mere exploitation. This process implied a significant change in the function of human labor. Increasing the amount of labor yielded increased returns yet did not result in the depletion of the natural base, at least in the short run. Much of this labor was invested in upgrading the productive capacity of natural systems (e.g., ploughing, fertilizing, flooding and irrigating, feeding of animals). The intensification of labour and the seeming increase in productivity both induced and permitted a large population to profit from it. Thus, much larger societies with elaborate social hierarchies and division of labour could develop and exist in the same environments at higher population densities" (Fischer-Kowalski and Haberl, 1997: 68).

Here, Fischer-Kowalski and Haberl fully recognise the existence of an agricultural feedback system in its entirety and are one of the first to do so. Expanding upon what both Shennan (2007, 2013, 2018) and Rindos (1980) argue, once agriculture took place, it was almost a requirement to colonise the environment, as agriculture required increased human labour dedicated to its upkeep and maintaining agricultural productivity, which simultaneously allowed for sustaining and growing populations, eventually resulting in hierarchical societies (Fischer-Kowalski and Haberl, 1997, Rindos, 1980, Shennan, 2007, Shennan, 2018). Fischer-Kowalski and Haberl take this argument a bit further to argue that although agriculture was successful for agrarian based societies, this type of system was inherently unsustainable:

> “[agricultural societies] depleted many of the natural resources on which they depended, such as forests and arable soil, and they eventually rendered no more than a fairly miserable, hard-working, and badly nourished lifestyle for most of their members. Improvements in technology, such as the use of iron ploughs and horses brought only temporary relief, soon counterbalanced by population growth. These societies’ natural limits to growth were set by the amount of available land and its capacity for food production” (Fischer-Kowalski and Haberl, 1997: 68).

Agriculture eventually led to a severe depletion of natural resources, required a hard, malnourished life, and productivity became reliant upon technological innovations that increased agriculture’s productivity, yet agriculture was limited by land. Thus, Fischer-Kowalski and colleagues argue that agriculture, being a colonising subsistence lifeway, is not sustainable in the long term. Fischer-Kowalski and Weisz even go so far as to argue that the Neolithic Revolution itself was, in essence, the origin of environmental colonisation (Fischer-Kowalski and Weisz, 1999: 235).

To demonstrate agriculture as a form of colonisation and their version of the agricultural energy feedback system, Fischer-Kowalski and colleagues compare the IPAT calculations with those they made for hunter-gatherer and industrial societies (the latter of which is presently beyond the focus of this thesis). Technologically speaking, Fischer-Kowalski and her co-authors argue that agricultural technology is based upon fireproof containers, converting land into suitable areas for agriculture, domestic animals as sources of food and labour, the deliberate intervention of plant and animal evolution (domestication), creating solid and permanent structures, mining for metals and minerals, and advancing their technologies specifically for making land more productive (Fischer-Kowalski, Krausnmann et al., 2014: 13-14). Focusing on energy use (A in the formula), agrarian society energy use is based upon biomass which is made of crop residues, wood (for shelter and tools), animal husbandry, fertiliser, and “more sophisticated” methods of food processing technologies (Fischer-Kowalski, Krausnmann et al., 2014: 22). Fischer-Kowalski and her co-authors quantify agrarian biomass use as 75 gigajoules per person per year, based on the assumption of double the amount of hunter-gatherer biomass use, abundant land and biomass availability, and biomass requirements for livestock (Fischer-Kowalski, Krausnmann et al., 2014: 23). Fischer-Kowalski and her co-authors maintain that their estimates are based upon historical constructions of biomass use, material flow studies of modern agrarian economies, and other ethnographic research (Fischer-Kowalski, Krausnmann et al., 2014). However, they do not provide how this was quantified, what activities this accounts for, or even what types of biomass, crops, or livestock are assumed. Further, *agriculture as a system* requires significant energy input. They have neglected to model agricultural activities separately; thus, they are missing the mechanism behind the agricultural energy feedback system, specifically agriculture’s cost and efficiency in relation to population growth and energy input. It is crucial to understand how agricultural energy flows through agricultural systems in relation to these costs and benefits, as this thesis demonstrates, and their model misses this.

With their models and quantifications, Fischer-Kowalski and her colleagues conclude that their model indicates that population, energy and technology are deeply entwined with one another depending on a society’s lifeway (Fischer-Kowalski, Krausnmann et al., 2014: 27). Because Fischer-Kowalski and her colleagues focus solely upon energy input and do not model how this energy *flows* within the societal systems they are modelling, they miss how to unravel the complexities between population, energy and technology, and take this conclusion no farther than this. Although Fischer-Kowalski and colleagues recognise the presence of an agricultural energy feedback system because they focus only upon total energy input instead of separate energy flows, they miss the opportunity to model and quantify this agricultural energy feedback and recognise the role energy plays within it. Unfortunately, Fischer-Kowalski’s approach and models are just too simplistic, ethnocentric, and do not utilise archaeological data.

However, Fischer-Kowalski and her colleagues' work are crucial to the foundation of this thesis. Fischer-Kowalski and colleagues fully recognise the existence of the agricultural energy feedback system and the “colonising” aspect of agriculture, potentially the first to bring these together. They also recognise and build from Odum’s arguments regarding agriculture's inherent unsustainability. Further, Fischer-Kowalski and her colleagues attempt to model energy systems through time *and* recognise the importance of modelling past energy systems, especially energy flows. The only hindrances with Fischer-Kowalski’s version of the agricultural energy feedback system are that they are missing the inherent dependency of agricultural processes and do not have a mechanism to model the agricultural energy feedback system properly. Because of this, they miss the relationship between agriculture and energy, which effectively results in the colonisation they discuss. This thesis builds from and improves upon Fischer-Kowalski’s work by presenting and enacting a methodology to calculate energy use in the past, model agricultural inputs separately, proves the existence of the agricultural energy feedback system, and utilises archaeological data, methods, and analyses to do so.

2.3.5 Earth Systems: Timothy Lenton

Timothy Lenton, a climate change and Earth Systems scientist seeks to understand the relationship between complexity and energy . In *Revolutions that made the Earth,* Lenton and his co-author exclusively focus on providing an evolutionary account of Earthly revolutions which profoundly changed the Earth system (Lenton and Watson, 2011). According to Lenton and Watson, the history of Earth can be divided into four revolutions, Inception, the Origin of Life, Oxygen (i.e., the origin of water-splitting oxygenic photosynthesis), Complexity (i.e., the development of an energy-rich environment which allowed for eukaryotes to flourish), and finally, Us, which includes the Cambrian period to society today (Lenton and Watson, 2011). All of these revolutions are marked by the following: physical and chemical changes to Earth’s environment: increasing complexity of the organisms on Earth, increased information processing, increased efficiency in recycling materials, and increasing use of energy (Lenton and Watson, 2011: 46). These revolutions were ground-breaking changes in energy and matter flow through the biosphere, and they all caused disruption on a global scale once they interacted with feedbacks in the Earth system (Lenton and Watson, 2011: 389). Further, most of these revolutions were actually positive feedbacks which, once they took hold, initiated major changes within the environment that became unstoppable (Lenton and Watson, 2011: 389).

Regarding human systems, Lenton argues that human systems are no different from any other system on Earth (Lenton and Watson, 2011, Lenton, Kohler et al., 2021). Like all other biological systems and organisms, humans have increased the amount of energy we harness and convert (Lenton and Watson, 2011). Lenton and Watson even argue and explain that agriculture, for example, is not just a human endeavour (Lenton and Watson, 2011). Ants, termites and other beetle species do in fact, practice cultivation; there are even hierarchies between insects and divisions of labour within agriculture performed by these species, just as there are within human agricultural societies (Lenton and Watson, 2011: 368-370). Another commonality between agriculture performed by humans and insects is that, yes, it provides both these species with energy, but agriculture also causes irreversible changes within their systems (Lenton and Watson, 2011: 368-370). Further, at first glance, Lenton and Watson explain, it seems that agriculture is beneficial and provides significant energy, however, sedentary agricultural societies are actually far more sensitive to environmental changes than other subsistence lifeways, as evidenced by the rise and fall of past agricultural civilizations (Lenton and Watson, 2011: 370). Past agricultural societies, especially early civilisations, absolutely contributed to climate change, at minimum, on a regional scale (Lenton and Watson, 2011: 370). As agricultural societies expanded over time, they impacted their environment, changes in climate and the environment greatly affected them, overexploited the surrounding environment, and degraded soils (Lenton and Watson, 2011: 370). To Lenton and Watson, this is evidenced by the ebb and flow of past civilizations reliant upon agriculture, and indicates that past agricultural societies were more impactful, sustainability wise, than previously thought (Lenton and Watson, 2011, Lenton, Kohler et al., 2021).

Aside from Odum and Fischer-Kowalski and colleagues, Lenton and Watson are one of the few who recognise potential impacts of past agricultural systems upon the environment and like others, suggest the existence of a positive feedback within agricultural systems, especially human ones:

> “Once the majority of productive land within a region had been turned to agriculture, subsequent population growth depended on increase in agricultural productivity. These have been achieved in a variety of ways, including adding water (irrigation), adding nutrients, and putting more energy in”, further, “successful increases in productivity depended not only on adding more nutrients, but also recycling them, in order to maintain or increase soil fertility. When crops are harvested, nutrient-rich material is removed from an agricultural ecosystem, but it can be returned (recycled) in the form of domestic animal dung (or human excrement)” (Lenton and Watson, 2011: 371).

Agriculture certainly provides energy to the agriculturalist but requires more work, demands high productivity levels, whilst at the same time degrading the environment and soil nutrients, which in themselves require more work and input. Although agriculture is a way by which to provide energy, those who are reliant upon agriculture become increasingly dependent upon it because it is a positive feedback system (Lenton and Watson, 2011, Lenton, Kohler et al., 2021). Here, Lenton and colleagues provide one of the key aspects of the agricultural energy feedback system investigated and proposed in this thesis: there is an inherent positive feedback within agriculture related to its processes and the energy agriculture overall, provides. Lenton and colleagues, however, do not model this feedback, energetically.

Lenton does expand upon this idea in a more recent piece where he collaborated with archaeologists, anthropologists, and ecologists, entitled, *Survival of the Systems* (2021). In this piece, Lenton et al. argue for a “survival of the systems” approach to understanding system development and complexity. Moreover, they argue that social and ecological systems work similarly, and both have present within them self-amplifying feedback systems which contribute to their growth and development (Lenton, Kohler et al., 2021: 334).

Lenton et al. argue that human systems, especially agricultural ones, self-amplify and recycle; this has allowed human systems to persist and spread worldwide (Lenton, Kohler et al., 2021: 336). Manuring in farming systems and soil enrichments by mobile herders in African savannah environments are examples of self-perpetuating positive feedback cycles in human systems (Figure 5) (Bogaard, Fraser et al., 2013, Lenton, Kohler et al., 2021: 336). Similarly, agriculture is a self-perpetuating positive feedback cycle. Agriculture allowed humans to capture solar energy, both human and animal labour allowed for a transformation of this solar energy into domestic foodstuffs, which itself provided more energy than economic systems based on wild resources (Lenton, Kohler et al., 2021: 336). Once agriculture started, typically in already fertile areas,

> “more settled households could better monitor plant growth and protect plants from predation by other animals or other people. They also accumulated waste which could be recycled to infields at very low cost, with high rewards to plant productivity. Where readily domesticated animals were available, recycling of animal manure added to a highly productive, self-perpetuating system” (Lenton, Kohler et al., 2021: 336).

When peoples or society invest or create technologies that improve agricultural productivity, such as the plough, this cycle self-perpetuates even further (Lenton, Kohler et al., 2021). However, there is a stipulation with this feedback; it also works in the opposite direction. For example, when the over-exploitation of soils, degradation of the environment due to land-use practices occurs, these self-perpetuating feedbacks help to bring about socio-ecological collapse (e.g. the dust Bowl) (Lenton, Kohler et al., 2021: 336-337).

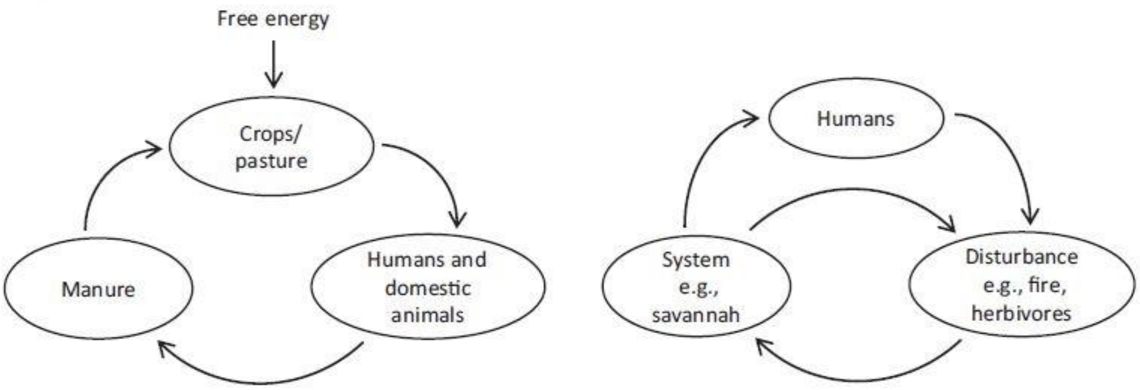


Figure 5: Figure adapted from Figure 1 pg. 338 Lenton et al. 2021. Examples of positive recycling feedbacks within human systems. The figure on the left demonstrates manuring in human agricultural systems as a positive feedback. The figure on the right demonstrates a positive feedback within a system, specifically a savannah, fire, herbivore, and human system, with a disturbance factor that of humans controlling fires and domestic animal grazing.

Although it is not necessarily energy focused, Lenton et al. make a profound argument for past agricultural systems pertinent to this thesis (Lenton, Kohler et al., 2021). Lenton et al. essentially discuss the agricultural energy feedback system and provide a key aspect of it, i.e., there is a positive feedback within agriculture related to its processes and surplus energy, but they exclude the role that energy plays within this feedback. Further, the primary issue with Lenton et al.’s argument is this lack of quantification and modelling based on archaeological data, methods, and analyses. Lenton et al. admit this is a problem and advocate for such quantifications within the “outstanding questions” portion of their article. Although Lenton et al. did not explicitly focus on energy, a focus on energy modelling, like in this thesis, would absolutely aid in Lenton et al.’s theory and help to answer their outstanding question, *how should persistence-based selection of feedback cycles be mathematically formalised and modelled*? Energy modelling is one way of formalising and modelling such feedback cycles, especially those within human systems. This thesis helps answer this outstanding question, proves the existence of an agricultural energy feedback system, and links together the role energy, agriculture, its processes play in positive feedbacks within agriculture, as a system.

2.3.6 An Ethnographic Approach to Agricultural Energy: Roy Rappaport

It would be negligent to neglect the anthropological work of Roy Rappaport (1968, 1971), who studied and modelled the agricultural energy system of the Tsembaga people of New Guinea. Although he primarily focused on ritual and its relationship to energy production and consumption within the Tsembaga, Rappaport is one of the few who models agricultural *inputs* and their relationship to ritual and subsistence, hence its importance for this thesis (Rappaport, 1968, Rappaport, 1971, Rosa, Machlis et al., 1988). Drawing both from Odum and White, for Rappaport, culture was the way by which humans maintained themselves in their environments (Rappaport, 1968). Rappaport argues that humans interact with the environment and ecosystems of which they are a part, and further, humans' energy capture and exchange with the environment can be measured and described quantitatively (Rappaport, 1968: 5-6). Regarding energy and population, Rappaport theorises the following:

> "The increasing size and complexity of human organisation is related to man's increasing ability to harness energy. The relationship is not simple rather it is one of mutual causation. As an example, increases in the available energy allow increases in the size and differentiation of human societies. Increased numbers and increasingly complex organisations require still more energy to sustain them and at the same time facilitate the development of new techniques for capturing more energy, and so on. The system is characterised by positive feedback" (Rappaport, 1971).

Here, Rappaport is suggesting the presence of a positive energy feedback system and that the energy it provides causes or leads to complexity. To Rappaport, humans harness more and more energy, which is related to their size and level of complexity. As they complexify and grow or as they harness more energy, more and more energy must be required to sustain them either way, forcing humans to seek out technologies that aid in obtaining more energy. Albeit not necessarily commenting on agriculture per se, Rappaport is implying an agricultural energy feedback system. To better understand this, Rappaport utilises his Tsembaga case study to examine how energy and materials in agricultural systems affects the ecosystems of which it is a part and understand the relationship between agriculture and social evolution (Rappaport, 1971: 117).

Rappaport quantified the energy flow within the Tsembaga agriculture system to understand energy's role in agriculture by drawing from his detailed records and accounts of agricultural activities (Rappaport, 1971). He provides a detailed account of the environmental surroundings and the ecosystem upon which the Tsembaga rely and manipulate, descriptions and recordings of subsistence activities, and Tsembaga agricultural activities. More specifically, he provides detailed records of the physical activities involved in converting an 11,000 square foot area of secondary forest into an agricultural garden (Rappaport, 1971: 117-118). With this, he even carried out time and motion studies whilst in the field and obtained daily crop yields for a year (Rappaport, 1971: 118). By drawing from human energetics data at the time to quantify the basal metabolic rate of individuals, he was able to calculate the amount of energy expended in each agricultural process, inputs, and outputs, and thus, provides us with a detailed energy model of Tsembaga agricultural energy (Figure 6). Although human energetics as a field was in development, Rappaport used equations from available modern human energetics studies to determine the minimum basal metabolic rates of women and men for his calculations. The methodology within this thesis (chapter 4) draws from this and utilises a similar approach with more updated equations and archaeological data.

Figure 6 (A) presents Rappaport's energy flow model within Tsembaga agriculture, demonstrating the major inputs; the most energy intensive activities are weeding and harvesting. The second diagram of Figure 6 (B) represents both pig and human energy flow requirements. Overall, energy wise, the short-term return for Tsembaga agriculture is significant: 16.5 to one for taro-yam gardens and 15.9 to one for sweet potato gardens. However, from this, every adult pig receives a daily rationing nearly equal to one person; energetically speaking, pig husbandry is costly. With this, Rappaport argues that in addition to helping to maintain the ecosystem in which the Tsembaga are a part and converting vegetable carbohydrates from human waste into high quality proteins, pig husbandry regulates relationships between local social groups and controls the frequency of warfare (Rappaport, 1971). Essentially, the Tsembaga religious beliefs and sacred rituals focused on pigs directly affects energy production and consumption practices for Tsembaga peoples (Rappaport, 1971). Here, Rappaport successfully brings together the social and links it to agricultural energy, using an energetic approach to do so.

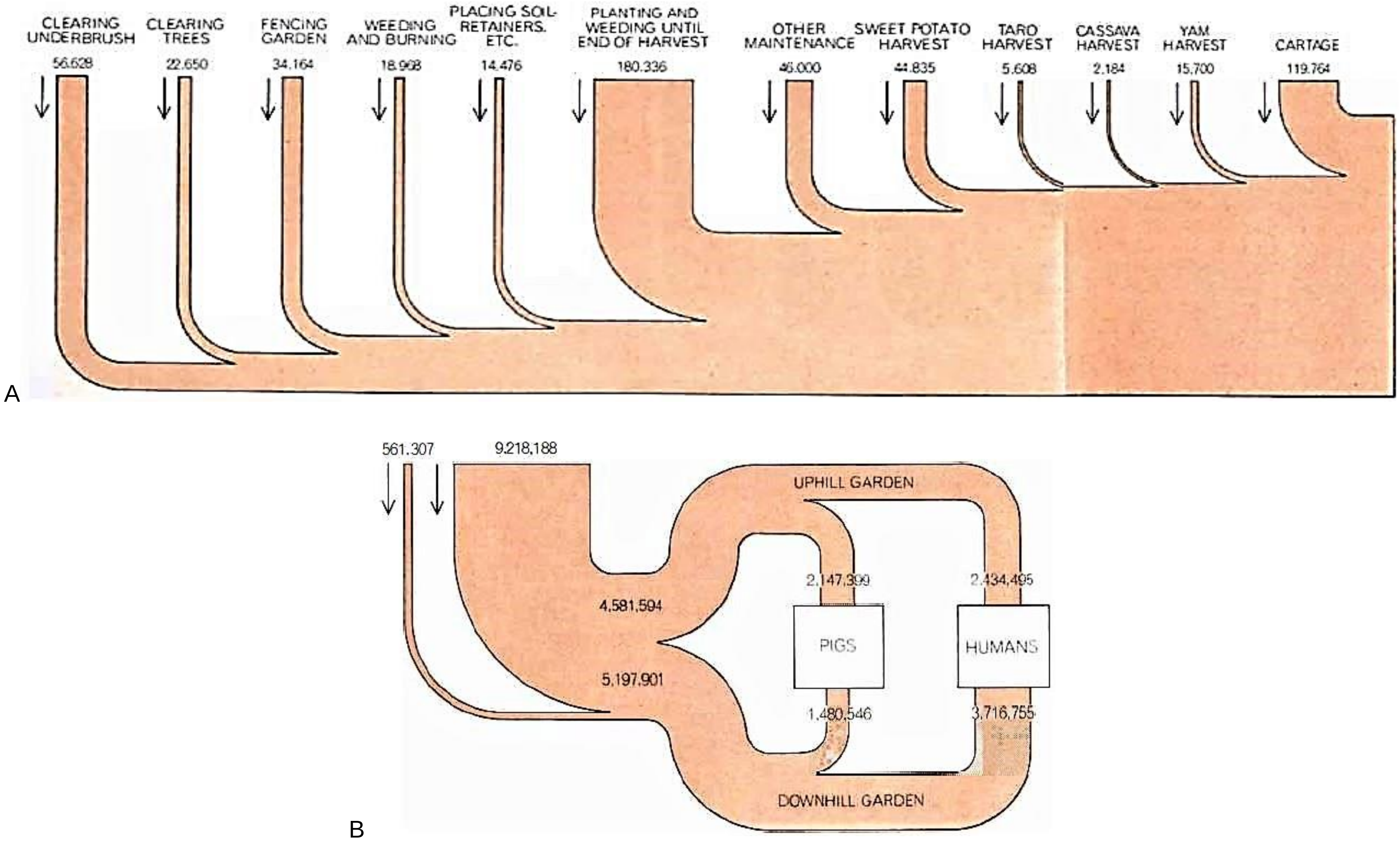


Figure 6 The flow of energy within the Tsembaga agricultural system, as presented by Rappaport (1971), pg. 120-121. Rappaport presents agricultural energy using a Sankey flow diagram; essentially the bigger the flow, the more energy that flow contains. Focusing on Figure A, these are the 12 major energy inputs of the Tsembaga gardening system in kilocalories per hectare. Focusing on diagram B, this is the biomass of the crop yield, in kilocalories showing the interconnectedness between Tsembaga agriculture and pig sustenance.

Overall, Rappaport's approach is an ethnographic anthropological one, and problematically stems from a social evolutionist framework; Rappaport even describes Tsembaga agricultural technology as being the "simplest tools" (Rappaport, 1971: 117, Rosa, Machlis et al., 1988). However, Rappaport provides a detailed energy model and socially contextualises this energy model within Tsembaga society. This energetic approach, aside from Kemp (1971), is one of the only to socially contextualise energy use within the society at hand. Further, and more importantly for this thesis, Rappaport suggests the presence of a positive feedback system within societal complexity and links this to energy. Finally, his human energetics approach formed the groundwork for the energy methodology utilised in this thesis.

2.4 ARCHAEOLOGICAL APPROACHES TO SOCIETY AND ENERGY

The previous chapter section focused primarily on critiquing those who attempt to understand energy's role in the complexity and evolution of society, often from a sustainability lens. This chapter subsection, however, focuses on those, mostly archaeologists, who have theorised specifically about society-energy relationships. Few archaeological studies have focused on understanding the past in terms of human energy systems, and even fewer have attempted to model, analyse, or compare past energy systems. The literature within this chapter subsection mainly argues for the recognition of the existence of an agricultural labour trap with the agricultural revolution (Fuller et al. 2010, to be discussed) and further investigation and understanding of the relationships between energy feedbacks and complexity (Binford, 2001). Thus, this chapter subsection aims to provide a brief overview of such literature.

2.4.1 Archaeology & Energy: Lewis Binford

Any discussion of archaeology and energy must include Lewis Binford. Binford, is known best for his emphasis upon a systems approach in archaeological thinking, where he advocated for viewing human systems as adaptations and responses to the environment (Binford, 1980, Binford, 2001). Regarding society and energy, Binford takes an approach very similar to both Odum and White, drawing from both of these theorists to argue that human systems are energy-capturing ones determined by both the environment from which energy is extracted and by the available technology (Binford, 1980). For Binford, the environment determines the energy availability to society and, thus, a society's structure and the adaptations of its human actors (Binford, 1980, Binford, 2001).

In *Constructing Frames of Reference,* Binford argues that to understand human systems, one must turn to energy and consider it as "a form of currency for human behaviours" (Binford, 2001: 41). Binford combines energy and risk approaches to argue that, on a more individual level, humans maximise their energy returns to synchronise their energy flows for food and technology and base these on accessing energy resources, which aids in reducing risk (Binford, 2001: 163). Binford even argues for modelling an energetic baseline, as we must know the basic energy levels required to sustain human life and understand the limits on people's energy expenditure (Binford, 2001: 161).

To demonstrate this, Binford focuses exclusively on modelling hunter-gatherer groups and identifies ranges of habitats, or what he deems as energetic domains, to argue that energy extraction processes are the basis for the organisation, structures, and dynamics of human systems (Binford, 2001). Like Odum, Binford suggests that ecosystems and social systems are organisationally similar and argues that hunter-gatherer groups can be viewed "as subsystems within organisationally more comprehensive ecosystems" (Binford, 2001: 164). However, unlike Chaisson (2.3.1), Binford suggests that ecosystems are more complex than most human systems; therefore, focusing and modelling the energetic conditions of the environment allows us to model various human responses to different environments or energetic domains (Binford, 2001: 164).

Binford does not quantify energy use but instead utilises ethnographic data to inform his models. More specifically, he utilises 339 ethnographic case studies and includes environmental data such as plant and animal biomass data, rainfall data, water balance data, temperature data, evapotranspiration data, and biomass productivity data (Binford, 2001). In addition, Binford includes population estimates, population densities, body weight and stature, subsistence practices, areas occupied, seasonality cycles, foraging and hunting trip data (for females and males), and even mobility data (including the number of moves per year and the distance moved per year) (Binford, 2001). Finally, he utilises this vast environmental and ethnographic data to produce many projection models and briefly compares these projections to patterns in a few hunter-gatherer archaeological case studies.

Binford does not quantify human energy per se but instead focuses exclusively on the amount of weighted environmental biomass to represent energy (Binford, 2001). Binford provides many modelled scenarios which are not presented here, as to critique every one of these is far beyond the scope of this thesis (Binford, 2001). In essence, Binford's models compare aspects of ethnographic hunter-gatherer data with this quantitated environmental variability, focusing on the production of plant production in respective environments (Binford, 2001: 55). He calculates the plant biomass necessary to feed the mass of humans, given their dependency on plants and based on ethnographic data (Binford, 2001: 186). Binford focuses on the biomass production of an environment as it represents the energy within an ecosystem; biomass production in an ecosystem, to Binford, provides energy and influences resource exploitation, energy extraction, human adaptability and social structure (Binford, 2001: 73).

With his projection models, generalisations and propositions, he argues he has obtained patterns and correlations between environmental and ethnographic variables, which can be projected into real-world situations (Binford, 2001: 471). Binford presents hundreds of propositions and generalisations, most relevant to this analysis being "the amount of food that is available during the least productive period of the year will limit the level of sustainable population within an area," and "habitat structure, species diversity, and habitat stability will affect the labour costs that humans, other things being equal, can expect to pay in the process of obtaining food" (Binford, 2001: 175-176). Essentially, the amount of energy available during the least productive part of the year limits a population, and environmental energy directly affects human energy expenditure (Binford, 2001).

Although Binford has utilised and provided a plethora of data and comparisons based on detailed statistical analyses, environmental and ethnographic data, overall, his model is extremely environmentally deterministic. Yes, the environment does provide energy to human populations; however, like Odum, Binford is neglecting the fact that *people* alter and help manipulate the energy flows within energetic systems in specific ways; the environment does not complete this independently. By focusing exclusively on the environment, he neglects the human aspect of our environmental and energy relationships. Further, Binford has no way to quantify human energy input, most likely because of this unwavering ecological approach. Although Binford, at one point, does argue that human energetics data is a crucial aspect, suggests utilising basal metabolic rates to understand energy inputs, he ends up neglecting this and does not quantify or model this (Binford, 2001). His analysis is focused on hunter-gatherer-forager groups, and he has a plethora of data to model energy flows, yet he does not energetically model the assortment of activities that hunting, gathering, and foraging entail.

Modelling energy flows within these groups could help strengthen his model projections, propositions, and generalisations, especially surrounding his theories of society and energy.

Focusing more on processes of evolution and systems changes, Binford argues it is crucial to understand the relationship between human systems and the variations, quantities, and changes in energy flow with the other living systems with which they participate and interact (Binford, 2001: 163). The flow of energy is the most crucial aspect of the relationship between humans, systems change, and energy (Binford, 1980, Binford, 2001). Systems changes are the direct result of changes in energy flows. Moreover, energy changes, such as the amount of energy available or a change in energy demands, resulting in the following: energy demands being unmet, an increase in energy demands, shifts of energy-capturing activities of human actors, increased competition between human actors, changes in technology and/or new means of organisation revolving around energy extraction or energy conservation, and experimentation with energy extraction, whether this be new energy, or previously untapped energy sources (Binford, 2001: 163). However, Binford does not model any *human* energy flows. This is the biggest downfall to Binford's approach. For example, although Binford himself does not relate this to agriculture whatsoever, the agricultural energy feedback system is a prime example of his theories. Agriculture provides a surplus of energy to societies which aids in population growth; in Binford's terms, a change in the amount of energy available occurs. As agriculture provides this excess energy, the group or society at hand must then dedicate more energy to agricultural processes to keep agriculture and the growing population at hand sustained. From Binford's perspective, this represents an increase in energy demands, a shift in energy capturing activities, and requires changes in new means of organisation surrounding this energy extraction method. Overall, he misses this because of his hyper-focus on the environment, and there was no methodology to quantify energy use in the past.

Despite the issues surrounding Binford's work, his efforts towards modelling an energetic baseline, emphasising the importance of doing so, and his attempts in understanding baseline sustenance and people's energy expenditure, and the role they play in human diversity have been crucial to this thesis. Thus, Binford's work has, overall, helped in grounding this thesis, helped to recognise the role energy plays in the agricultural energy feedback system, and underpin the agricultural energy feedback system itself.

2.4.2 Autopoiesis and Energy: John Barrett

As aforementioned, archaeology does not inherently focus on understanding how humanity's energy systems have developed over time. John Barrett, however, argues that this is precisely what archaeology's disciplinary focus should be. Throughout his work, Barrett has consistently argued for an energy approach to understanding humanity and the development of complex systems within human systems (Barrett, 2011, Barrett, 2013a, Barrett, 2013b, Barrett, 2014, Barrett, 2021, Barrett, in prep.-a, Barrett, in prep.-b, Ion and Barrett, 2016). Human history, in essence, developed due to flows of information, materials, and energy (Barrett, 2021). To Barrett, one of the biggest challenges archaeology faces is to understand how different societal systems arose and were transformed over time (Barrett, 2014: 66-71). All living systems, including social systems, are determined by the way in which they process energy and information (Barrett, 2014: 66). Moreover, all living things are involved in their own self-making processes, i.e., autopoiesis (Ion and Barrett, 2016).

Somewhat similar to societal metabolism approaches, autopoietic approaches view organisms as metabolic systems operating within a boundary across which energy is imported to facilitate their own self-renewal; Barrett argues that this is how archaeology should view human development, including our social systems and the development of social complexity (Barrett, 2013b: 9). Further, applying an autopoietic approach allows us to critique Darwinian approaches to social development, i.e. that natural selection directs historical processes and expands beyond such reductionist views (Barrett, 2011, Barrett, 2013a: 575, 581). Take agency, for example; this is wholeheartedly unaccounted for from biological literature, Darwinian approaches, and within most energy approaches (Barrett, 2013a). Agency is essential to organisms, requires energy intake, has intentionality, and has material consequences; most theories of social evolution do not account for agency or these aspects of it (Barrett, 2013a: 576-577). The problem with these approaches also lies in that they do not account for the fact that agency is *required* to build organisms: agency has intentionality (Barrett, 2013a: 577). Moreover, Barrett explains:

> "to do work and thus to construct order requires the transference of energy, which means that the developmental system, such as the cell or the population, can only sustain an agency by means of a permeable boundary across which energy may be imported. Of course this describes the process of metabolism, which is a defining characteristic of life, but it also allows for energy to be differentially appropriated, stored, and distributed in a complex structure… life, if one might put it this way, is the construction of meaning, the operation (and therefore the outcome) of which is partly contingent upon the material to be read and the sources of energy that are available to be utilised" (Barrett, 2013a: 578).

Regardless of the system at hand, an individual cell or a population of humans, the only way to sustain agency, or intentionality, is via energy (Barrett, 2013a). Metabolism itself is the common aspect to all living things and life itself. Here, Barrett provides us with an energetic approach that allows for intentionality and agency, something completely missing from other approaches. Further, he argues, such an autopoietic approach can and should be applied to human social systems, as it emphasises the *development* of systems and organisms rather than their products (Barrett, 2013a: 578). Further, humans require energy for their own development and the societal structures and environments of which they are a part (Barrett, 2013a: 579, Ion and Barrett, 2016: 136). Social systems are structured and maintained by the processing, flow, and acquisition of both energy and materials that sustain them (Barrett, 2013a: 580). Humans and human systems have, therefore, developed within the complex networks of bodies, things, and nature, and metabolise energy to sustain life and renew themselves; archaeology must and can help to understand this process, these systems and how such complexities developed (Barrett, 2013a, Barrett, 2013b, Barrett, 2014: 72, Barrett, 2015, Ion and Barrett, 2016). Barrett argues that the way to do so is by applying such an autopoietic, energetic framework to our archaeological understandings and modelling (Barrett, 2011). Barret provides us with a potential autopoietic model, similar to his notions of agency, to the Neolithic Revolution of Europe, to demonstrate this further (Barrett, 2011).

Regarding the Neolithic Revolution, Barrett argues that it is inherently linked to changes in energy procurement and flows of energy (Barrett, 2011, Barrett, 2013a). Instead of viewing the Neolithic revolution as an *event* "caused" by changes in human wants, which is, in fact, an argument based on biased, a priori assumptions, we must instead view the Neolithic Revolution as a process of changes in energy management (Barrett, 2011: 67). The Neolithic Revolution was, in essence, a systemic energy change that included changes in ecologies (Barrett, 2011). To understand the processes of this change, however, we must also understand the difference between foraging and farming systems.

The primary differences between foraging and farming systems, or what Barrett deems as "ecologies," are how populations manage energy resources and flows to support and reproduce themselves both socio-culturally and economically (Barrett, 2011: 67-72). These ecologies are thermodynamic systems whose differences lie in energy transfers and energy management (Barrett, 2011: 73). In autopoietic terms, foraging and farming ecologies differ in the way they reproduce themselves via energy. Foraging ecologies *directly* extract energy from plants and animals, whereas farming ecologies store their energy via the *growth* of domestic plants and animals (Barrett, 2011: 85). Further, farming ecologies reproduce themselves via increased energy investment in labour organisations, different from foraging ecologies (Barrett, 2011: 72).

Regarding the Neolithic and the transition from a foraging ecology to a farming one, such increased energy investment could have been achieved in several ways, he argues, such as being due to the potential for more energy being exploited from domestic plant and animal resources, greater levels of energy efficiency in labour organisation, changes in energy storage, or a combination of such events (Barrett, 2011: 72). He emphasises, however, that the transition to agriculture cannot be heeded as resulting from a single event or motivation (Barrett, 2011: 76). Instead, taking an autopoiesis approach, the Neolithic arose from feedback loops that took place at the ecological level, and included complex energy entanglements:

> "The Neolithic, according to our model, emerged as the expression of a particular system of ecological reproduction, basic to which was the shift away from the direct procurement of energy through foraging strategies towards the means of storing the energy resources that were ultimately derived from the land. These storage procedures maintained the resources essential to enable the work of human agency. The investment made, through the growth of animals, the secondary products they provided, and through the evolution of plants, ultimately secured a greater energy return on labour expenditure per unit area of land than will have been possible with a forager ecology. This implies that we might expect the move from forager to farming ecologies to have been marked by a move from geographies of extensive exploitation to those that were more place-bound and intensive in their operation. Such systems both required, and indeed facilitated, the growth of community identities and of social complexity by increasing the use of ideological representations of commonly held value systems. *The potential here is for a developing set of feedback relationships that could sponsor a period of rapid development in early agricultural systems almost immediately upon the establishment of farming ecologies"* (Barrett, 2011: 80; emphasis my own)

The emergence of agriculture resulted from a series of complex feedback processes that included energy, ecology, social identity, ideology, and human agency. The shift from direct energy procurement (foraging ecology) towards one based on the *storage* of energy via domestic plants and animals required energy investment. This new energy investment not only required changes in energy flows but led to an increased energetic return on this investment, i.e., the input was worth the productive output. Storage systems were also crucial in changing from a foraging ecology to a farming one (Barrett, 2011: 76). Simultaneously, the transition from an extensive form of energy exploitation to an intensive exploitation required investment in the land and, more than likely, permanent settlements. Together, such changes in energy flows and ecologies led to changes in social structure, identities, values, ideologies, and even human agency. As Barett puts it, agriculture is neither an *event* in itself nor is it the "invention of domestication" but, it is a complex process involving ecologies, ideologies, energy intake, material and ideological consequences (Barrett, 2011: 79-80). Thus, agriculture is a process of managing energy resources.

In essence, Barrett is explaining an agricultural energy feedback system but taking an autopoietic, ecological approach. The strength of his model is that it allows us to see these differences, feedbacks, and complexities and contextualise them within human history (Barrett, 2011: 73). Barrett's model brings much to the table that is missing from much literature previously discussed throughout this chapter. First, he recognises the investment in agriculture and what is required of it. Although he does not quantify it, he recognises that it plays a significant role in agricultural feedbacks. Second, he brings the humanistic perspective into play; in his model, people have agency and seek to renew themselves, their social structures, and the ecologies of which they are a part. Most energy theories in themselves do not account for this agency, nor do they attempt to contextualise history. Third, he does not treat history as a single trajectory of progress, like so many others (White 1943, Chaisson 2003, 2005, 2011, 2013, 2014a, 2014b, 2015; Smil 2000, 2008, 2013, 2017; Fischer-Kowalski and Haberl 2007, 199; Fischer-Kowalski et al. 2014, and Fischer-Kowalski and Weisz 1999, for example), and he does not place subjective judgements upon history. Finally, Barrett has demonstrated that an energetic approach is required to understand human development, human systems, and life itself, but using archaeology to do so.

I agree with and support Barrett's model and approach; however, his model could be enhanced by quantifying the energy feedback he is discussing, using robust archaeological data. Further, I would argue that additional exploration of agricultural energy input is warranted. Although storage is pivotal in the feedback systems Barrett is discussing, storage can only occur when other agricultural processes are successful. This is one of the caveats of agriculture as a system and a pivotal aspect of the agricultural energy feedback system posited in this thesis; all of agriculture's processes must be successful in order for it to be successful.

Regarding understanding the energy inputs of agricultural processes, others have recognised this issue. For example, Fuller et al 2010, argue that threshing and winnowing are post harvesting processes that must be heeded and are of significant importance in the development of domesticated crops (Fuller, Allaby et al., 2010). Threshing was one of the "new" processes that came with domestication; previously, it was not required to consume wild cereals (Fuller, Allaby et al., 2010). Fuller et al. take this point further and argue that threshing itself is an agricultural labour trap and must be further studied. Once the process of domestication occurred,

> "people fell into a 'trap' of new work: threshing and winnowing… few have tackled the dynamics of how threshing and winnowing emerged as the result of new morphogenetic adaptations of domesticated cereals and a new labour cost of cultivation… If the evolution of domestic traits was the unintended consequences of how humans cultivated and harvested early crops, then a knock-on effect, presumably also unintended, was the addition of these early stages of crop processing" (Fuller, Allaby et al., 2010 :16).

According to Fuller et al., the act of threshing was not only one of the critical elements of cereal domestication but is also one of the key developments which effectively locked those in the process of domestication into agriculture and, thus, into a labour trap. Thus, threshing is an agricultural process that requires further investigation regarding domestication and the adoption of agriculture. Further, Fuller et al. argue we must consider the labour organisation surrounding threshing and winnowing and include them in our understandings of the domestication process and its relationship to sedentism and agricultural lifeways. This has significant implications for how we might think about the investment of labour in seasonal activities that were not agricultural. Fuller et al. differ from Barrett's arguments, as they do not focus exclusively on energy but on very specific agricultural processes, threshing and winnowing; however, both emphasise the importance of understanding the energy relationships of agricultural processes more generally.

The focus of this thesis does not argue that threshing and winnowing alone were the key elements of the agricultural feedback system. Instead, I argue that agriculture *as a system* comes with the caveat that agricultural processes, together, become increasingly dependent upon one another's success in order to produce an energetic surplus. As people become reliant upon this energetic surplus, the energetic investment required of agriculture, combined with this caveat causes a sort of agricultural trap, along with a plethora of unintended consequences (see Figure 1). Nonetheless, quantifying the energy of agricultural processes at an archaeological site like Çatalhöyük provides an avenue to understanding the significant questions around Barrett's model, the issues surrounding Fuller et al.'s argument, but more importantly, has the potential to aid in understanding the uptake of domestication and agriculture. By quantifying and modelling a past agricultural system this agricultural energy feedback system can be quantified and demonstrated, energetically, as presented throughout the remainder of this thesis.

2.4.3 Resilience and Archaeology: Charles Redman

Resiliency theory focuses on understanding the role and source of change in adaptive systems, particularly transformational changes across space and time (Gunderson, 2001: 9, Holling, Gunderson et al., 2002a: 5, Redman and Kinzig, 2003: 9). Overall, resiliency theory seeks to "transcend" disciplinary boundaries to understand change and persistence within various earthly systems, in the hopes of understanding solutions to today's global environmental challenges (Holling, Gunderson et al., 2002a: 5-10). Such a "Hollingesque" resiliency theory attempts this by specifically viewing and investigating change in ecosystems, economies, and society within what is known as an adaptive evolutionary framework (Holling, Gunderson et al., 2002a: 10-13, Redman and Kinzig, 2003). Within this evolutionary framework, all systems, including ecosystems and human social systems, are not viewed as stable or transformative, but instead move between states of stability and transformation, through what is known as an *adaptive cycle,* as demonstrated in Figure 7 below (Holling and Gunderson, 2002: 32, Redman, 2005).

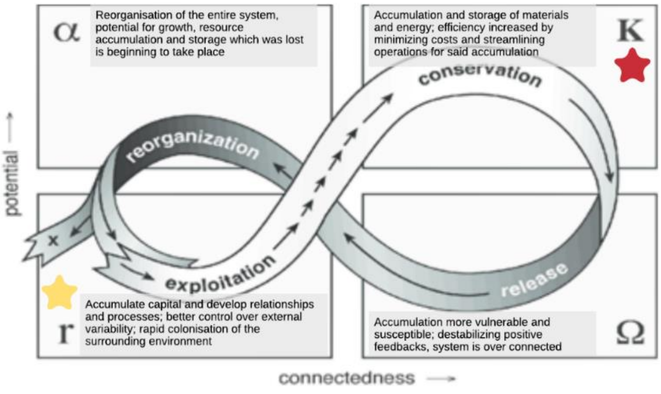


Figure 7: Figure adapted from Figure 2-1, pg. 34 Holling and Gunderson 2002. The adaptive cycle demonstrated by Holling and Gunderson 2002 with descriptions of what occurs in each phase of the adaptive cycle. The

ecosystem cycle progresses from the exploitation phase (r-phase) to conservation phase (K-phase), rapidly to release (Ω phase), to reorganisation (α-phase) and back to exploitation phase (r-phase). On the y-axis is potential and the x-axis demonstrates connectedness. Most societies remain in the r-phase (indicated by yellow star) whereas society today is in the K-phase, indicated by the red star.

This adaptive cycle involves three systemic properties, potential, connectivity, and resilience, and four phases: exploitation (r-phase), conservation (K-phase), release (Ω phase), and reorganisation (α-phase). Whether they be ecosystems or human systems, Holling and Gunderson argue that this adaptive cycle occurs as follows: from the exploitation phase (r-phase), slowly to the conservation phase (K-phase), very rapidly to release (Ω phase), quickly to reorganisation (α-phase), and back to exploitation (r-phase) (Holling and Gunderson, 2002).

Potential, or potential for change, includes the structures, productivity, relationships, inventions, and mutations within a system and sets the limits for a system's future (Holling and Gunderson, 2002: 51). Potential within an ecosystem would be, for example, biomass, nutrients, or even agricultural productivity; social or cultural potential could include the accumulation of networks of relationships between people, and economic potential can include usable knowledge, inventions, and skills (Holling and Gunderson, 2002: 51). Connectivity is the strength of internal connections which help moderate the external environment; in other words, connectivity is the degree of internal control a system has over external variability or how much a system can control its own destiny (Holling and Gunderson, 2002: 50-51). A system with high connectedness is affected and influenced very little by external variability as it is controlled by strong internal regulatory processes; however a system with low connectedness is heavily influenced by external variability, and thus, more reliant upon external processes and factors (Holling and Gunderson, 2002: 51). Finally, resilience is the system's ability to experience disturbances or fluctuations and still maintain its functioning; resiliency determines how vulnerable a system is to unexpected disturbances or surprises that can change or break the system itself (Holling and Gunderson, 2002: 49-50). Together, potential, connectivity, and resilience help to shape the adaptive cycle (Holling and Gunderson, 2002: 50-51).

Within a human system the adaptive cycle would take place as follows. The adaptive cycle starts with the exploitation phase (r-phase), which consists of rapid colonisation of the surrounding environment; people start to accumulate capital and develop relationships and processes which control external variability, thus reinforcing their own systemic expansion (Holling and Gunderson, 2002: 43, Redman, 2005: 73). Following this r-phase, the society at hand experiences a rapid conservation (K-phase) (Holling and Gunderson, 2002, Redman, 2005). During this K-phase, there is a continuation of the accumulation and storage of energy and materials and the system increases its efficiency via minimizing costs and streamlining operations for said accumulation (Holling and Gunderson, 2002: 43, Redman, 2005: 73). Also during this phase, the resilience of the system at hand *decreases* and thus, the system becomes more vulnerable to external influences and/or surprises (Holling and Gunderson, 2002: 44). As this system becomes less resilient it reaches the release phase (Ω phase) (Holling and Gunderson, 2002: 43, Redman, 2005: 73). During the release phase, the instability, and vulnerability of the system continues and due to the system being "over connected," in other words the controls over external environment are too entangled, resulting in destabilizing positive feedbacks which further the system's instability (Holling and Gunderson, 2002: 35). This leads to the reorganisation or α-phase (Holling and Gunderson, 2002). Resiliency and potential during this α-phase are high, whereas connectedness is low and internal regulation is weak, thus the α-phase has the greatest uncertainty and greatest chance of unexpected forms and renewal (Holling and Gunderson, 2002: 41-43). In other words, what could have been predictable, fixed systemic changes are now unpredictable due to controls over external variability and changes being weak (Holling and Gunderson, 2002:

46). As a result, during the α-phase, resources are typically reorganised into a new system, or alternatively, the system reverts back to an old system (Redman, 2005: 73). Once this system is reorganised, it "begins" again with the exploitation or r-phase (Holling and Gunderson, 2002, Redman, 2005, Redman and Kinzig, 2003).

Such adaptive cycles, or phases of adaptive cycles, have been observed in ecosystems such as coniferous forests within the Northern hemisphere, temperate deciduous forests, aquatic systems such as kelp forests and coral reefs, shallow lakes and lagoons, semiarid savanna environments, and productive grasslands with deep soils, in addition to bureaucracies and industries (Holling and Gunderson, 2002: 33-60). Within most of these systems, specific phases of the adaptive cycle are observed, as opposed to completed adaptive cycles. Holling and colleagues describe that most of the aforementioned ecosystems, some bureaucracies and industries, and even societies remain the r-phase whilst they accumulate capital; other systems, like society today spend most time in the K-phase trying to maintain the resources accumulated in the past (Holling and Gunderson, 2002: 35, Redman, 2005). To better understand adaptive cycles and resiliency within human systems, Holling and colleagues argue that we must:

> "turn to examples where there is adequate history—examples of interaction between people and nature at regional scales. There we see patterns of change that are similar to more recent global ones—but examples where there has been more history of response. These include dramatic changes in the ecosystems and landscapes of ecosystems, with subsequent changes for society and economic conditions" (Holling, Gunderson et al., 2002a: 5).

Holling and co-authors are calling for including societal case studies with a deep history of human-environmental interactions. Although Holling and colleagues provide both ecosystemic, modern, and even ethnographic examples of the adaptive cycle or phases within it, and argue for turning to historical examples, they do not utilise archaeological case studies or data to do so. Charles Redman argues that this is exactly where archaeology, as a discipline, plays a role (Redman, 2005, Redman and Kinzig, 2003).

Redman argues that what is missing from resiliency theory is the past. Redman has spearheaded the call for archaeological contributions to resilience theory as well as the use of resilience theory in archaeological discourse arguing that the two can benefit from one another (L., 2005, Redman, 1999, Redman and Kinzig, 2003). Redman maintains that combining resiliency theory with archaeology aids in a better understanding of societal change and helps us to understand and potentially solve today's global sustainability issues (Redman, 2005: 70, Redman and Kinzig, 2003). Archaeological case studies, he argues, are evidence of completed adaptive cycles, thus allowing us to understand the phases of adaptive cycles, how adaptive cycles are linked, and how history cycles as systems reorganise; this allows for an in-depth monitoring of understanding the resiliency of human systems (Redman, 2005: 70, Redman and Kinzig, 2003). The data archaeologists have, i.e., demography, subsistence strategies, paleoenvironmental reconstructions and data, and temporal sequences are not just evidence of adaptive cycles but provide the "bread and butter" for understanding human impacts upon the environment (Redman, 1999: 4-5, Redman, 2005, Redman and Kinzig, 2003). Archaeology, he states "has a great deal to tell us about how people confront threats to the sustainability of relationships between social and environmental systems" (Redman, 2005: 71).

For example, quite often archaeology provides evidence of episodes of environmental degradation related to societal and social collapse; from a resiliency framework, Redman argues, this is the Ω or release phase of an adaptive cycle (Redman, 2005: 70). Thus, the environmental degradation and societal collapse we see archaeologically can help us to understand what makes human systems more vulnerable and less resilient, and aids in effectively disentangling the relationships between environmental and social feedbacks which destabilise systems (Holling and Gunderson, 2002, Redman, 2005). Although the r and K-phases of the adaptive cycle are well studied, the Ω (release) and α (reorganisation) phases of the adaptive cycle are poorly understood within human systems (Redman, 2005: 73). The 'collapse' of societies provides evidence of the Ω phase, how it occurs, and substantiates the claim that the Ω phase of adaptive cycles occurs quickly and unexpectedly during the K-phase (Redman, 2005: 71-73). Archaeologically known societies, then, provide a way of understanding the Ω (release) and α (reorganisation) phases of the adaptive cycle (Redman, 2005: 71-73).

Others throughout this chapter (Lenton and Watson, 2011, Lenton, Kohler et al., 2021, Odum, 1973, Odum, 2007, Odum and Odum, 1977, Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017) argued that to understand human systems we must treat them no differently from any other ecosystem on Earth; society is no different from the biosphere and both should be treated and modelled equally. Within a Hollingesque adaptive framework, however, human systems differ from ecological systems specifically in the following ways (1) people have foresight and intentionality unlike ecosystems, (2) people communicate ideas and experiences unlike ecosystems, and (3) human technologies transform our actions which influence, alter, and affect our environments whilst simultaneously allowing humans to accumulate more and more energy (Holling, Gunderson et al., 2002b: 99-101). Within ecological systems, information flow is not purposefully manipulated (Holling, Gunderson et al., 2002b, Redman, 2005). Information within an ecological system is created under specific environmental conditions on evolutionary time scales and results from genetic inheritance, mutations or natural selection, and information is transmitted as the direct result of external disturbances (Holling, Gunderson et al., 2002b, Redman, 2005, Redman and Kinzig, 2003). Thus, potential, connectivity, and resiliency are not purposefully manipulated by ecosystems; ecosystems do not set their own future (potential), they do not control their own destiny (connectivity), and they do not manipulate their own resiliency, purposefully.

Redman, however, points out that the primary aspect tying these differences together is information, or culture, and its relationship to the systemic properties of the adaptive cycle (Redman and Kinzig, 2003). The way in which information functions and change occurs within human systems and ecosystems is distinct, and directly effects systemic potential, connectivity, and resiliency. Although Holling and colleagues recognise the importance of culture within human systems, they are missing *how* culture is related to human foresight and intentionality, how it is tied to human communication, culture's relationship to technology, and the adaptive cycle itself (Redman, 2005, Redman and Kinzig, 2003). Redman argues that culture is crucial to understanding potential, connectivity, resiliency, and adaptive cycles within human systems (Redman, 2005, Redman and Kinzig, 2003). Redman states:

> "the way in which a society filters and conveys knowledge at a variety of levels of organisation is itself an essential element in the resilience of that society…. The culture of a society creates structures that in a reciprocal manner facilitate or constrain the subsequent flow and content of information" (Redman and Kinzig, 2003)

Within human societies information is both purposefully manipulated and information is created via culture (Redman, 2005, Redman and Kinzig, 2003). Culture or information is created, passed on, conveys knowledge and thus creates relationships, structures, and even human responses (Redman, 2005, Redman and Kinzig, 2003). Culture is what helps provide people with foresight and intentionality, helps to communicate ideas and experiences, helps to create and pass along the technology that transform human actions and which subsequently influence, alter, and affect our environments, and, allows humans to accumulate energy (Holling, Gunderson et al., 2002b: 99-101, Redman, 2005, Redman and Kinzig, 2003). Potential, connectivity, and resiliency are purposefully manipulated, controlled, and effected by human actions and culture. Unlike ecosystems, Redman states:

> “humans, as individuals and as arranged into higher-level organisational units, are *self-reflective—evaluating where they and their system are—and goal oriented… they make decisions in part to move the system towards a desired state*” (Redman, 2005: 74).

Human systems, and humans themselves, unlike ecosystems, remember and learn from past mistakes, past disturbances and surprises and deal with them via culture. Thus, unlike ecosystems, humans actively partake in change, manipulate change, and can adjust their individual or systemic position within the adaptive cycle (Redman, 2005). With culture, human systems and can and do try to purposefully set their own future (potential), they try to control their own destiny (connectivity), and they do manipulate their own resiliency. Further, societies actively seek to stay within the r-phase (e.g. colonising their environments, accumulating capital, developing relationships and processes and controlling external variability) or the K-phase, where they attempt to increase their efficiency and minimize costs for the continued accumulation of materials, storage, and overall, energy (Redman, 2005: 73). Culture, Redman argues, is crucial for societies to ensure their place in the adaptive cycle, and, to maintain efficiency (Redman, 2005, Redman and Kinzig, 2003). Human systems, then, organise themselves towards efficiency to maintain resiliency of their system (Redman and Kinzig, 2003).

Efficient behaviours within human systems, as described by Redman and Kinzig (2003), include specialisation of activities, reducing redundancy within processes, and streamlining a system’s connectivity to be faster, simpler, and/or more effective (Redman and Kinzig, 2003).. Such behaviours, Redman and Kinzig argue, allow for a society to produce more at a lower cost of labour, materials, and energy, making the system more efficient (Redman and Kinzig, 2003). Making the societal system more efficient creates a sort of positive feedback. An increase in system efficiency allows for a society to gain a surplus beyond direct consumption needs thus, enabling a concentration of power or storage of capital (Redman and Kinzig, 2003). This in itself increases the resources for adaptive behaviours, making the system more efficient, and thus increasing adaptive capacity (Redman and Kinzig, 2003). In other words, energy and increased efficiency allow for a society to reach and sustain the r-phase (exploitation phase) and K-phase (conservation phase) (Redman and Kinzig, 2003). This positive feedback between accumulating a surplus and maintaining efficiency is what can help to facilitate the emergence of complex society and keeps human adaptive cycles going (Redman and Kinzig, 2003). Similar to Smil (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017), Redman and Kinzig (2003) recognise and argue that efficiency plays a substantial role in complex societies. Once human systems become more complex:

> “they channel as much productivity as possible to current operation, minimizing inefficiencies or redundancies in the process… this requires the system to maximize power (energy) output to support the emergent complex organisation, but it does so by giving up significant adaptive capacity in others aspects of the system, such as those inherent in certain inefficient social and trade relationships” (Redman and Kinzig, 2003).

In resiliency terms, once societies begin the exploitation phase and accumulate capital, develop relationships and processes, and ‘colonise’ the surrounding environment, they must maintain their potential, connectivity, and resilience; they require efficiency, energy, and productivity to support themselves. As a society continues to maintain itself, it may reach the conservation (K-phase), where it continues continue to accumulate energy and materials, increase efficiency to minimize cost and streamline operations and behaviours. However, to maintain itself in the K-phase, the society at hand must also make cultural or economic changes to maintain this efficiency, energy, and productivity. If things go awry, i.e., accumulation becomes more vulnerable or susceptible, the system can essentially ‘collapse’ or break and enter the release and reorganisation phases. By utilising an adaptive framework and modelling adaptive cycles in the past, Redman and colleagues argue that archaeology can aid in helping us to understand *how* humans set their own future, control their own destinies, and manipulate their own resiliency.

This positive feedback between societal efficiency and an accumulation of a surplus may allow for a society to reach and sustain the r and K-phases and is what facilitates the emergence of complex society. However, what underpins accumulating a surplus and maintaining efficiency is energy. Understanding how energy plays a role within adaptive systems, accumulating a surplus, and maintaining efficiency is crucial and it is the only aspect missing from Redman’s approaches to a Hollingesque adaptive cycle. Redman’s approach provides a framework, but what is required is the empirical modelling of these processes and understanding *how* societies utilise energy to maintain themselves and their resiliency. How do certain behaviours, cultural lifeways, and/or human decisions lead to efficiency and allow for societies to accumulate materials and energy? How do certain behaviours and decision-making processes make societies more or less resilient? Do certain behaviours, such as subsistence patterns for example, lead to, accelerate, or event prevent a society from transitioning to the release and reorganisation phases? What role does energy play, overall, within adaptive systems?

Redman and colleagues essentially discuss a positive feedback system between accumulating a surplus and maintaining efficiency aids in facilitating the emergence of complex society (Redman and Kinzig, 2003). However, they lack an empirical model which can aid in better understanding this feedback and human adaptive cycles more generally; this lack of quantification and modelling based on archaeological data, methods, and analyses is a substantial issue to their approach. Although Redman and colleagues do not necessarily have a way by which to model energy, energy is a way in which we can model efficiency and resiliency. Redman and colleagues specifically call for archaeologists to utilise an adaptive cycle framework and call for resiliency theorists to utilise archaeological data. Past societies, they argue, provide deep time perspectives on the collapse of social and ecological systems, allowing for a full examination of human-environmental interactions over both long time scales and across multiple organisational scales, e.g. individuals, villages, cities, and civilisations (Redman and Kinzig, 2003). The fact that archaeology allows for such a holistic perspective of completed adaptive cycles, especially across multiple organisational scales, makes it invaluable to resilience theorists as such perspectives, e.g. that of linked and multi-scalar adaptive cycles, are often inaccessible to scientific and other social disciplines (Redman, 2005, Redman and Kinzig, 2003). Redman’s approach, although not energetically focused, not only calls for the inclusion of archaeological data in sustainability and adaptive cycle frameworks but lays out why exactly archaeological data should be included in models.

Further, as aforementioned in section 2.3, many energy relationships in the past which were quantified were too generalised and mistaken assumptions not based on archaeological data or conclusions. Thus, Redman’s adaptive cycle approach allows for the incorporation of unintended or unanticipated consequences of past human decisions and actions upon the environment which are often missing from past energetic models (van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). Within an adaptive cycle framework, the accumulation of unanticipated consequences is also included and would allow for a more contextualised understanding of how our unsustainability problems have developed (Malm and Hornborg, 2014, van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). Further, Redman is one of the few who calls for contextualising culture's role in a societal systems and points out its crucial role of helping to maintain societal efficiency and resiliency. Redman does not simplify or over-generalise culture. Unlike White, who equated culture to more energy use, or Odum, who equated culture to a tool by which to process energy, Redman argues that culture itself plays a role in human adaptive cycles, resiliency, and that culture's informational capacity is what allows humans to purposefully set their own futures and manipulate their own resiliency.

With regards to this thesis, the agricultural energy feedback system is a sort of adaptive cycle. Agriculture allows for a society to accumulate energy and capital, develop new relationships and processes, and as argued by others (Fischer-Kowalski and Haberl, 1997: 64-67, Fischer-Kowalski and Weisz, 1999: 231, Rindos, 1980, Shennan, 2007, Shennan, 2018), colonises the surrounding environment. In terms of the adaptive cycle, the agricultural energy feedback system begins with the exploitation or r-phase. As accumulation continues, so does the storage of materials and energy, leading to the conservation or K-phase. Also, during this K-phase is the increased efficiency of the system completed via minimizing costs and streamlining operations. As posited in the agricultural energy feedback system introduced in chapter 1, agriculture provides surplus energy to societies. As agriculture provides this excess energy, societies become increasingly reliant upon agriculture due partly to becoming increasingly more invested in agricultural processes to sustain agricultural activity and a growing population. Moreover, agriculture's energetic cost and efficiency *improve* when more people participate in agriculture, which reinforces a reliance upon agriculture. In adaptive cycle terms, this improvement in cost and efficiency helps the agricultural society to maintain its conservation or K-phase. Once societies receive and maintain an energy surplus, they must invest more energy to upkeep its processes and improve efficiency and costs. However, this improved energy cost and efficiency are only beneficial if agriculture has enough people participating, enough land, and sufficiently high yields. Additionally, agriculture's processes in themselves are dependent upon one another's success. If one agricultural process fails, the entire agricultural system, and the subsequent energy flows of which it is a part, break down. Further, agriculture itself is tied to a plethora of unintended consequences, including permanent changes to the environment and changes in diet and nutrition, material culture, technology, animal relationships, and even ritual practise. At this point in the agricultural energy feedback system, the agricultural system at hand would be in the release or Ω phase, in which accumulation is more vulnerable and susceptible, positive feedbacks can be easily destabilised, and the system itself is overconnected (Holling and Gunderson, 2002: 35). As this system continues to the α-phase, resources are typically reorganised into a new system, or the system reverts back to an old system (Redman, 2005: 73).

2.5 CONTEXTUALISING MODELLING IN ARCHAEOLOGY

Few archaeological studies have focused on understanding the past in terms of human energy systems, and even fewer have attempted to model, analyse, or compare past energy systems. However, archaeological quantitative modelling itself is not a new feat. To explore all quantitative modelling within archaeology is beyond the scope of this thesis, however, approaches such as agent-based modelling and optimal foraging theory approaches are particularly suited to help justify the model presented within this thesis. Both of these approaches, much like the model within this thesis, are “simplified representations of real-world systems” whose basic assumptions, modelling goals and understandings, and applications differ (Kohler and van der Leeuw, 2007: 3, Romanowska, Crabtree et al., 2019: 179). Thus, within this chapter subsection, these modelling approaches will be defined, their overall goals will be outlined, and how each approach compares and contrast to the model within this thesis will be presented. Chapter subsection 2.5.1 focuses on optimal foraging theory and modelling whilst 2.5.2 focusses on agent-based modelling. .

2.5.1 Optimal Foraging Theory and Behavioural Costs and Benefits

Archaeologists have always utilised models, methods, and theories from fields outside of our discipline, what is often termed “interdisciplinary borrowing;” this is precisely how Optimal Foraging Theory made it to the discipline in the 1960s to 1970s (Keene, 1983: 138). Optimal Foraging Theory or Modelling (OFT/OFM) and its costs and benefits analyses are particularly important to contextualise the model used within this thesis; therefore, it is the focus of this chapter subsection. As OFT is a development of (Human) Behavioural Ecology, before delving into OFT, we must first contextualise its roots within Behavioural Ecology.

Behavioural ecology (BE) is a subcategory of evolutionary ecology which analyses fitness-related behavioural trade-offs that organisms face within their environments to understand animals' foraging, social, and reproductive behaviours (Bird and O'Connell, 2006: 144). Overall, BE is concerned with the “fitness” aspects of behaviour, i.e., survival and reproduction; thus, most BE models have principles of evolution and Neo-Darwinism embedded within them and interpret behaviours as such (Bird and O'Connell, 2006: 145, Winterhalder and Smith, 2000: 52). From a BE perspective, natural selection favours those individuals whose behaviours allow for the capacity to solve fitness-related trade-offs successfully and efficiently within their social and ecological environments (Bird and O'Connell, 2006: 145, Winterhalder and Smith, 2000). Thus, an organism's behaviour tends towards (or should tend towards) efficiency (Kennett and Winterhalder, 2006). Furthermore, because such behaviours are often predictable and universal, BE seeks to focus its models and hypotheses around why certain behaviour patterns and what behaviour patterns are adopted under specific conditions (Bird and O'Connell, 2006: 145, Kennett and Winterhalder, 2006). Behaviours and their alternatives are identified and assessed in terms of costs and benefits associated with survival and reproduction (Bird and O'Connell, 2006: 145, Kennett and Winterhalder, 2006).

Not long after BE’s development, ethnographic researchers adopted behavioural ecology and applied it to analyse and understand human behaviour, aptly known as Human Behavioural Ecology (Bird and O'Connell, 2006: 144). Human Behavioural Ecology (HBE) seeks to apply evolutionary ecology models to understand the diversity of human behaviour and draws from and is embedded within a BE framework (Winterhalder and Smith, 2000). From an HBE perspective, the diversity of human behaviour results from the variability of specific socioecological settings, each with its own “fitness-related landscape” in which humans operate (Bird and O'Connell, 2006: 145). Like BE, HBE views human behaviours as being rooted in natural selection and often emphasises generality to predict behaviours and the adoption of behaviours under specific socio-economic conditions (Winterhalder and Smith, 2000). The original merit and drive in utilising BE within human frameworks was that understanding human foraging could be enhanced by utilising research and models on our nonhuman foraging counterparts' behaviour (Bird and O'Connell, 2006: 144, Keene, 1983: 139). As summarised by Keene 1983, many of the questions and concerns with nonhuman foragers are the same ethnographers had about human foraging strategies, specifically concerning subsistence strategies and how resources are chosen, utilised, and scheduled:

> “Why are some resources favored over others? Given certain requirements and constraints, which resources can best be exploited at what locations, at what times of the year, and in what quantities?... What are some of the advantages of an aggregated versus a dispersed settlement pattern? What territory size can be exploited with maximum security and efficiency? What are the costs and benefits to be derived from the establishment and defense of a home territory?” (Keene, 1983: 139).

Such questions are deemed crucial to understanding nonhuman behaviour and adaptation to specific environments within biology and ecology; thus, ethnographers in the 1960s and 1970s linked this to studying modern foragers and understanding human behaviour (Keene, 1983: 139). Unsurprisingly, archaeologists picked up on such questions and understandings within HBE and saw its suitability to past subsistence and settlement systems; hence, it was picked up quickly within archaeological discourse (Keene, 1983, Kennett and Winterhalder, 2006). Such questions and models would allow for archaeologists to investigate and understand stresses on human populations in the past and understand, predict, and quantify the success or failure of certain behavioural responses to these stressors (Keene, 1983: 139). It is also worth noting that around this time in archaeology (the 1960s to 1980s), a nomothetic processual archaeology was taking off, which emphasised behavioural laws, systemic processes, and cultural evolutionism (Ion and Barrett, 2016). As stated by Keene 1983, archaeology reasoned that paying more attention to subsistence behaviours and investigating the utility, abundance, predictability, and distribution of past food resources could lead to a better understanding of the archaeological record (Keene, 1983: 149). It is no wonder that archaeology latched on to BE and HBE models and frameworks, as, archaeological researchers recognised the merit of BE to help to develop testable, generalised models of past human behaviours and processes. Moreover, because BE also utilises cost-benefit frameworks and analyses to develop its models, making BE and HBE models quantifiable, and, thus, objective, reproducible, and comparable, all three of which are foundations of processual archaeology. Finally, BE models, thanks to their cost-benefit analyses and quantifications, had sets of predicted foraging patterns in various environments, known as Optimal Foraging Models (OFM) (Keene, 1983: 139).

Within the context of this thesis, Optimal Foraging Models (OFM) and Optimal Foraging Theory are particularly relevant as there are parallels and contrasts between the model used within this thesis and OFT. Thus, the remainder of this chapter subsection will focus on summarising OFT/OFM and discussing parallels and contrasts concerning this thesis.

All OFMs have the following characteristics: a goal, currency, set of constraints, a decision or “alternative set,” and finally, an optimisation assumption (Keene, 1983: 140-143, Kennett and Winterhalder, 2006: 13-14, Winterhalder and Smith, 2000: 51-54). The goal within OFT and its models, no matter what, is always for the forager to optimise its net acquisition rate or energy capture (Kennett and Winterhalder, 2006: 13-14, Winterhalder and Smith, 2000: 51-54).

If we put the model within this thesis in terms of OFM characteristics, the model within this thesis is in sharp contrast. The goal in the model presented within this thesis is *not* for Çatalhöyük, or individuals within Çatalhöyük, to optimise its net energy capture. The goal for Çatalhöyük’s agricultural energy system, which is not focused on individuals, is, put simply, to sustain agriculture and its processes, under various domestic cereal reliance and yield scenarios as its population grew and declined throughout its occupation. This model does not assume this is done with maximum energy efficiency as Catalhoyu’s primary goal. As will be discussed in sections 7.2.2 and 7.2.3, the results of the model within this thesis relate energy efficiency to yield, domestic cereal reliance, and population growth which may *result* from Çatalhöyük’s modelled reliance on agriculture. Further, I highlight efficiency with respect to increasing agricultural costs and potential energetic conflicts occurring at its population peak and compare and analyse these to Çatalhöyük's archaeological data. Thus, the "goal" of the model within this thesis is in great contrast to OFT models.

Another characteristic of OFT models is currency. Currency is the measure used within OFM that assesses and analyses the measure of energy return or the cost and benefits (Bird and O'Connell, 2006: 147, Keene, 1983: 140, Kennett and Winterhalder, 2006: 13, 170, Stiner and Kuhn, 2016, Winterhalder and Smith, 2000: 51). Typically, the currency is measured by any feature of a resource that gives it value, which is most frequently the net acquisition rate of energy; however, it could also be a material need, protein, carbohydrates, or even monetary prestige (Kennett and Winterhalder, 2006: 13, Winterhalder and Smith, 2000: 51). The costs and benefits of a resource are designated as follows. The costs of a resource includes searching for or acquiring the resource and processing it once it is selected (Kennett and Winterhalder, 2006: 170). The benefits, then, are the return rate, the measure of energy returned (or another value) after search and processing costs are considered (Kennett and Winterhalder, 2006: 170).

Once again, if we frame the methodology and model of this thesis in terms of OFM characteristics concerning currency, there are parallels and contrasts. Like OFT, the currency utilised in this thesis is energy: the energy input requirements of agriculture, the energy received from agriculture, and the losses of agriculture. Also similar to OFT, the analyses in 7.2.2 and 7.2.3 use the resulting energy model from this thesis to understand the cost and efficiency of agriculture, its processes, and how this changes Çatalhöyük's population grows and declines depending on domestic cereal reliance and yield. Similar to OFT, costs of agriculture include the human energy requirements to sustain agriculture, the potential seed, crop processing, and harvesting losses, and the total amount of energy gained once these processes are completed. With respect to currency, OFM and the model in this thesis are similar.

Regarding "constraints" within OFM, these are the social and environmental context of the OFM; this could include the availability, distribution, density and/or nutritional content of resources, the social factors limiting access to resources, information available, the technology utilised, or even the size of the forager (Kennett and Winterhalder, 2006: 13, 112 , Winterhalder and Smith, 2000: 51-54) typically all constraints but one are fixed (Kennett and Winterhalder, 2006: 13, Winterhalder and Smith, 2000: 51-54).

The constraints of the energy model within this thesis are detailed thoroughly throughout chapter 4. However, this model's social and environmental context is dictated by Çatalhöyük's own archaeological data. Regarding resources, the energy model within this thesis makes the following assumptions surrounding agriculture at Çatalhöyük: all agricultural processes are successful regardless of yield, storage is always successful, losses are average, a 25%, 50%, and 75% reliance upon four domestic cereals, and Çatalhöyük peoples have equal access to land (chapter 5). On the subject of energy requirements of Çatalhöyük's population, these are thoroughly outlined throughout chapter 4. However, briefly summarised, it is presumed that the Çatalhöyük bioarchaeological measurements and data represent the Çatalhöyük population, the physical activity levels of the population are moderately and vigorously active, and nutritional requirements were met at Çatalhöyük. With respect to the technology utilised and processing methods, this is based on Çatalhöyük's archaeological data but combined with experimental archaeological data and ethnographic data. The timings for each agricultural activity were based on relevant ethnographic and experimental resources agricultural activity, how this was combined with archaeological evidence, and from what resources they were drawn is presented and described within each agricultural activity section of chapters 5 and 6.

With regards to the "decision" or the "alternative set" of an OFM, this is the behaviour that is to be examined or the range of possible behavioural actions a forager can take; the decision is short term, intentional, or goal-directed (Kennett and Winterhalder, 2006: 13, Winterhalder and Smith, 2000: 51-54). Comparing this to the energetic model created and enacted within this thesis (Chapters 4-6), I do not believe that there is an “alternative set” within this thesis. The model within this thesis is not predictive; consequently, there are no “decisions” that Çatalhöyük’s population makes aside from successfully sustaining agriculture and participating in its processes as the population grows and declines.

Finally, the optimisation assumption within an OFM ties together the model, as it brings together constraints, the currency, goal, and costs and benefits of an individual’s decision (Kennett and Winterhalder, 2006: 13, Winterhalder and Smith, 2000: 51-54). There are many assumptions for all OFMs, regardless of the model's focus. First, it assumed that the forager receives the reward or energy, and the forager has knowledge about a resource’s costs and benefits when selecting it; thus, they will select the resource or bypass it in search of a more optimal or profitable resource (Bird and O'Connell, 2006: 147, Kennett and Winterhalder, 2006: 13, 170, Stiner and Kuhn, 2016: 178, Winterhalder and Smith, 2000: 54). Second, natural selection and competition are the consequences of reproduction in a fixed environment (Keene, 1983: 140). Third, adaptive processes select behaviours that allow individuals to efficiently and effectively achieve their “life goals,” i.e., satisfy their basic metabolic needs, avoid predators, and reproduce (Keene, 1983: 140). Further, to achieve these “life goals,” individuals must maximise their efficiency for energy capture (Keene, 1983: 140). In other words, this third assumption is that humans make rational decisions to maximise the net rate of energy captured or “optimise” their energy efficiency (Reitz and Wing, 2008, Winterhalder and Smith, 2000: 54). This optimisation assumption is the overarching assumption for all OFT models.

By optimising their energy capture and efficiency, not only do individuals satisfy their life goals, but they enhance their fitness (Bird and O'Connell, 2006: 146, Hawkes and O'Connell, 1992: 64, Keene, 1983: 140-143, Kennett and Winterhalder, 2006: 95, 111-112). Concerning optimising energy capture and efficiency, individuals can do this either by increasing nutrient or energy intake or reaching this energy intake threshold more quickly (i.e. saving time); this allows for the individual to free time and energy to pursue other fitness-related activities (Bird and O'Connell, 2006: 146). In other words, foragers who maximize their energetic return rates and efficiency will have more resources and/or extra time to invest in family, offspring, or towards reproduction, thus enhancing their reproductive success (Hawkes and O'Connell, 1992: 64, Keene, 1983: 140-143, Kennett and Winterhalder, 2006: 95, 111-112). Put simply, with OFT, whether the individual is human or nonhuman, their behaviours tend toward optimisation and efficiency as a result of both natural and cultural evolutionary processes (Kennett and Winterhalder, 2006: 11).

Concerning the model in this thesis, there is no “assumption” equivalent to that within the OFT modelling. Chapter 7 of this thesis suggests that the efficiency and costs of Çatalhöyük’s agricultural system signify that its population could have maintained or improved its agricultural efficiency by increasing the amount of energy received from agriculture or decreasing its population. The model within this thesis also implies and empirically quantifies that improving efficiency would have been required at Çatalhöyük when its peak population was reached. Furthermore, during its occupation, there were points in which Çatalhöyük could have more energy and time to dedicate to processes outside of agriculture. However, these are not inherent assumptions that formed the model within this thesis. Finally, another sharp contrast between the model in this thesis and OFM is that the latter is predictive modelling focused on the behaviour of individual actors within static, unchanging conditions (Bird and O'Connell, 2006, Hawkes and O'Connell, 1992, Keene, 1983, Kennett and Winterhalder, 2006). On the other hand, the former is not based on individuals, does not seek to explore individuals’ decision making, and incorporates variability in crop yield, domestic cereal reliance, and population growth.

Optimal foraging models are not all the same, and it is beyond the scope of this thesis to delve into every model. However, there is an assortment of models that have developed hypotheses about most optimal strategies for dietary composition and food choice (optimal diet), group organisation and size (optimal group size), and size location and patch use (habitat movement, optimal foraging space) (Keene, 1983: 139, Reitz and Wing, 2008, Winterhalder and Smith, 2000: 54). Some of the characteristics of these OFMs vary depending on the hypotheses being tested. For example, a Diet Breadth (otherwise known as or Prey-Choice) OFM is the simplest, most used, and most powerful OFM (Winterhalder and Smith, 2000: 61). The decision for a forager, for example, is to obtain a resource based on its quality, its density (search costs), and its processing costs (Hawkes and O'Connell, 1992: 63, Kennett and Winterhalder, 2006: 170). The “decision” or “alternative set” of the forager is to maximise the mean rate of energy gain; the forager will always choose the resource that will give a higher return (Hawkes and O'Connell, 1992: 63, Kennett and Winterhalder, 2006: 170). Another example of an OFM is a Settlement relocation OFM. This type of OFM focuses on predicting when foragers will relocate their central place of living as a result of depletion of resources, seasonal shifts, the availability of local or distant resources, seasonal shifts, or any other shifts in values related to settlement location (Kennett and Winterhalder, 2006: 17).

More recently, within archaeology, OFMs have been expanded to focus on subsistence related technological changes, the origin and spread of agriculture, the development of social hierarchies, the evolution of human life history, understanding resource transport, exploring the links between foraging and technology, and, colonisation processes among foragers (Bird and O'Connell, 2006: 144-148). Clearly, OFT and OFM allow for investigating, predicting, and understanding the choices and behaviours of past individuals. It is beneficial for archaeologists to utilise OFT because it allows us to attempt to predict and test past behaviours for which we have no direct observations (Stiner and Kuhn, 2016: 177). As Keene (1983) argues, OFT allows for archaeologists to (1) generate alternative hypotheses and interpretations of the archaeological record that are *testable* and (2) to consider and model behaviours or decision making processes that are not apparent in the archaeological record, which (3) allows for a better, quantifiable understanding of the costs and benefits of different resources (Keene, 1983: 149).

Although OFT models are helpful for archaeologists, some issues arise with utilising them, more specifically with regards to estimating return rates, costs and benefits, the focus on the individual, and excluding variability in behaviour (Bird and O'Connell, 2006, Hawkes and O'Connell, 1992, Keene, 1983, Kennett and Winterhalder, 2006). As explained by Kennett and Winterhalder, assessing return rates in the past is problematic because it depends on known encounters, procurement techniques, processing techniques, and transportation costs, which are not directly available from the archaeological record (2006: 112). Furthermore, costs and benefits of certain resources are also unknowable; we must utilise ethnographic and experimental studies that estimate return rates and labour investment (Kennett and Winterhalder, 2006, Stiner and Kuhn, 2016). Furthermore, the archaeological record rarely allows us to interpret individuals' dietary choices and resource acquisition strategies. Finally, as Kennett and Winterhalder point out, “the archaeological record commingles the behaviour of many individuals over varying but long periods of time,” whereas OFT and its models focus specifically on individuals under explicit conditions during short periods (2006: 112).

Although there are some significant issues with OFT and its modelling, its approaches and cost and benefits analyses are still useful for archaeological discourse and still utilised today. In fact, Agent-Based Modelling allows for iterative models of OFM to be incorporated to understand group dynamics and processes in the past throughout extended periods of time. With this, agent-based modelling effectively helps to improve upon OFMs shortcomings and is extremely useful for archaeological modelling of past processes. Thus, agent-based modelling is the focus of the following subsection.

2.5.2 Agent-Based Modelling in Archaeology

Agent-based modelling is a form of computer simulation that seeks to investigate and understand change within systems throughout time and space, whether these changes result from external factors or the internal dynamics systems (Romanowska, Crabtree et al., 2019: 178-179). Agent-based modelling (henceforth ABM) focuses explicitly on simulating the actions of individuals, i.e., agents, within an artificial environment, to understand how their actions and decision-making processes produce patterns which over time produce global patterns (Epstein and Axtell, 1996: 5, Kohler and van der Leeuw, 2007: 4, Lake, 2015, Romanowska, Crabtree et al., 2019: 178). Although agents' decision-making processes are determined by the modeller and probability factors, agents within ABM must adhere to the following: agents must be autonomous, goal-directed, change their behaviour in response to their environment, have specific locations within the environment, and, they must interact with other agents around them (Lake 2015: 4-5). Much like a computer game version of OFM, the agents, their behaviours, decision-making processes, and interactions with, as well as responses to the environment and other agents, are played out (e.g. "exercised" or simulated) over time and throughout space (Epstein and Axtell, 1996: 5, Kohler and van der Leeuw, 2007: 4, Lake, 2015: 23). The computer simulation effectively tests and reveals how agent behaviours and processes work and what sort of changes occur from their individual actions (Epstein and Axtell, 1996: 5, Kohler and van der Leeuw, 2007: 4, Lake, 2015: 23). Overall, ABM seeks to explore and understand, via computer simulation, how systems and their characteristics arise from a system's parts and the interacting dynamics of systems through time (Kohler and van der Leeuw, 2007, Lake, 2015).

Over the last 20 years, agent-based modelling has been one of the most utilised forms of computational modelling in archaeology, accounting for over half of computer simulation within the field (Lake, 2015: 7, Romanowska, Crabtree et al., 2019: 178). Agent-based modelling approaches within archaeology typically seek to investigate and understand the patterns witnessed in the archaeological record across time and space and more broadly, change within past human systems (Romanowska, Crabtree et al., 2019: 178). ABM allows archaeologists to investigate the dynamics of past human systems and test explicit hypotheses and theories regarding past human behaviour and decision-making processes and their potential effects (Lake, 2015, Romanowska, Crabtree et al., 2019). ABM also provides a way for archaeologists to construct artificial societies and their environments and "see" how external and internal forces in the past (e.g. climatic fluctuations, social changes, technical innovations, or behaviours) functioned and produced long-term changes (Romanowska, Crabtree et al., 2019: 180-181). In a way, ABM allows archaeologists to effectively observe past processes and behaviours, test which processes and behaviours did not take place, examine and explore "what-if" scenarios, model feedbacks between individuals and the environment, and compare simulated models against the archaeological record (Kohler, Bocinsky et al., 2012, Lake, 2015: 4-5, Romanowska, Crabtree et al., 2019: 180-181). Thus, the shortcomings of OFT based models are improved upon by ABM. Furthermore, ABM allows for archaeologists to test the cumulative effects of individual actions and behaviours, cognitive processes, communication, cultural transmission, and even the impact of specific events throughout time and space (e.g., bad harvests, devastating droughts, disease in the population, etcetera), (Romanowska, Crabtree et al., 2019). Viewing such dynamics and feedbacks and testing theories and hypotheses within past human systems spatially and *temporally,* thanks to computer simulation, is nearly impossible with a static archaeological record. Thus, ABM provides an exciting opportunity for archaeologists to explore and understand the past.

An exemplary example of ABM, which also serves as an appropriate comparison to the model within this thesis, includes that of the Village Ecodynamics Project (VEP). This agent-based modelling project focused on simulating prehispanic Puebloan ("Anasazi") populations in the

Southwestern United States from AD 600 and 1600 (Kohler, Bocinsky et al., 2012: 31). These populations underwent two cycles of population growth and decline, which are currently attributed to climate affecting maize farming; the second decline resulted in the depopulation of the Northern Southwest during the 1200s AD (Kohler, Bocinsky et al., 2012: 31). With regards to these population growth and decline events, the VEP project sought to explore the following (1) the possible depression of regenerating resources (fuelwood and deer) by Puebloan societies and the potential effects on turkey intensification, (2) understanding household locations and residential site size change over time, (3) the effects of exchange on settlement patterns and population size, (4) changes in carrying capacity of the study area under various rates of resource and production use, (5) exploring the factors tied to the emergence of complex societies throughout the VEP study region, and finally, (6) exploration of potential factors that could be tied to Puebloan societies vacating the study region during the thirteenth century AD (Kohler, Bocinsky et al., 2012: 30-31).

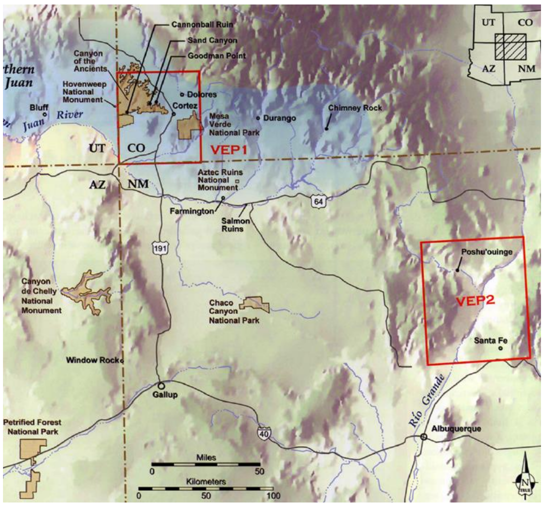


Figure 8: Kohler et al. 2012's VEP 1 and VEP 2 study areas (2012: fig. 1, pg, 31) constituting the VEP study region.

"Agents" within the VEP's models represented Pueblo households who optimise their locations and resource use based on household needs (Kohler, Bocinsky et al., 2012: 31). Household needs were based on age and sex of members, more specifically, caloric and protein needs (Bocinsky, Cowan et al., 2012, Kohler, Bocinsky et al., 2012: 33). Utilising an OFM model to inform agent behaviour, households choose resources based on the resource value for each household, which is measured by the amount of calories expended to procure that specific resource and its proximity to water (Kohler, Bocinsky et al., 2012: 32, 39). Resources included growing maize, collecting dead wood and/or harvesting live wood for fuel, hunting three different animal species (mule deer, rabbit, and hare) to meet protein requirements, and turkey intensification (Kohler, Bocinsky et al., 2012: 32-33). Finally, the VEP model allowed population size and household location to emerge from these model parameters and interactions, to which they compared to estimates generated by the archaeological record (Kohler, Bocinsky et al., 2012: 31).

Focusing first on population estimates, the VEP model estimated the first period of occupation from AD 600-725 to be roughly 300 households (just over 1800 people) (Kohler, Bocinsky et al., 2012: 32-33). From this point, the study area's population increased until AD 880, when 8200 people lived in the study area; then, the population sharply declined to 1700 between AD 920 and 980 (Kohler, Bocinsky et al., 2012: 32-33). The population remained low until AD 1060-1100 when immigration increased population to roughly 8300 people peaked to 19,400 in the mid-1200s (Kohler, Bocinsky et al., 2012: 32-33). Finally, the area was depopulated between AD 1260 to 1285 via migration to the south(Kohler, Bocinsky et al., 2012: 32-33).

Overall, the VEP simulation identified and confirmed two cycles of population formation and growth between AD 780-920 and the second between 1060-1280, in which 70% of the population lived in villages at the end of these cycles (Kohler, Bocinsky et al., 2012: 32-33). Moreover, for the first population cycle (AD 600-920), the simulation found that households located themselves based on efficiency concerning resources sought after, and efficiency peaked at the end of each population cycle (Kohler, Bocinsky et al., 2012: 32-33).,

Concentrating on maize, the VEP model based yearly maize yield estimates on moisture level from local tree ring data and elevation (Kohler, Bocinsky et al., 2012: 32). Utilising an OFM approach, households attempt to produce enough calories from growing maize within the study area (Figure 8 VEP 1 and VEP 2), and protein requirements were designated as 10g-25g of protein per day (Bocinsky, Cowan et al., 2012: 148, Kohler, Bocinsky et al., 2012: 32). If a household experiences maize shortages, the household “deals” with these by utilising storage reserves, increasing farming plots depending on household work capacity, or if storage and expansion fail, say, due to soil degradation, which is also included in the simulation, the household relocates (Kohler, Bocinsky et al., 2012: 32). More specifically, households relocate by selecting locations where the caloric expenses of farming, hunting, and acquiring water and fuelwood are minimal (Kohler, Bocinsky et al., 2012: 32). Regarding turkey intensification, the VEP project simulated households to either meet all protein requirements from hunting three species or switch to domesticating turkeys (Kohler, Bocinsky et al., 2012: 36). Households hunt until the return rate from hunting rabbits, hares, and deer falls below raising turkeys (Kohler, Bocinsky et al., 2012: 36). However, if and when households do switch to domesticating turkeys, the model assumes they have the number of turkeys to feed the household for a year and the household must grow maize to feed the turkeys; simulated households are not allowed to deplete their storage to raise turkeys (Kohler, Bocinsky et al., 2012: 36).

The VEP project also simulated marriage, the formation of new households, economic specialisation, bartering between households, and the emergence of leadership (Kohler, Bocinsky et al., 2012: 36-38). Finally, time and calories were limited for VEP households. Households were limited to the number of calories and work time they dedicated to tasks; the VEP project set this limitation to no more than 6 hours per day for each adult member of the household, whereas children under the age of 7 were deemed not to contribute (Kohler, Bocinsky et al., 2012: 38). Overall, households in the model dedicate their time to hunting, farming, gathering wood, and water procurement explicitly based on family needs, competition with other households and trade(Kohler, Bocinsky et al., 2012: 38-39). Households can also exchange with neighbours if some of their resources are insufficient (Kohler, Bocinsky et al., 2012: 38-39).

The VEP ABM simulation results were subsequently compared to the archaeological data from the VEP project. The results fill a book; however, for the sake of brevity, the simulation allowed for the following: an explanation for changes in the zooarchaeological assemblage, a discrediting of a hypothesis regarding drought potentially leading to the area’s depopulation, and insights to potential exchange relationships, the efficiency of household locations, and time dedicated to subsistence activities (Kohler, Bocinsky et al., 2012: 31, 33-34).

Comparing population estimates to the archaeological record, the ABM model created overestimated population in the AD 900’s and AD 1200s and underestimated it during the period of AD 1000 through the mid-1200s (Kohler, Bocinsky et al., 2012: 32-33). However, the population estimates did allow for the project to investigate efficiency concerning resource use and subsistence related activities (Kohler, Bocinsky et al., 2012: 32-33). VEP project simulations estimated that at the population peak, each worker (anyone over seven years old), would have spent over 5 hours a day on subsistence chores (Kohler, Bocinsky et al., 2012: 33-34). However, this time and caloric estimate does not include grinding maize, making and maintaining ceramics, lithics, and basketry items which form the foundation for hunting farming, nor does it include the building and maintaining of storage and agricultural features (Kohler, Bocinsky et al., 2012: 34). Essentially, all non-subsistence activities are unaccounted for (Kohler, Bocinsky et al., 2012: 34). Despite this, the VEP model indicates that the study area at its peaks was significantly intensified to the point where it was at its carrying capacity for sustaining farming (Kohler, Bocinsky et al., 2012: 34). With the ABM data produced, the simulation also discredited a hypothesis regarding local populations depleting drinking water supplies which subsequently led to the depopulation of the study area (Kohler, Bocinsky et al., 2012: 33). The simulated model, which includes past environmental data on moisture and water resources, including seasonal and permanent springs, indicate this was not the case (Kohler, Bocinsky et al., 2012: 33). Populations did *not* significantly deplete water sources in the area, and this was not necessarily an issue for the population (Kohler, Bocinsky et al., 2012: 33). Instead, the sustainability and efficiency of household maize farming was the most significant determinant of depopulation in the study area (Kohler, Bocinsky et al., 2012). Here, the ABM simulation clarified and understood household formation, carrying capacity, subsistence activities and even discredited a hypothesis. Such understandings could not be reached utilising archaeological data on its own.

Focusing on the zooarchaeological data, the VEP project data indicates that the proportion of deer declines throughout occupation with jackrabbits, cottontail rabbits, and turkey replacing them (Kohler, Bocinsky et al., 2012: 33). Furthermore, the VEP simulations indicate that if households hunt deer based on hunting radius and/or protein sought, whether protein sought was 10g or 25g of protein, no matter the situation, simulated Puebloan populations depress the deer population (Bocinsky, Cowan et al., 2012, Kohler, Bocinsky et al., 2012: 33) This helps to explain why the proportion of deer within the zooarchaeological assemblage decreases over time (Bocinsky, Cowan et al., 2012, Kohler, Bocinsky et al., 2012: 33). Thus, in this case, this ABM simulation allowed for a better understanding of the processes occurring with the relationship between deer decline and turkey intensification; understandings and findings which could not have been reached utilising the archaeological record of its own accord.

The ABM approach briefly summarised above allowed for investigating change throughout a particular human system over time and space, drawing from OFM and based on individual activities, decisions, relationships, and even environmental factors and responses (Romanowska, Crabtree et al., 2019: 179). In other words, ABM allowed archaeologists to model feedback between agents and the environment and create archaeologically informed simulations that individual behaviours can drive (Lake, 2015: 5, Romanowska, Crabtree et al., 2019: 181). Although many ABM approaches like the VEP project are computer simulations with agent behaviour informed and decided by the modeller, ABM is no different from any other model utilised in archaeology. Romanowska et al. 2019, for example, argue that ABM is no different from ethnoarchaeological approaches or experimental archaeology approaches used within our field; all three allow for a direct comparison of past archaeological processes:

> “an agent-based modeller constructs an artificial society governed by a strictly defined set of behavioral rules, making processes and causal relationships directly observable. The consequences of the simulated processes are then compared to the patterns in archaeological data. The aim of both types of research is to understand the dynamics of an accessible and, therefore, well-understood system well enough to be able to infer whether similar processes might have taken place in the past” (Romanowska, Crabtree et al., 2019: 180).

ABM is an accessible, reproducible, comparable, and easily tested type of modelling, especially because its simulations are rigorously defined; thus, ABM is a legitimate and plausible form of modelling that can greatly contribute to archaeological discourse (Romanowska, Crabtree et al., 2019). Further, because ABM expands and enhances archaeological modelling, it allows us to incorporate individuals, their agency, their interactions, various feedbacks, *and* global level patterns resulting from their combined effects over time (Romanowska, Crabtree et al., 2019: 180-181). With regards to broader sustainability issues, ABM allows for the incorporation of unintended or unanticipated consequences of past human decisions and actions upon the environment, which is often missing from past energetic models. Furthermore, it offers and allows for the simulation and formal testing of such matters. Again, formal testing of such issues would allow for a firm understanding and evidence-supported models of how our unsustainability problems have developed in the long term (Malm and Hornborg, 2014, van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). More specifically to this thesis, although the model presented here is not agent-based, it absolutely sets the foundation for a future agent-based model exploring agricultural decision making at Neolithic Çatalhöyük. However, there are differences and similarities between ABM approaches and the model presented within this thesis.

First and foremost, the model presented in this thesis is neither a simulation nor is it iterative over long periods of time (Lake, 2015). As will be established throughout chapter 4-6, the model in this thesis recalculates archaeological data through the lens of a modern human energy requirements framework. The model focuses explicitly how Çatalhöyük's agricultural system functioned and on the energy requirements of Çatalhöyük's agricultural system as its population grew and declined. My model is a detailed and specific model of Çatalhöyük's agricultural energy system based on 4 domestic cereals with varying cereal reliance and yields, operating over a short time span which is informed by observed archaeological data, experimental archaeological data, and ethnographic data. If this thesis were an ABM approach, it would instead focus on how Çatalhöyük's agricultural system came to be and utilise computer simulation to understand how Çatalhöyük's individuals made decisions on domestic cereal reliance and agricultural activities and "exercise" them throughout time (Kohler and van der Leeuw, 2007). This is not the aim of the model within this thesis, although future research should take the work within this thesis towards this step. Further, there are no autonomous agents simulated, they do not interact with others, and they do not respond to the external environment.

Like an ABM approach, or any archaeological modelling approach, a set of archaeologically and ethnographically informed and explicit assumptions are made to set the foundation of the agricultural energy model within this thesis (Chapter 4.1-4.4, Chapters 5.2 through 6). Also like an ABM, the model within this thesis is quantitative and begins to form a comparable standard (for understanding energy in the past) (Kohler, Bocinsky et al., 2012: 30, 40, Lake, 2015: 5-7).

As reiterated throughout this chapter thus far, many have recognised the importance of energy. The energy-systems method and analysis presented in chapters 4 to 6 helps bridge the energy understanding gap in archaeology, could contribute to OFM and ABM models, and demonstrates that quantifying and assessing past energy systems using archaeology's data and methods is possible.

2.6 CONCLUDING THOUGHTS: A BACKGROUND TO SOCIETY AN ENERGY

This chapter has focused on how various theorists attempt to understand the relationship between society and energy. Section 2.2 set the foundation of this chapter, outlining the work of energy theorist Leslie White. Section 2.3 primarily focused on those in the sustainability realm who have attempted to understand the relationship between energy and complexity, often taking a grand theory approach to analyse life, earth, the universe, or all the above. Quite often, however, quantifications of past energy systems were either missing or, if they were made, they were quantifications unsubstantiated by archaeological data, methods, or analyses. Because of this, many models promoted or relied upon deterministic understanding of history and cultures and thus, resulted in problematic and reductionist models. Instead of utilising archaeological data to substantiate and refine models of energy use in the past, sweeping, simplified generalisations were often made, and it seems that the tools archaeology has at its disposal are underappreciated and underutilised. Related to this, social and cultural context are also frequently misrepresented or generalised. It was clear that many energy theorists do not fully understand the cultural diversity or intricacies within human societies; therefore, they are missing the complexities of energy within these cultures, societies, and within agriculture itself, both in the past and present.

Further, understanding the complexities of energy within society is also an archaeological problem. Very few archaeological studies have focused on understanding the past in terms of human energy systems, and few have attempted to model, analyse, or compare past energy systems. The archaeological narratives discussed in section 2.4 and 2.5 argue for an energetic approach to understanding humanity's development and overall demonstrate that energy is being discussed in our field, yet, at present, there is no methodology by which to calculate systemic energy use in the past, until now.

Much of the literature presented throughout this chapter, no matter what discipline they are from, have commonalities. First, energy, the environment, and humanity have a complex, unique relationship that must be teased out. This is something White (1943), Chaisson (2003, 2005, 2011, 2013, 2014a, 2014b, 2015) , Smil (2000, 2008, 2013, 2017), Odum, (Odum and Pinkerton 1955, Odum and Odum 1977, Odum 1977, 2007), Fischer-Kowalski and colleagues (Fischer-Kowalski and Haberl 2007, 1997, Fischer-Kowalski et al. 2014, Fischer-Kowalski and Weisz 1999), Lenton and co-authors (Lenton and Watson, 2011, Lenton, Kohler et al., 2021), Rappaport (1971), Binford (2001), Redman and colleagues(1999, 2005, Redman and Kinzig, 2003), and Barrett (2011, 2013a, 2013b, 2014, 2021, Ion and Barrett, 2016) all argue, in one way or another. Human systems themselves are energy systems; however, human lifeways and subsistence pathways play a fundamental role in how they extract energy. Hence, nearly every theorist discussed throughout this chapter attempted to compare and contrast methods of energy extraction. Understanding humanity's relationship with energy is clearly an inter-disciplinary and sustainability issue. Second, all the authors agree that agriculture and the Neolithic Revolution were and required fundamental changes in energy flow through the biosphere, including within human systems. Throughout this chapter, it has been made clear that once agriculture took hold, major changes occurred, which were unstoppable. Further, although all the theorists throughout this chapter make this point and understand that agriculture produces significant amounts of energy, requires sedentism, changes social organisation, many are missing the complex mechanisms that are required of agriculture and are not contextualising it within the history of humanity. They simply are not modelling agriculture or its processes separately and energetically, which would allow them to tease out these mechanisms at work. Finally, archaeological research is wholeheartedly missing from many energy research models, and energy models require archaeological data, narratives, and analyses. From Chaisson's emphasis and calculations of on energy rate density, Smil's energy input and efficiency calculations, Fischer-Kowalski's formulaic approaches, Odum's macroscopic ecological approaches, Lenton's systems analyses, Binford's environmental approaches, Barrett's autopoietic approach, and Redman's focus on adaptive cycles and resiliency framework, all emphasise and beget the need for the following: a methodology by which to quantify energy use in the past.

The authors discussed throughout this review chapter have made significant contributions forming the foundation of this thesis. White (1943), for example, renewed a focus on society-energy relationships, pushed for understanding society-energy relationships. Further, he emphasised that energy extraction is culturally specific, related to technology, and was one of the earliest to provide a theory close to the agricultural energy feedback system (White, 1943). Chaisson (2003, 2005, 2011, 2013, 2014a, 2014b, 2015) emphasised and highlighted the importance of energy flows, using energy as a mechanism to compare system complexity upon the same scale, and advocates for utilising the energy of past systems to better understand the present. Smil (2000, 2008, 2013, 2017) emphasised the importance of energy flows, conversions of energy, highlighted the importance of energy input and output, and highlighted energy efficiency. Energy efficiency is utilised in this thesis to analyse Çatalhöyük's agricultural energy system, directly influenced by Smil's work. Odum (1955, 1973, 1977, 1988, and 2007) was one of the first to suggest that agriculture comes with specific, potentially unsustainable dependencies. Agriculture as a system is neither energetically advantageous nor sustainable, as it traps societies into depending upon certain energy sources (Odum, 2007, Odum and Odum, 1977). Odum also emphasises that populational ebbs and flows result from energy balances (Odum, 2007, Odum and Odum, 1977). Fischer-Kowalski and colleagues work takes Odum's arguments surrounding agriculture's unsustainability a bit further. Fischer-Kowalski and colleagues argue that agriculture itself is a form of environmental colonisation; once agriculture took place, there was no turning back, as it came with a plethora of unintended, irreversible consequences (Fischer-Kowalski and Weisz, 1999: 236). More importantly, Fischer-Kowalski and colleagues recognise the existence of an agricultural feedback system in its entirety and are one of the first to do so. This thesis draws from Fischer-Kowalski and Haberl's work and takes it further by energetically modelling a past agricultural energy system based on archaeological data and methodologies and *proves* the existence of an agricultural energy feedback system.

Similarly, Lenton and colleagues fully recognise that there is a positive feedback within agriculture, directly related to its processes and the energy surplus agriculture provides (Lenton and Watson, 2011, Lenton, Kohler et al., 2021). Redman and colleagues call for archaeological contributions to resilience theory, highlights the importance of culture in relation to resiliency and adaptive cycles within human systems, emphasises the efficiency of behaviours on human systems, and, argues that a positive feedback system between accumulating a surplus and maintaining efficiency facilitates the emergence of complex society (Redman, 2005, Redman and Kinzig, 2003). Further, Rappaport's ethnographic work on agricultural energy work suggests the presence of a positive feedback within complex societies and utilises a human energetics approach to understand agricultural energy and its relation to ritual practices (Rappaport, 1971). Binford's (2001) work and emphasis on energetic baselines, specifically concerning sustenance and energy expenditure, helped drive this thesis' focus on creating an energetic baseline based on archaeological data. Further, Lenton et al. 2021, Rappaport 1971, Kemp 1971, and Fuller et al. 2010, Barrett 2011 aided in ensuring this thesis explicitly focused on modelling agriculture's processes *separately* and energetically. Further, Barrett's work (Barrett, 2011, Barrett, 2013a, Barrett, 2013b, Barrett, 2014, Barrett, 2021, Ion and Barrett, 2016) helped this thesis' focus on understanding agricultural feedbacks in relation to energy, population growth, and ecologies, and, attempting to understand the Neolithic as a process of changes in energy management (Barrett, 2011: 67). Finally, optimal foraging theory modelling has aided in using the resulting energy model form this thesis to understand the cost and efficiency of agriculture (see 7.2.2 and 7.2.3). Overall, this thesis builds from these authors by emphasising energy flow, building from their models of society and energy by creating and enacting methodology which calculates a past agricultural system based on archaeological data, and proves the existence of the agricultural energy feedback system.

Some of the biggest questions archaeology as a discipline faces are understanding the relationship between agriculture, population growth, and sedentism, understanding limits to population growth, and understanding the mechanisms behind the Neolithic revolution. These are all questions about humanity's energy use and sustainability. Agriculture, as many have argued and tried to demonstrate, is inherently dependent upon energy use. It was during the Neolithic, as well, however, quantifying our past relationships with agricultural energy, using archaeological data, methods, analyses, and perspectives, has never been attempted. Further, archaeology has never attempted to quantify this and has not fully recognised the energetic dependencies of agriculture and its processes. Nevertheless, archaeology has the tools at its disposal, the data, and methods to help us better understand how processes of energy extraction flow and function and potentially lock us into unsustainable trajectories. Sustainability is in itself an archaeological problem. Therefore, to address these significant gaps, the remainder of this dissertation will enact and present an energy methodology by which to quantify and model past energy systems focusing on Neolithic Çatalhöyük. Çatalhöyük makes an excellent case study not just because of the data available from the site, but, because Çatalhöyük is known to be one of the sources of the western expansion of agriculture, thus, understanding the agricultural energy relationships at Çatalhöyük concomitantly allows for a better understanding of the spread of agriculture during the Neolithic, and its relationship to agricultural energy (Barrett, 2011, Barrett, 2016, Barrett, 2019, Shennan, 2018).

3 CHAPTER 3: A HISTORY OF ÇATALHÖYÜK

This dissertation aims to enact and present an energy methodology to quantify and model a past energy system, using the Neolithic agricultural system at Çatalhöyük as an example. This chapter focuses on presenting Çatalhöyük and its data as a case study and will demonstrate that the agricultural energy feedback system was indeed occurring at Neolithic Çatalhöyük.

Similar to many other Neolithic sites reliant upon agriculture, Neolithic Çatalhöyük saw significant changes throughout its occupation, especially during its rapid growth period (6700-6500 cal. BC), including high levels of crowding, increases in fertility, increased workload and labour demands, increased mobility of humans and animals, more dietary diversity along with an increased reliance upon cereal grains, a growing dependence on domestic sheep, and even changes in sources of pottery and bead manufacture, wood resources, and obsidian procurement (Hodder, 2017, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019). These changes during Çatalhöyük's Neolithic occupation were radical and interpreted as being related to its growth of up to 2500 ± 500 people; this growth resulted in Çatalhöyük needing to expand its resource catchment zone, decrease labour, and increase the efficiency of daily processes (Bernardini and Schachner, 2018, Hodder, 2014b). Further, Hodder himself argues that population increase was produced due to practical, daily entanglements at Çatalhöyük (Hodder, 2016: 34, Hodder, 2021a) Çatalhöyük's entanglements resulted in Çatalhöyük responding to increased labour demands by increasing its population (Hodder, 2016: 33-34, Hodder, 2021a: 276-280). I will demonstrate that what is missing from this narrative is a discussion of the energy requirements to sustain this growth, and the mechanism that required Çatalhöyük to decrease labour in certain activities has greater efficiency of various processes and expand resource catchment zones. This mechanism, I argue, was the agricultural energy feedback system.

Referring to Figure 1, by providing more energy, agriculture facilitated Çatalhöyük's population growth and increased fertility; a cyclical requirement by which population growth and increased fertility required energy input from the population to sustain agriculture. As Çatalhöyük grew and became more dependent on agriculture, it had to dedicate more time and energy to agriculture and its processes and herding, gathering, and foraging, hunting, and feasting. Çatalhöyük was also depleting its environment and resources, thus forcing Çatalhöyük to expand its resource catchment area. To account for agriculture's extra time and energy requirements, Çatalhöyük had to find ways to adjust to these energy demands. With this, Çatalhöyük saw changes in diet and nutrition, plant relationships, resource procurement, and even in animal relationships (Hodder, 2014b, Larsen, Knüsel et al., 2019, Pearson, Buitenhuis et al., 2007). Such considerations of agricultural energy input and dependencies are absent from discussions of agriculture throughout SW Asia and from interpretations of Çatalhöyük itself. All agricultural processes provide food to enable people to live and perform other activities, require energy to perform, and depend on one another's success. If any agricultural process fails, the entire agricultural system, and the subsequent flows of which it is a part, breaks down.

The discussion and quantification of this feedback system, agricultural energy, and the dependencies of agriculture's processes are missing from the literature of the Neolithic as well as interpretations of Çatalhöyük. Çatalhöyük's expert-led excavations, plethora of archaeological evidence, 21 meters of stratigraphic sequencing, paleoenvironmental data, and nearly 2000 years of occupation, with no breaks in stratigraphic sequence, make it a remarkable case study for exploring energy use among early historic communities during the

Agricultural revolution (Farid, 2014, Hodder, 2014a). Before establishing an energy methodology and modelling Çatalhöyük's agricultural system to quantify and understand this feedback system, we must first understand Çatalhöyük itself: its local and regional environment, the lifeways, and temporal changes occurring throughout its occupation. Section 3.1. provides a background of Çatalhöyük in relation to broader Neolithic trends, especially focusing on the Agricultural Revolution. Section 3.2 presents Çatalhöyük's environment, regionally and locally. Following this, Section 3.3 presents the subsistence, health, population, material, and overall temporal changes which occurred at Çatalhöyük. Section 3.4 summarises and demonstrates that the agricultural energy feedback system occurred in the Neolithic at Çatalhöyük.

3.1 ÇATALHÖYÜK'S BACKGROUND AND SIGNIFICANCE

Çatalhöyük was first excavated by James Mellaart in the 1960's and a new research project directed by Ian Hodder started in 1993 (Hodder, 1996, Hodder, 2000, Hodder, 2013, Mellaart, 1961, Mellaart, 1962, Mellaart, 1963). Çatalhöyük is one of the largest (13.5 ha, 0.13km^2) Neolithic sites in southwest Asia and provides evidence of a flourishing early farming settlement (Atalay and Hastorf, 2006: 291-292, Baird, 2002, Baird, 2005, Filipović, 2014 :2, Hodder and Cessford, 2004, Kuijt, 2000, Rollefson and Köhler-Rollefson, 1989). It is the impetus of Europe's agricultural colonisation and represents one of the most critical transitions in human history, The Agricultural Revolution (Flannery, 1973, Hodder, 1990, Shennan, 2007, Shennan, 2018). This transition was a fundamental turning point for humans as it brought new ensembles of human activities, behaviours, and technologies, all of which permitted cereal cultivation, unprecedented population growth, surplus production, and changes in nutrition, workload, mobility, and social interaction (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larsen, Knüsel et al., 2019, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995). Archaeological evidence at Çatalhöyük indicates that it was a complex society as it consists of community and political organisation, long-distance trade and mobility, increasing symbolic practice, craft specialisation, ritual practice, and an organised social structure, making it an archetype of "Neolithization" and the "Neolithic package" (Figure 9) (Childe, 1951 (1936), Despina and Relaki, 2020 :156, Fowler, Harding et al., 2015, Hodder, 2018, Robinson, Hadjikoumis et al., 2011).

Figure 9: a) Mudbrick House Structures in North area of excavation; indicates settlement plan-community and political organisation (Quinlan, 2000). b) Obsidian in a burial; indicates long distance trade & mobility and craft specialisation (Quinlan, 2000). c) Pot with faces; indicates increasing symbolic practice (Quinlan, 2000). d) Coloured disc beads in an infant burial; indicates craft specialisation & social organisation (Quinlan, 2000). e) Burial of a pregnant woman and infant remains; indicates ritual practice & social organisation (Quinlan, 2000). f) Horn core installation on a pedestal in Building; potentially indicates early evidence of institutionalised religion (Quinlan, 2000).

Çatalhöyük was occupied throughout the Neolithic, from ca.7100-5950 cal. BC, which more broadly coincides with the Levant Pre-Pottery Neolithic B (PPNB, 8,800 to 6,500 BCE) and Pottery Neolithic (PN, 6,400 to 3,500 BCE) (Figure 10) (Hodder, 2021b: 11). The Çatalhöyük team have designated Çatalhöyük's occupation into three broad periods: Early (pre-peak, 7100-6700 BCE), Middle (peak, 6700-6500 BCE), Late (post peak, 6500-6300 BCE), and Final (6300-5950 BC) (Figure 10) (Hodder, 2021b, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019, Sadvari, Charles et al., 2017). Henceforth, this phasing is utilised for the remainder of this thesis. Although Çatalhöyük is one of a few large "megasites" that emerged in Southwest Asia during the PPNB, it is one of the very few which survived what is known to be a major population shift or "collapse" of the PPNB (Baird, 2002, Baird, 2005, Filipović, 2014, Kuijt, 2000, Rollefson and Köhler-Rollefson, 1989). However, unlike other PPNB sites, Çatalhöyük continued well into the pottery Neolithic and flourished until the Chalcolithic. Çatalhöyük's East Mound, the primary focus of this analysis, was occupied during the Early Neolithic (e.g., PPNB, PN), then, the settlement shifted to the West mound followed by population dispersal (Bayliss, Brock et al., 2015, Cessford, 2001, Cessford, 2005, Cessford, 2006, Filipović, 2014, Larsen, Hillson et al., 2015).

At first, Çatalhöyük's population was small and likely limited to a few families. However, throughout its Middle Period, it reached its peak population (Figure 10) (Cessford, 2005, Hodder, 2021b, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019). Bioarchaeological data indicates that this rapid increase in population was not due to an influx of new members outside of Çatalhöyük but instead, its growth was driven primarily by increased fertility and birthrate, one of the direct results of a reliance upon domestic plant carbohydrates (Larsen, Knüsel et al., 2019) [1]. This is a common theme throughout Neolithic sites during the transition to agriculture and an increased dependency upon domesticated animals, as often crop husbandry and animal husbandry reinforce one another, and, animal husbandry has the ability to supplement grain based diets (e.g. Neolithic *Linearbandkeramik* -LBK) (Bogaard, 2004, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019).

These changes and the overall transition from the Middle to Late periods have been characterised as quite radical (Hodder, 2014b). In addition to expanding resource catchment areas, Çatalhöyük saw substantial changes throughout the community, including new forms of social, economic, and religious organisation (Hodder, 2014b). More specifically, Hodder describes that there was a shift from household and neighbourhood continuity and sharing of resources to one that was more individualistic with more independence between households (Hodder, 2014b). Houses took control of their own food and material goods production as Çatalhöyük's catchment area became more extensive (Hodder, 2014b). In fact, archaeological evidence at Çatalhöyük shows that as its population grew, there was a "temporal depletion of resources farther from the community" (Larsen, Knüsel et al., 2019: 12619). As Çatalhöyük's population grew, Çatalhöyük had to expand its resource catchment area, as more and more resources, or energy sources, were required to keep it going. By the Late period, after it reached its peak population in 6250 BC, the Neolithic East Mound was quickly abandoned, the Chalcolithic West Mound was occupied and Çatalhöyük's population decreased significantly and dispersed (Figure 10), (Larsen, Hillson et al., 2015).

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[1] Settlement data indicates the region outside of Çatalhöyük, even during its peak, had a very small population (Baird 2002, Baird 2005, Larsen et al. 2015)

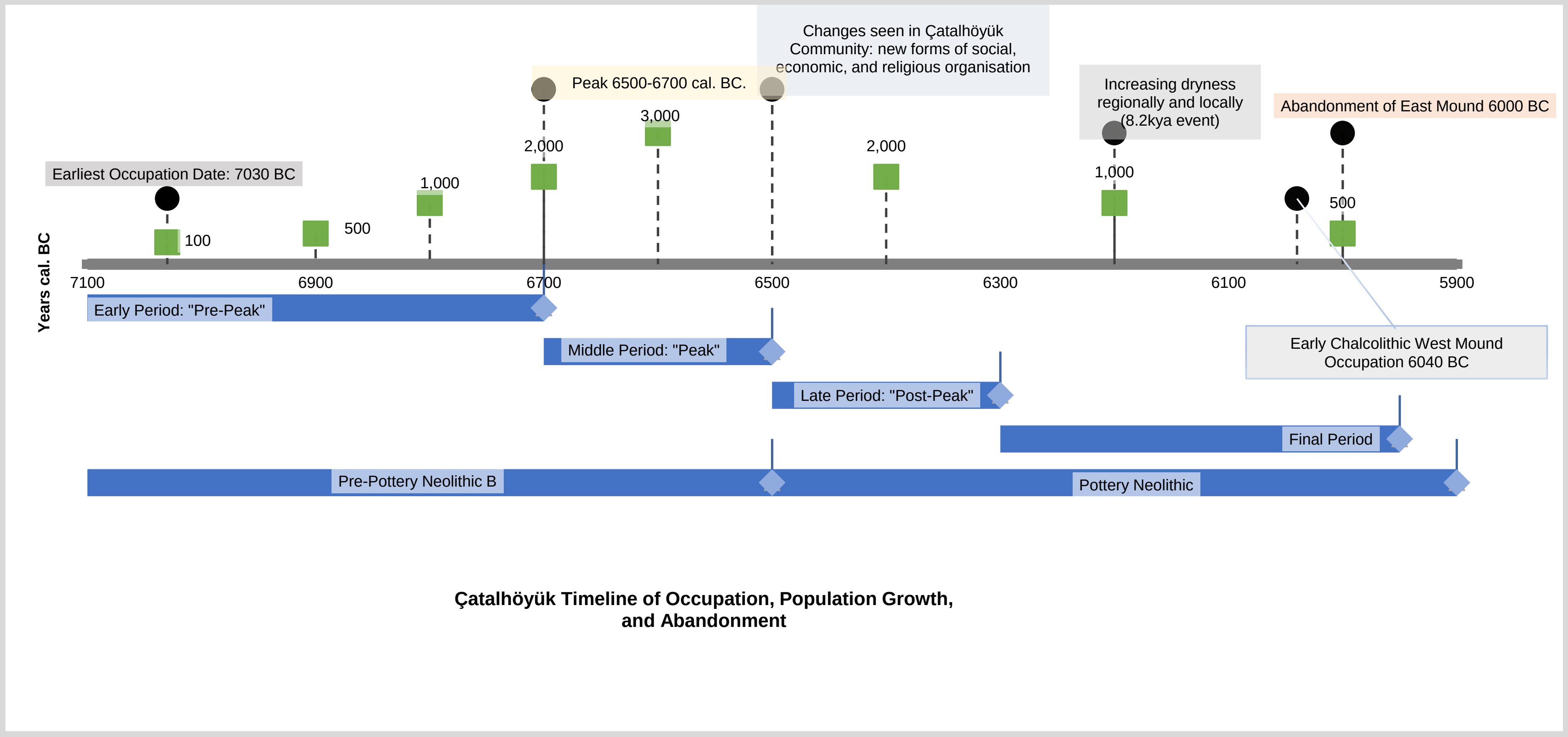


Figure 10: Çatalhöyük Timeline of Occupation, Population Growth, and Abandonment. Timeline is represented in Years cal. BC. Circles designate major Çatalhöyük Events. Green squares represent population growth and decline over time. Also specified are the Early, Middle, and Late periods of occupation throughout the site, and the more regional Neolithic time periods (Pre-Pottery Neolithic B, Pottery Neolithic). This phasing (Early period, Middle period, and Late period) is utilised for this analysis (Hodder, 2021b). Further, the population is represented as 100 people for 7030 cal. BC, rising to 2000 to 3000 people during its peak (6500-6700 cal. BC) and decreasing after the Middle Period, during the Late and Final periods.

These crucial changes have been explained as Çatalhöyük's need for less labour and greater efficiency in processes (Hodder, 2014b). However, I hypothesise that the mechanism taking place which requires a need for less labour and greater efficiency in Çatalhöyük people's daily lives was agriculture and the agricultural energy feedback system. Therefore, discussing and quantifying this feedback system must be completed and doing so for Çatalhöyük allows for a remarkable case study for exploring energy use among early historic communities during the Agricultural revolution (Farid, 2014, Hodder, 2014a). However, we must better understand both the immediate and regional environment of Çatalhöyük before making such quantifications. This is the focus of the next subsection.

3.2 ÇATALHÖYÜK'S REGIONAL AND LOCAL ENVIRONMENT

Subsistence pathways, like agriculture, are one of the means by which humans extract energy to sustain themselves. The environment provides access to energy in the form of plants and animals. Agriculture is dependent upon land, its productivity, and its availability. Knowing and understanding Çatalhöyük's immediate and surrounding environment is crucial in understanding and quantifying Çatalhöyük's agricultural energy system and will aid in presenting a more accurate and sounder model of Çatalhöyük's agricultural system; thus, understanding Çatalhöyük's local and regional environment is the focus of this chapter subsection.

Çatalhöyük is located on the Çarşamba river alluvial fan of the Konya Plain, central Anatolia, in Turkey (Figure 11) (Ayala, Wainwright et al., 2017, Charles, Doherty et al., 2014, Roberts and Rosen, 2009). Today, Çatalhöyük's environment is that of a cold-steppe environment, with very little annual precipitation: approximately 300mm to 350mm per year (Charles, Doherty et al., 2014). The difference between winter and summer is quite drastic; Çatalhöyük has hot, dry drought-like summers and very cold, wet winters with temperatures ranging 20 C between these two seasons (Ayala, Wainwright et al., 2017, Charles, Doherty et al., 2014). Today the area is too dry for rain-fed cultivation, therefore artificial irrigation takes place (Charles, Doherty et al., 2014). However, Neolithic Çatalhöyük's local and regional climate, vegetation, and landscape were far different from today's (Figure 12).

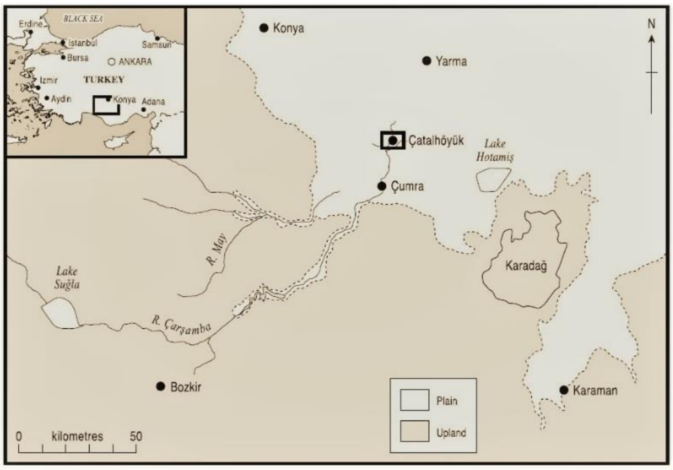


Figure 11: Çatalhöyük location between uplands and the Konya basin, altered from Ayala et al. 2017.

Figure 12: Çatalhöyük East Mound in the Konya Plain. Photo by Jason Quinlan, Copyright Çatalhöyük Research Project

Pollen and paleoclimate data indicate that during the Neolithic, the Konya Plain was dominated by grassland steppe with woodlands throughout, which contained species as oak, elm, maple and hazel (Charles, Doherty et al., 2014: 71). Paleoclimatic data also indicates that the Konya plain was wetter than it is today, and annual precipitation would have been 350-550 mm per year, sufficient for rain-fed agriculture (Charles, Doherty et al., 2014: 71). Çatalhöyük summers would have been less than four months and with a limited drought, unlike what is seen today (Charles, Doherty et al., 2014: 71).

Wide-ranging research has been completed on Çatalhöyük's immediate environment, including on the flooding regime at Çatalhöyük (Boyer, Roberts et al., 2006, Roberts, Black et al., 1999, Roberts, Boyer et al., 2007, Rosen and Roberts, 2005). It should be noted that previous environmental accounts described Çatalhöyük's environment as being so inundated by seasonal flooding that the closest viable agricultural areas were 12 kilometres from the site (Ayala, Wainwright et al., 2017: 42, Rosen and Roberts, 2005). This is no longer believed to be the case. Geomorphological research now indicates that during the Neolithic, Çatalhöyük's landscape was less prone to flooding than previously thought (Ayala, Wainwright et al., 2017, Charles, Doherty et al., 2014, Filipović, 2014). Ayala et al. 2017 undertook an extensive coring programme between 2007 and 2013 at Çatalhöyük to get a better resolution of the paleoenvironmental landscape in the immediate vicinity of the site. We now know that areas within Çatalhöyük's floodplain would have allowed for agricultural opportunities close to the site (Ayala, Wainwright et al., 2017: 41). Arable land *was* available close to Çatalhöyük, although its exact extent has yet to be determined (Charles, Doherty et al., 2014, Doherty, Charles et al., 2008). Moreover, this arable land persisted annually from autumn to summer for decades (Bogaard, 2004, Filipović, 2014, Halstead, 1987, Halstead, 2006, Jones, Bogaard et al., 1999). There is, however, evidence of increasing dryness which occurred around 8.2kya (6200 BC, noted in Figure 10), just after Çatalhöyük's population reached its peak, which is supported by regional lake geochemistry in addition to more localised research in the form of hydrogen isotope analysis of cooking pot residues (Bogaard, Filipović et al., 2017: 21, Dean, Jones et al., 2015, Flohr, Fleitmann et al., 2016, Pitter, Yalman et al., 2013, Roberts, Allcock et al., 2016).

Overall, Çatalhöyük's local environment has been described as a "mosaic" of both wet and dry conditions, due to its location near an anabranching channel of the Çarşamba river (Ayala, Wainwright et al., 2017: 41). The initial occupation of the East mound has been described as occurring during the point at which the river channel was what is defined as "dryland anabranching," thus, the landscape around Çatalhöyük was variable and contained both wet and dry conditions (Ayala, Wainwright et al., 2017: 41). Figure 13 A and C shows reconstructions of the occupation of Çatalhöyük's East mound, approximately 7150 and 7100 cal BCE when Çatalhöyük reached its peak population and with dryland anabranching conditions located in the west (Ayala, Wainwright et al., 2017: 41-42 , Bayliss, Brock et al., 2015). Wetlands were limited but present; immediately west of Çatalhöyük would have been wetter; however, the east would have been drier, which further emphasises this "mosaic of both wet and dry conditions" (Ayala, Wainwright et al., 2017: 41). This is also confirmed by Çatalhöyük's archaeobotanical, zooarchaeological, and isotopic data (Asouti, 2005a, Atalay and Hastorf, 2006, Ayala, Wainwright et al., 2017, Bogaard, Henton et al., 2014, Charles, Doherty et al., 2014, Doherty, Charles et al., 2008, Filipović, 2014, Jenkins, 2005, Russell and Martin, 2005, Russell, Twiss et al., 2013). Zooarchaeological data, specifically isotopic and dental microwear of Çatalhöyük sheep, indicate sheep were herded on the margins of wetlands, arable lands, and the plain itself (Charles, Doherty et al., 2014: 80-82). Archaeobotanical data also indicates both dry woodland and wetland exploitation throughout the Konya plain during Çatalhöyük's occupation, especially with the types of firewood collected and the fruit and nuts gathered (Charles, Doherty et al., 2014: 86). Stable isotope and weed ecology data, which provide information on growing environment, the permanence of plots, crop sowing, and even agricultural intensity, demonstrate that Çatalhöyük peoples planted crops on "moderately moist to very dry areas" of the local alluvial landscape (Charles, Doherty et al., 2014: 76). Finally, zooarchaeological data also supports that Çatalhöyük peoples exploited a variety of habitats including open plains, woodlands, and wetlands, indicated by the presence of equids, cervids, suids, waterfowl and water voles in Çatalhöyük's zooarchaeological assemblage (Charles, Doherty et al., 2014).

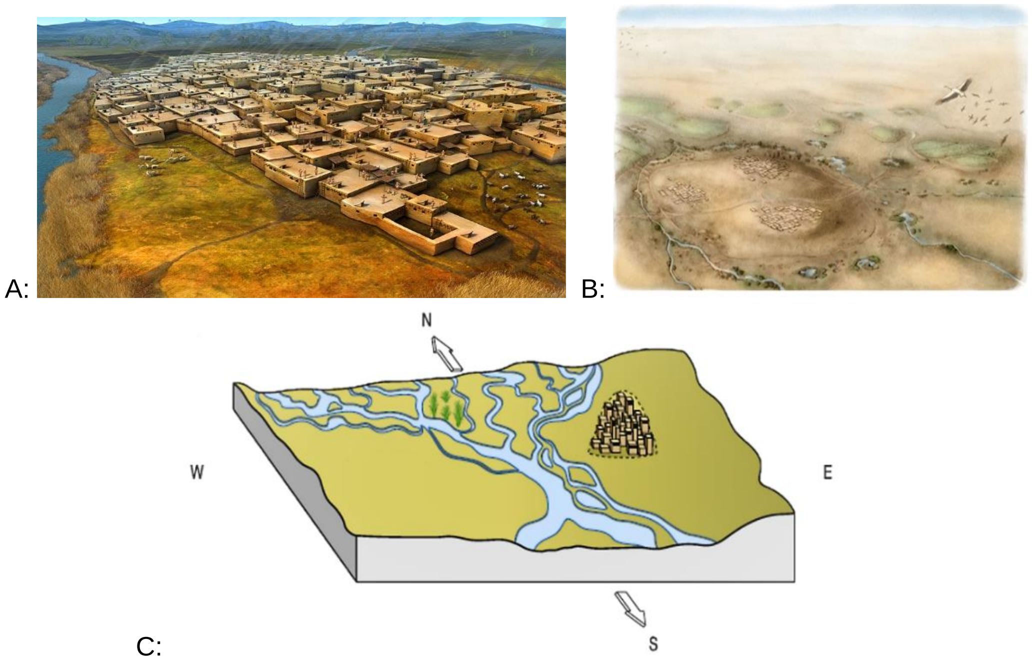


Figure 13: Reconstructions showing Çatalhöyük in relation to the Çarşamba River and surrounding environment. Çatalhöyük's East mound would have been quite dense whilst located in what has been described as a "mosaic" of both wet and dry conditions. A: Artist's impression of Çatalhöyük by Dan Lewandowski, indicating the density of Çatalhöyük at its peak and use of rooftop space. B: Illustration depicting the East Mound with the Çarşamba River

and surrounding environment by Kathryn Killackey. C: Çatalhöyük location in relation to the Çarşamba River based on paleoenvironmental analysis altered from Ayala et al. 2017.

Çatalhöyük's environment allowed for its population to accommodate long-lived plots and a variety of viable seasonal grazing areas for its herds which likely allowed for its success (Charles, Doherty et al., 2014: 86). Çatalhöyük was surrounded by a mosaic of plains, wetlands, dryland, and woodland environments, which would have allowed for arable land available near Çatalhöyük, and a plethora of resources could have been utilised. The focus of the section below is the ways in which these resources were used, the Çatalhöyük lifeways, subsistence practices, and changes in these over Çatalhöyük's occupation.

3.3 TEMPORAL CHANGE AT ÇATALHÖYÜK

Çatalhöyük's subsistence economy can be defined as small-scale intensive "garden" crop cultivation with animal herding and has been described as a "successful sheep and crop farming package" (Charles, Doherty et al., 2014, Filipović, 2014, Sadvari, Charles et al., 2017: 168). Çatalhöyük peoples relied primarily upon the intensive cultivation of domestic plants and cereals, intensive cultivation being defined as cultivation with high labour inputs per unit area which includes and requires actions such as tillage, weeding, or even manuring crops; archaeological evidence indicates that these activities did indeed occur at Çatalhöyük (Bogaard, 2004, Filipović, 2014, Halstead, 1995). Additionally, archaeobotanical evidence including taxa present, weed flora, and flowering data indicate that most Çatalhöyük crops were autumn-sown upon permanent, dry fields (Fairbairn, Asouti et al., 2005, Filipović, 2014 :132-133). Although Çatalhöyük peoples primarily relied upon domestic plants and animals, they also took advantage of the landscape's foraging options, and its ecotonal setting allowed for a range of activities to take place, including but not limited to cultivation, herding, foraging, clay exploitation, and firewood collection (Charles, Doherty et al., 2014, Filipović, 2014: 23-24, Sadvari, Charles et al., 2017: 168). Overall, archaeological evidence indicates that Çatalhöyük's combination of intensive cultivation, animal (caprine) herding, and reliance upon wild resources were key contributing factors to Çatalhöyük's long-term success (Bogaard, Ater et al., 2019, Bogaard, Filipović et al., 2017, Filipović, 2014: i,4).

As Çatalhöyük's occupation continued and its population grew, however, there were significant changes in Çatalhöyük's health, diet, relationships to plants and animals within the household itself (physical and symbolic), religiosity, resource procurement, and material production (Hodder, 2014b). Many of these changes occurred throughout the Middle period (peak, 6700-6500 BCE), and have been interpreted by the Çatalhöyük team as relating to an increasing need for more efficient yet less labour-intensive processing, requiring more resources, and a shift towards individualism and more independent forms of domestic production (Bogaard, Filipović et al., 2017, Hodder, 2014b). Archaeological evidence including bioarchaeological, archaeobotanical, zooarchaeological, stone tool, pottery, burial, architectural, and even isotope data further indicate these overall patterns (Asouti, 2005a, Atalay and Hastorf, 2006, Ayala, Wainwright et al., 2017, Bogaard, Henton et al., 2014, Charles, Doherty et al., 2014, Doherty, Charles et al., 2008, Filipović, 2014, Jenkins, 2005, Russell and Martin, 2005, Russell, Twiss et al., 2013). However, these changes and the archaeological data also indicate the presence of the increasing energy conflicts act Çatalhöyük, potentially resulting from the agricultural energy feedback system. Thus, the remainder of this chapter subsection will present how the archaeological data at Çatalhöyük fits within the agricultural energy feedback system.

Throughout life, human long bones undergo forces such as bending and twisting during walking, running, and general physical activity (Larsen, Hillson et al., 2015: 41). Therefore, long bones, biomechanical analysis, and the presence of osteoarthritis can indicate past activity levels. Furthermore, the presence of osteoarthritis usually indicates "persistent mechanical stress and/or trauma" on joints, especially vertebral bodies and other limb joints (e.g. hand, elbow, knee) (Larsen, Hillson et al., 2015: 43-44). The Çatalhöyük bioarchaeology team analysed biomechanics and the presence of osteoarthritis within the Çatalhöyük burial population to draw generalisations about levels of activity at Çatalhöyük. Their analyses illustrated that workload, indicated by osteoarthritis percentages, peaks in the Middle Period, and decreases in the Late period for adults and juveniles (Larsen, Hillson et al., 2015: 41, Larsen, Knüsel et al., 2019). Overall, the Çatalhöyük population were hard-working and lived an arduous life (Pearson and Meskell, 2015). Mobility indices based on femora measurements indicate that the population at Çatalhöyük was very mobile, especially during the Middle and Late Periods, again, for both juveniles and adults (Larsen, Hillson et al., 2015 :41). This is not necessarily surprising, as, in addition to practising intensive cultivation and herding, the Çatalhöyük peoples hunted and relied upon other wild fauna and flora. This increase in mobility at Çatalhöyük is surmised to be directly related to Çatalhöyük reaching its peak population numbers during the Middle period; as Çatalhöyük's population increased and its occupation continued, the resource catchment area also had to expand (Hillson, Larsen et al., 2013, Larsen, Hillson et al., 2015: 33). Bioarchaeological evidence also indicates high levels of crowding, increased mobility of humans and animals due to Çatalhöyük's expansion, more dietary diversity yet a continued reliance upon cereal grains, and a growing dependence on domestic sheep; fertility, birthrate, physiological stress, intracommunity interpersonal violence, and the presence of illnesses also increases substantially during this period (Hodder, 2014b, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019). This is also evidenced materially, as building materials, clay, and food and fuel resources were acquired further and further from Çatalhöyük during its occupation (Hillson, Larsen et al., 2013, Larsen, Hillson et al., 2015: 33). Overall, the bioarchaeological evidence indicates that with more people present at Çatalhöyük, people were working harder, living a vigorously active lifestyle, and likely investing more time and energy into daily processes. However, by the Late Period, bioarchaeological analysis indicates the opposite, as bioarchaeological data indicates activity was lighter in terms of mechanical loading, and mobility increased (Larsen, Hillson et al., 2015). During this period, when Çatalhöyük's population effectively fragmented and dispersed across the landscape, there was a decrease in workload, fertility, birthrate, physiological stress and the presence of illness also decreased (Hodder, 2014b, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019).

Archaeobotanically, the Çatalhöyük team has identified a similar picture of a need for more efficiency yet less labour-intensive processing, more resources being required, and a shift towards individualism and more independent forms of domestic production over time (Bogaard, Filipović et al., 2017, Hodder, 2014b). As explained in the previous subsection, arable land was available around Çatalhöyük and would have been so for decades, allowing for domestic crops to be intensively cultivated (Bogaard, 2004, Halstead, 1987, Halstead, 2006, Jones, Bogaard et al., 1999). Throughout its occupation, Çatalhöyük peoples relied consistently upon six domestic cereals (emmer, einkorn, new type glume, two and six-row naked barley, bread wheat), three domestic and non-domestic pulses (lentils, peas, bitter vetch), three nut types (almond, acorn, pistachio), two fruits (fig and hackberry), and wild mustard (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Charles, Doherty et al., 2014). Although archaeobotanical evidence generally suggests that Çatalhöyük's production system and crop cultivation were all successful and reliable over time, there are substantial changes with Çatalhöyük's use and reliance upon plant resources over time, most of which occur during Çatalhöyük's Middle period (Bogaard, Charles et al., 2009, Bogaard, Filipović et al., 2017, Filipović, 2014 :140, Hodder, 2014b).

During Çatalhöyük's Early Period, the human population was more heavily reliant nutritionally upon emmer and einkorn, free-threshing wheat (bread wheat), lentils and naked barley, and non-domestic plant resources such as sedge tubers or nutlets, acorn, figs, wild mustard, almond, pistachio, hackberry, bitter vetch, and figs (Atalay and Hastorf, 2006, Bogaard, Charles et al., 2009, Bogaard, Filipović et al., 2017, Filipović, 2014: 140, Hodder, 2014b, Larsen, Hillson et al., 2015). By the Middle and Late periods, however, this changed. Instead, there was more reliance upon free-threshing wheat, naked barley, peas, the appearance of a "new" glume wheat (NGW) which replaced emmer, the introduction of a new hulled barley and, a decreasing reliance upon einkorn, acorn, and bitter vetch. The increasing reliance upon free-threshing wheat, lentils and peas, and the decreasing reliance upon einkorn and bitter vetch can at least be partially explained by the ease in processing. There is a substantial difference between threshing hulled and free-threshing species of wheats and barleys (further discussed in section 6.2). Essentially, hulled wheat species such as einkorn require significantly more time to process than free-threshing species, which has been attested for ethnographically and is quantified within this thesis (see 6.2 and 7.2) (Bogaard, 2004, Halstead, 2014, Hillman, 1983). Similar to processing hulled cereals, lentils and bitter vetch both require more processing time and labour to process. At Çatalhöyük, lentils were the primary domestic legume relied upon, especially during the Early period. Many species of lentils have a toxic seed coat which makes them unpalatable to humans; to make them palatable, they must be soaked or leached to avoid their harmful effects (Bogaard, Filipović et al., 2017: 22, Halstead, 2014: 292). With regards to non-domesticated plants at Çatalhöyük, there is a decreasing reliance over time upon bitter vetch, which is poisonous if it is not soaked or leached (Bogaard, Filipović et al., 2017: 22, Halstead, 2014: 292). Thus, bitter vetch is a time and energy-consuming energy resource. In Çatalhöyük's case, the increasing reliance upon free-threshing wheat and peas and decreasing reliance upon einkorn and bitter vetch fits well with the preference towards less labour-intensive processing and more efficiency. However, again this also alludes to the energy costs of agriculture and, the agricultural feedback cycle's presence at Çatalhöyük. As more energy was required to keep Çatalhöyük sustained as it grew, more energy and time had to be dedicated to carrying out agriculture and its processes, along with the other activities occurring at Çatalhöyük (i.e., herding, foraging, gathering, etcetera). To account for agriculture's additional time and energy requirements, Çatalhöyük had to find ways to adjust whilst dedicating time and energy to keep itself and agriculture sustained. Some of these changes are manifested within the archaeobotanical evidence, in the form of a decreasing reliance upon einkorn and bitter vetch, both of which are time-consuming plants to process. This, I argue, indicates the Çatalhöyük population's need to multitask and become more time-efficient (Hodder, 2014b), which is the result of the agriculture energy feedback system. This is further evidenced by other plants upon which Çatalhöyük relied, further discussed below.

With the barleys at Çatalhöyük, there is a different picture. The barleys present at Çatalhöyük are primarily two-row and, less frequently, six-row barley; two-row barley is known to be more drought-resistant (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017). According to the Çatalhöyük team, the reliance upon this barley was likely a response to the 8.2kya drying event which occurred during Çatalhöyük's occupation. Isotopic analysis of the barley present at Çatalhöyük indicates that it was grown under drier conditions than the wheat at Çatalhöyük; perhaps drought intolerance, and therefore better efficiency, was preferred (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017). Similarly, another substantial change in Çatalhöyük's plant subsistence is that of a crop innovation at Çatalhöyük, known as a "new" glume wheat (NGW, henceforth). This NGW is a curious one, as it is a hulled wheat which is distinct from emmer and einkorn and appears at Çatalhöyük during its Middle Period (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Russell and Bogaard, 2014: 64-65). Initially, NGW wheat was adopted by a few households, then, by the Later Period was the preferred glume wheat, as it was a hardy and potentially drought-resistant crop suited to the local environment and Çatalhöyük's culinary tradition (Bogaard, Filipović et al., 2017 : 22). This NGW was even grown and stored separately from other crops, and it eventually entirely replaced emmer (Bogaard, Filipović et al., 2017: 15, Jones, Valamoti et al., 2000). The presence and use of this NGW has been interpreted by the Çatalhöyük team as being related to the 8.2kya drying event and suggests that Çatalhöyük needed a more resilient crop to help keep it sustained. Further, regarding both the NGW and the new hulled barley being a reaction to this drying event, this does not disprove that the agricultural energy feedback system was occurring at Çatalhöyük. In fact, I argue this is yet another indicator of the agricultural energy feedback system at work at Çatalhöyük, more specifically concerning Çatalhöyük needing to maintain efficiency to sustain its population. Agriculture, as a system is inherently sensitive and intricate. All of its processes depend upon one another's success; all of the processes must be successful in order to produce an energy surplus, and if external factors, including a drying event such as Çatalhöyük's 8.2kya event, disrupts agriculture or its processes, the system itself has great potential to fail. To prevent this system from failing, perhaps the NGW and hulled barley were additional mechanisms to keep Çatalhöyük's reliance upon agriculture, and thus its agricultural system, sustained and efficient.

The decreasing reliance upon and use of acorn is directly related to changes in Çatalhöyük's wood sourcing due to the greater need for efficiency (Asouti, 2005b, Asouti, 2013, Bogaard, Filipović et al., 2017, Filipović, 2014). During the Early period, Çatalhöyük's primary wood source for building houses was oak (Asouti, 2013). However, as Çatalhöyük's population grew and houses became larger over time, during the Middle period, the wood source changed from oak to juniper (Asouti, 2013, Bogaard, Filipović et al., 2017, Hodder, 2014b). The Çatalhöyük team surmises that this change indicates a need for more efficiency as well as more resources being required at Çatalhöyük (Asouti, 2013, Hodder, 2014b). Although both oak and juniper would have been widely available throughout the Konya plain, juniper is sturdier and more durable, yet it is more difficult to work and requires tools with a greater cutting edge; oak, on the other hand, is much easier to work but it is less durable (Charles, Doherty et al., 2014: 86, Hodder, 2014b: 11). With Çatalhöyük's population growing and houses getting larger, sturdier wood was required to help support houses; Çatalhöyük needed more resources to sustain itself. Additionally, the reliance upon juniper could also indicate "low-intensity" human impact on the landscape due to herd grazing and oak logging throughout the area; this is indirectly supported by Çatalhöyük's increasing reuse of timbers over time (Asouti and Austin, 2005: 14-15). Essentially, as Çatalhöyük's population grew, it is likely that they overexploited oak and thus needed to rely upon juniper. This also may indicate that Çatalhöyük's population had a direct and potentially lasting impact upon the environment. The long-term effects of Neolithic Çatalhöyük's impacts upon its environment, however, have not been fully investigated.

On the whole, the Çatalhöyük archaeobotanical evidence suggests the presence of the agricultural feedback cycle at Çatalhöyük. The increasing reliance upon free-threshing wheat, the appearance of the NGW which replaced emmer, the introduction of a new hulled barley, and an overall decreased reliance upon einkorn, acorn, and even bitter vetch are all, in one way or another, evidence the need to maintain efficiency at Çatalhöyük. As agriculture provided surplus energy to Çatalhöyük, it facilitated population growth whilst requiring more energy to keep Çatalhöyük sustained. Even the NGW and the new hulled barley could very well be part of a reaction to environmental changes occurring during Çatalhöyük's occupation, i.e., as more energy was required and the reliance upon agriculture intensified, more and more resources were required, and the need to ensure agriculture's success became more pivotal, especially if environmental changes occurred. Simultaneously, Çatalhöyük peoples may have caused changes to the surrounding environment. Çatalhöyük's clay brick production more heavily emphasises environmental changes over time.

The quarrying or collecting of clay was a pivotal aspect of life at Çatalhöyük. Clay is present in the form of clay balls for cooking, figurines, walls, bricks, tokens, various objects, and eventually cooking pots; clay was central to Çatalhöyük's development (Doherty, 2013: 51). Doherty (2013: 51) has estimated that 675,000 cubic metres, or 1 million metric tonnes of clay would have been required *just* to build Çatalhöyük's East Mound. Doherty also describes that extracting this clay would have been strenuous and significantly impacted Çatalhöyük's environment (Doherty, 2013: 51). Çatalhöyük's houses are all made from locally sourced mudbricks; however, the types of local clay and the ways in which they were produced changed over time (Doherty, 2013). During the Early period, bricks were long and thin and sourced from available backswamp clays (Doherty, 2013). However, by the Middle Period, this changed, as Çatalhöyük's population depleted the backswamp clays and its increasing population required more houses and larger houses with more support (Doherty, 2013). Çatalhöyük's houses needed more structural support; thus, during the Middle Period Çatalhöyük instead utilised the underlying sandier, reddish clay and deltaic sands to build thicker and more supportive bricks for their houses; it should be noted that this change is also reflected in other clay objects at Çatalhöyük (Doherty, 2013: 64-66).

With the clay extraction for bricks also came the invasive plant species *Phragmites australis* (common reed) (Sadvari, Charles et al., 2017: 171). Common reed is indicative of human disturbance and has been interpreted by the Çatalhöyük team as being a "corollary of anthropogenic disturbance;" it is very likely that the increase of *Phragmites* was due to the overexploitation of clay by Çatalhöyük's population (Sadvari, Charles et al., 2017: 171). Although *Phragmites* was present throughout Çatalhöyük's initial occupation and Early Period, its presence increased dramatically by Çatalhöyük's Middle and Late period, to the point where its presence was dominant over sedges and grasses (Roberts, Boyer et al., 2007, Ryan, 2013, Sadvari, Charles et al., 2017: 171). Çatalhöyük peoples did use *Phragmites* in basketry, fuel, and construction; however, Ryan 2013 explains that the clay extraction pits and pockets of wetter areas caused by Çatalhöyük's clay extraction pits would have allowed this invasive species to thrive (Roberts, Boyer et al., 2007, Ryan, 2013: 188-189). This over-exploitation of clay by Çatalhöyük peoples more than likely caused *Phragmites* to flourish. One of the major negative impacts of *Phragmites* is that the invasive species causes a significant reduction in plant biodiversity; *Phragmites* presence would have had major implications for Çatalhöyük's inhabitants, as it would have altered the wild plant taxa upon which Çatalhöyük inhabitants relied (Butzer, 1982, Ryan, 2013 :188-189, Sadvari, Charles et al., 2017 :171). Altering the wild plant taxa would have forced Çatalhöyük to alter its resource procurement strategies and to forage farther from the site for wild plant resources, thus, increasing their mobility, and, extending their resource catchment zone, all of which corresponds with Çatalhöyük's archaeobotanical and zooarchaeological data (Sadvari, Charles et al., 2017 :171-172). Archaeobotanically, there is a decrease in phytoliths of other wild grasses at Çatalhöyük, especially after its peak population was reached (Ryan, 2013 : 188, Sadvari, Charles et al., 2017). Zooarchaeological isotope data also suggests an expanded use of the environment at Çatalhöyük over time (Bogaard, Henton et al., 2014, Fairbairn, Asouti et al., 2005, Pearson, Buitenhuis et al., 2007, Russell and Bogaard, 2014, Russell and Martin, 2005, Russell, Twiss et al., 2013).

Overall, these changes in Çatalhöyük's archaeobotanical assemblage have been interpreted by the Çatalhöyük team as due to a preference towards less labour-intensive processing, more efficiency and a shift towards individualism and more independent forms of domestic production. Although the Çatalhöyük archaeological evidence supports these, it is also evidence of the agricultural feedback system occurring at Çatalhöyük. As agriculture provided additional surplus energy to Çatalhöyük, it facilitated population growth and simultaneously required more energy to keep Çatalhöyük sustained. As this occurred, Çatalhöyük became increasingly invested whilst requiring more resources to sustain it. As more and more resources were required, simultaneously, Çatalhöyük was also altering and impacting its own environment, which it also had to adjust to, thus forcing Çatalhöyük to expand its resource catchment area. Furthermore, as Çatalhöyük' reached its peak population, which was dependent upon domestic cereal reliance, and its agricultural system reached its threshold, Çatalhöyük had to make its system more efficient to keep sustaining self. Thus, Çatalhöyük saw changes in diet and nutrition, plant relationships, resource procurement, and even in animal relationships, which are further discussed below (Hodder, 2014b, Larsen, Knüsel et al., 2019, Pearson, Buitenhuis et al., 2007).

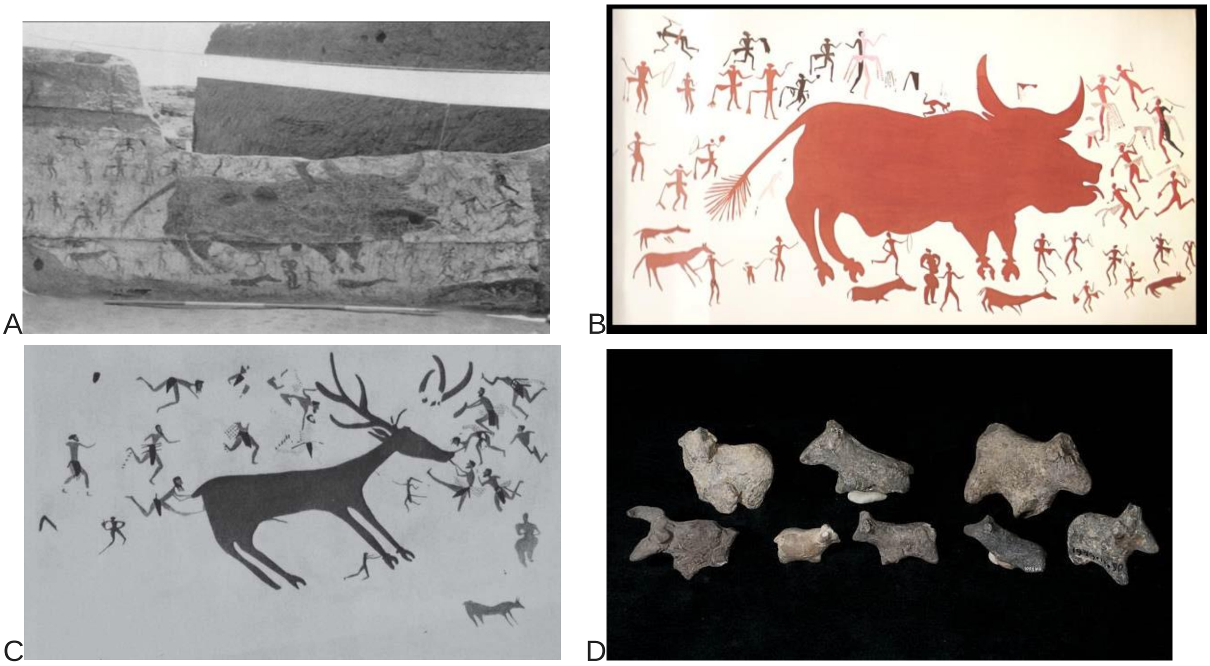
Animals, both domestic and non-domesticated, were important at Çatalhöyük both in symbolism and subsistence. Zooarchaeological and bioarchaeological evidence indicate that throughout its entire occupation domestic caprines are consistently the main source of animal protein at Çatalhöyük and domestic sheep and goat were more intensely exploited over time (Russell and Martin, 2005). Cull and herd reproduction patterns of domestic caprines also correspond with being utilised for meat; they were not used for dairy or wool (Russell and Martin, 2005, Russell, Twiss et al., 2013). With regards to subsistence and butchery patterns, almost no parts of domestic caprines went to waste; nutrients were intensively extracted from domestic sheep and goat carcasses: meat was removed, marrow extracted, bone grease was produced, and hides were prepared; every part of the animal was used (Russell and Martin, 2005: 79). During Çatalhöyük's Early period, zooarchaeological and isotopic data indicate that domestic caprines were pooled in herds closer to the site, and they had a diet of grasses and wetland reeds or sedges, and little reliance upon domestic fodder (Henton, 2012, Henton, 2013). Natural pastures nearby were adequate for Çatalhöyük's herds and there was no need to depend on crop by-products (Henton, 2013: 312). However, by Çatalhöyük's Middle Period, this changed. By Çatalhöyük's Middle Period, there is evidence of greater intervention in herd management in the form of early birthing for lambs, evidence of penning on site, increased herding labour, and a shift towards family-based herding practices (Bogaard, Henton et al., 2014, Henton, 2013, Russell and Martin, 2005, Russell, Twiss et al., 2013). Early birthing in itself is related to and very much entwined with agricultural practices. Early birthing allows for flocks to be taken away from ripening crops to protect crops from being consumed by sheep and goats (Henton, 2013: 313). During Çatalhöyük's Middle period, more crops would have been required to sustain Çatalhöyük during its peak, and, amalgamated with the continued reliance upon domestic cereals, means that crops had to be protected. By the Middle period, is it estimated that Çatalhöyük flocks reached the thousands; this would have posed a real and significant threat to cereals as an energy source (Cribb, 1987, Russell and Bogaard, 2014: 66). Since agricultural processes are dependent upon one another's success, protecting crops to ensure their success was extremely important and *had* to take place to keep Çatalhöyük's agricultural system intact. However, the caveat of early birthing and needing to protect crops is that it requires food provisioning in the form of fodder for flocks (Henton, 2013).

Thus far, there is no direct evidence to establish the use of cereal by-products as the primary source of fodder for domestic caprines at Çatalhöyük (Henton, 2013, Henton, 2010). Straw was minimally used at Çatalhöyük and was not consumed by animals or even used as temper in dung cake manufacture (Filipović, 2014: 136-138, Ryan, 2011). Instead, zooarchaeological and isotopic evidence indicates that domestic caprine diets were primarily "based on grasses and *possibly* cereals," and potentially include fallow plants, legume by-products, and field edge weeds (emphasis added) (Henton, 2010: 338). Further, archaeobotanical evidence in the form of weed seeds in dung indicates that Çatalhöyük inhabitants either expanded their herds across the landscape over time (Fairbairn, Asouti et al., 2002, Henton, 2013, Henton, 2010: 166, 197). Isotopically, domestic caprine d13C and d15N ratios indicate herds were indeed herded over a wider environmental range in multiple ecological zones, as this is caused by differences in the ratios of specific plant biomasses (Pearson, Buitenhuis et al., 2007: 2177-2178). Pearson et al. 2017 describe this as being the result of a larger scale of herding, sending herds to different areas potentially due to task scheduling and Çatalhöyük's increasing scale of food production (Pearson, Buitenhuis et al., 2007: 2177). Further, the early birthing present at Çatalhöyük thereby required peoples to utilise foddering, thus requiring more energy either in the form of collecting fodder from farther away or, moving herds further across the landscape. Finally, by Çatalhöyük's Late Period, after the 8.2kya drying event and post-population peak, there is a significant change in how domestic caprines are herded. By Çatalhöyük's Late period, there is less separation by age and sex, no evidence of early birthing, caprines were moved and herded over much wider territories, and they consumed a variety of plants throughout the Konya plain (Russell, Twiss et al., 2013: 231-236, 250).

The changes identified in Çatalhöyük's herding practices suggest a preference towards more efficiency, and potentially, that the agricultural feedback system was occurring at Çatalhöyük, which was affecting and potentially compounding Çatalhöyük's herding practices and relationships with animals. Moreover, Çatalhöyük's reliance upon agriculture was becoming difficult to sustain. As agriculture provided additional surplus energy to Çatalhöyük, it could have facilitated population growth and which required more food to keep that population sustained. Çatalhöyük's population growth, therefore, required more energy in the form of *both* domestic cereals and caprines. As more cereals were necessary and Çatalhöyük's herds grew in the thousands, a reliance upon domestic cereals required more protection of crops from growing herds in the form of either collecting natural fodder from across the landscape or, herding domestic caprines across the landscape. As argued in this thesis, once Çatalhöyük reached its population threshold of 2000-3000 people, its agricultural system had to be made more efficient to keep sustaining itself. Either way, an extended resource catchment had to occur, which is reflected in many other aspects of Çatalhöyük life. Further, these changes in herding practices at Çatalhöyük during the Middle Period have been recognised by the Çatalhöyük team as also representing herd management becoming more integrated or entangled with farming practices (Henton, 2013: 313). However, this is also representative of the agricultural feedback system and the resulting changes which occur in diet and nutrition, plant relationships, resource procurement, and animal relationships with respect to maintaining efficiency. These changes were not just occurring within practices and relationships surrounding domestic caprines, but, also, with non-domestic animals, pottery, and obsidian.

At Çatalhöyük, non-domestic animals were utilised and treated differently from domestic animals, especially during the Early period (Hodder, 2014b). Although they made up a portion of the Çatalhöyük diet, non-domestic animals were still fundamental and had significant symbolic and religious importance at Çatalhöyük (Figure 9, Figure 14) (Hodder, 2014b, Russell and Bogaard, 2014, Russell and Martin, 2005, Russell, Twiss et al., 2013). Hunting, fishing, and trapping were relatively common in Çatalhöyük's Early period, with wild fauna such as equids, wild caprines, wild cattle, boar, deer, birds, and fish being utilised for subsistence (Russell and Bogaard, 2014, Russell and Martin, 2005: 96-97). Symbolically, wild animals, especially leopards, bears, and wild bulls, are featured prominently by symbolic representations throughout Çatalhöyük in the form of paintings, bucrania installations, and reliefs (Figure 9, Figure 14) (Hodder, 2014b). Wild fauna which were present, but not necessarily consumed at Çatalhöyük, include wolves and bears and deer, which made it back to Çatalhöyük primarily as pelts and skins; deer are extremely rare in the zooarchaeological record aside from the presence of their antlers and distal skeletal elements (Atalay and Hastorf, 2006, Russell, Twiss et al., 2013).

During the Early period is also an occurrence of what Ian Hodder has interpreted as a strict separation between the secular and sacred, especially present with the treatment of domestic and non-domestic animals (Hodder, 2014b). More specifically, domestic caprines and their by-products, for example, were used on a daily basis in everyday consumption and subsequently treated as butchery waste to be tossed in middens, whereas wild fauna were utilised in feasts and wild bucrania, horns, and antlers are often used symbolically in paintings or in more religious and ritual contexts such as shrines (Figure 9) (Hodder, 2014b, Russell, Twiss et al., 2013: 243-244). For feasts at Çatalhöyük, during the Early period, wild fauna was consumed, especially wild cattle, boar, or equids, with wild bulls being preferred (Atalay and Hastorf, 2005, Atalay and Hastorf, 2006, Hodder, 2014b, Russell, Twiss et al., 2013: 216, 223).



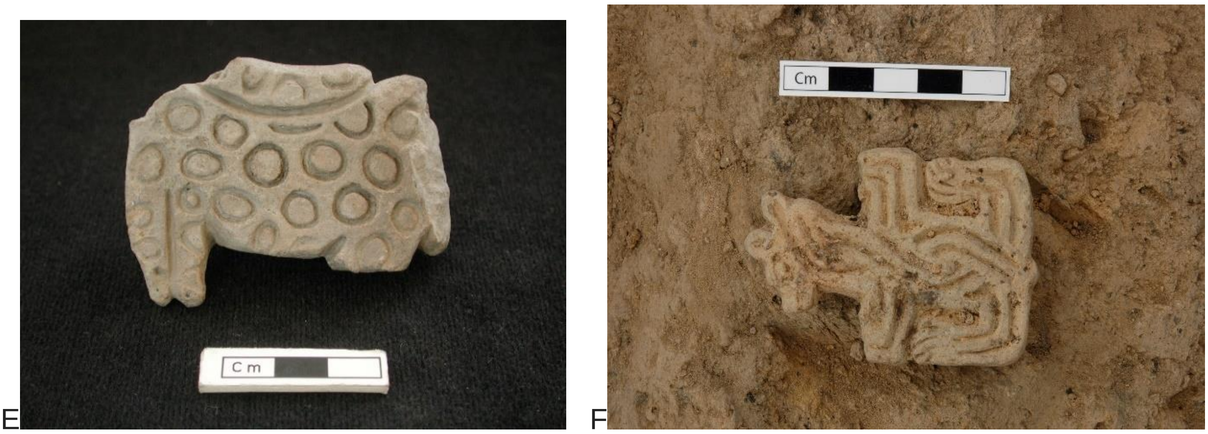


Figure 14: Wild animals had significant symbolic and ritual importance at Çatalhöyük. A: Wall painting of the Çatalhöyük Bull Hunting scene. Original, J. Mellaart and Çatalhöyük Research Project; B: Reconstruction of A). C: Wall painting of the teasing and baiting of stag from Çatalhöyük Source: J. Mellaart and Çatalhöyük Research project. D: Animal figurines from Çatalhöyük. E: Decorated Clay object, a leopard stamp seal/figurine, photo by Jason Quinlan Çatalhöyük Research Project. F: Clay Bear Stamp Seal, photo by Jason Quinlan, Çatalhöyük Research Project

By the Middle and Late periods, the relationships between wild fauna and people substantially changed. By the Middle period, the presence of bucrania installations and reliefs across Çatalhöyük peaks (Hodder, 2014b). However, by the Late period, they are less common and become more present in another new form that appears only during Çatalhöyük's Late period—stamp seals (Hodder, 2014b). With regards to wild fauna, the presence of equids peaks in the Middle period, then decreases substantially by the Late period, interpreted by the Çatalhöyük team as more than likely resulting from hunting pressure imposed by the Çatalhöyük peoples, upon an already shrinking equid population (Russell, Twiss et al., 2013: 225-226). The presence of boar and deer decreased proportionally over time, but they are both still rare (Russell, Twiss et al., 2013: 225-226). Feasting patterns also changed. From the Middle period onwards, feasting events appear to have been more common, occurring within 'households' instead of between multiple 'households', and domestic caprines are increasingly used in feasting (Hodder, 2014b). In sum, from the Middle to the Late period, there is a shrinking use of wild cattle in feasting, and the reliance upon wild fauna and hunting substantially decreases (Hodder, 2014b, Russell and Bogaard, 2014). It is also by the Late period that domestic cattle are introduced into Çatalhöyük, and cattle herding occurs on a very small scale (Hodder, 2014b). These changes in animal symbolism and exploitation indirectly suggest the presence of the agricultural feedback system at Çatalhöyük, specifically the resulting changes in human-animal relationships and diet that result concerning maintaining efficiency. The shift in equids, which is due to hunting pressure by the Çatalhöyük peoples during the Middle period, is reminiscent of the changes in human-animal relationships which could result from the agricultural feedback system.

The ways in which meat from animals was consumed also changed over time at Çatalhöyük in Çatalhöyük's Early period, zooarchaeological evidence indicates that larger, wild fauna were roasted in larger pieces while still on the bone whereas smaller domestic caprines were filleted off the bone and cooked in small pieces; it is also during this period that clay balls were utilised for cooking, as opposed to ceramic pots (Hodder, 2014b, Russell and Martin, 2005, Russell, Twiss et al., 2013: 241). By Çatalhöyük's Middle period, there is an overall increase in filleting and a decrease in cutmarks on faunal skeletal elements (Russell and Martin, 2005, Russell, Twiss et al., 2013). This trend increases from the Middle period onwards, suggesting that meat was removed from the bone before cooking, indicative of relying more upon stewed meat, rather than roasted meat (Atalay and Hastorf, 2006, Russell and Martin, 2005, Russell, Twiss et al., 2013). This is also substantiated by ceramic evidence.

In the Early period, Çatalhöyük peoples cooked with clay balls (boilers) and baskets to cook food in hearths and ovens; pottery was minimally used and made from local clays with a vegetable-based temper which was inadequate for cooking (Doherty and Tarkan, 2013, Yalman, Tarkan et al., 2013). Putting oven-heated clay balls in baskets, animal skins, or even leaves, it is possible to cook, toast, roast, and even boil food (Atalay and Hastorf, 2006: 293). By Çatalhöyük's Middle period, however, much of this changed. The presence of pots and other ceramics increases significantly, clay balls decrease, cooking practices themselves reflect more of a reliance upon pots for making stews, and, pottery is made with mineral temper using nonlocal clays from volcanic regions west of Çatalhöyük (Atalay and Hastorf, 2006, Hodder, 2014b, Russell and Martin, 2005, Russell, Twiss et al., 2013, Yalman, Tarkan et al., 2013). Pottery residues from the Middle period onwards even indicate that pottery was used for meat processing (Hodder, 2014b, Pitter, Yalman et al., 2013).

Overall, these changes in cooking regiment, which directly affected how pottery was made and how animals utilised for subsistence were consumed, has been interpreted by the Çatalhöyük team as being driven by a preference towards less labour-intensive processing and more efficiency; in this case, to reduce the "attention to cooking, as herding and feast preparation demanded more labour" (Atalay and Hastorf, 2006 : 250, Russell, Twiss et al., 2013). Using clay balls for cooking requires a significant amount of work; as Atalay and Hastorf (2006: 309) describe, clay balls require "constant stirring to keep the hot clay balls from burning through the basket or skins and continuous replacement of heated balls if the stew needed coking for a long time". Utilising clay balls for cooking takes patience, constant watch, takes attention away from other activities, and requires more time and energy. Clay pots, on the other hand, "require less constant attention in terms of stirring and ball transfers, freeing up some of the cook's time" (Atalay and Hastorf, 2006 :309). Clay pots free up time and labour and allow for multitasking.

In general, changes in cooking practices, hunting, and even meat consumption all indicate Çatalhöyük peoples adjustments to multitask and become more time-efficient (Atalay and Hastorf, 2006: 309, Hodder, 2014b). Again, this preference towards less labour-intensive processing and more efficiency indicates the agricultural feedback cycle's presence at Çatalhöyük, especially with Çatalhöyük's agricultural system needing to be made more efficient to keep relying on agriculture and sustaining itself. As agriculture provided surplus energy to Çatalhöyük, it facilitated population growth whilst requiring more energy to keep Çatalhöyük sustained. As more energy was required, a reliance upon domestic cereals continued to occur, Çatalhöyük's domestic caprine herds grew to the thousands, more and more resources were required, and subsequently, more time was required dedicated to carrying out these processes. Çatalhöyük had to dedicate more time and energy to keeping itself sustained, whilst dedicating energy to agriculture and its processes as well as herding, gathering and foraging, hunting, and feasting. To account for increases in both time and energy input, Çatalhöyük had to find ways to adjust and successfully sustain itself. In this case, the change from using clay balls towards using clay pots freed up time, attention, and energy which could be dedicated to other processes. In addition to there being a preference towards less labour-intensive processing and more efficiency at Çatalhöyük from its Middle period, there is also ample evidence of needing to expand resource catchment areas and extend Çatalhöyük's networks with surrounding areas and peoples, further evidenced by obsidian stone tools.

Obsidian was ubiquitous at Çatalhöyük; the amount of obsidian discarded at Çatalhöyük throughout its entire occupation is estimated to be 105 to 160 tonnes, with yearly "consumption" estimates by Cessford and Carter estimated at 120 to 320 kilograms per year (Cessford and Carter, 2005: 305-309). During Çatalhöyük's Early period, obsidian tools were primarily sourced from Cappadocian East Göllü Dağ, 190 kilometres from Çatalhöyük (Figure 15) (Carter, 2011, Carter and Milić, 2013, Carter, Poupeau et al., 2006, Carter and Shackley, 2007, Cessford and Carter, 2005). Although there is a much closer obsidian source to Çatalhöyük, Hasan Dağ, there is no evidence for obsidian being sourced from here (Carter, Poupeau et al., 2006).

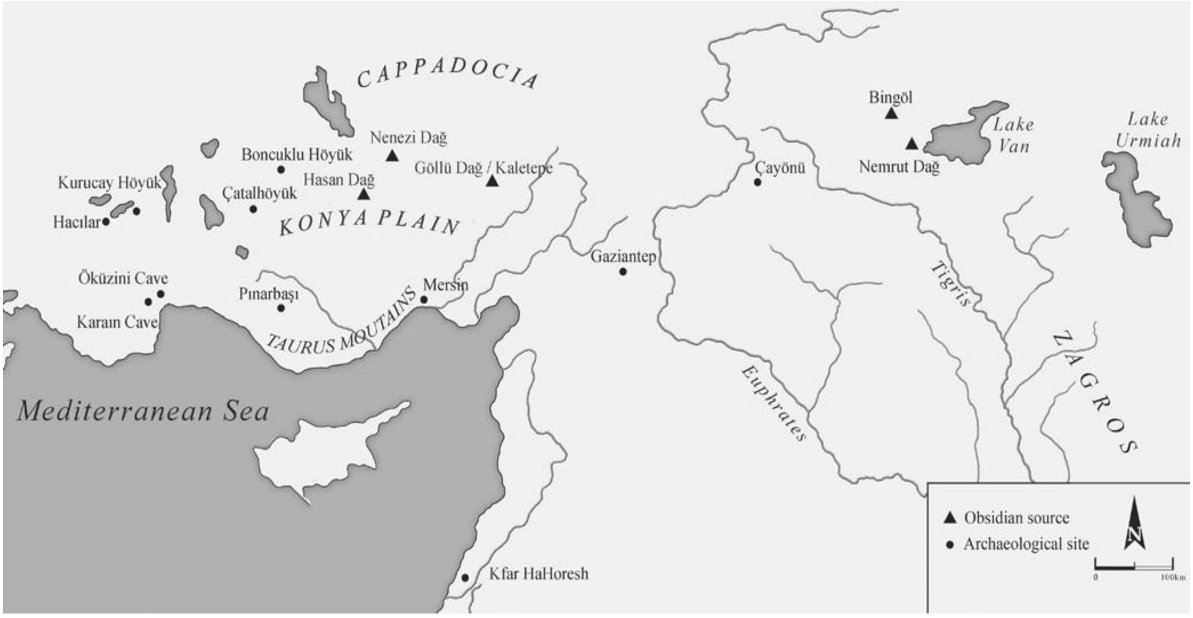


Figure 15: Map of Anatolia with archaeological sites (circles) locations of obsidian procurement sources (triangles), from Carter and Milic 2013. Nenezi Dağ and Göllü Dağ-east are both 190 kilometres from Çatalhöyük, and only 7 kilometres apart from one another.

During Çatalhöyük's Early period, obsidian is found in nearly every house either in the form of caches beneath floors or as knapping discard on house floors in front of ovens and hearths (Carter and Milić, 2013). Also, during this period, the primary source of choice for Çatalhöyük was East Göllü Dağ obsidian and tools were made via flaking or percussion (Carter and Milić, 2013). By the Middle period, obsidian consumption changed radically. Obsidian tools were, instead, made via pressure-flaking *and* percussion techniques, blades with greater cutting edges were created, there were more types of obsidian tools (backed and notched blades, reappearance of large scrapers), and, the obsidian source changed to Nenezi Dağ, only 7 kilometres from the East Göllü Dağ (Carter, 2011, Carter and Milić, 2013, Carter, Poupeau et al., 2006, Cessford and Carter, 2005, Hodder, 2014b). The changes in tool types at Çatalhöyük are significant and related to and further evidenced by figurines and stone beads. In Çatalhöyük's Early period, stone beads are made from a limited range of raw materials and colours; by Çatalhöyük's Late period there is a substantial increase in the diversity of materials for stone beads; more colours are being used (e.g. more greens and blues), their raw materials are also coming from farther away, and finally, they are being made with more technological skill (Hodder, 2014b). To make stone beads with more skill, one must have adequate tool kits, and better obsidian tools that allow for working stone and creating more intricate figurines, for example. Further, pressure-flaking and percussion techniques involve "different took kits, motor habits, and arguably levels of skill," which also indicates a "greater interaction with those people working at the Nenezi Dağ quarry workshops;" in other words, more efficient tools were needed, and with this came an increasing dependence on external labour and good exchanges (Carter, Poupeau et al., 2006, Hodder, 2014b: 907). Related to this, the changes in obsidian production also relate to the wood sourcing change from oak to juniper, as blades with longer cutting edges would have made the juniper much easier to work with (Asouti, 2005b, Asouti, 2013, Hodder, 2014b). By the Late period, obsidian is no longer fully ubiquitous throughout Çatalhöyük; it is not found in every single house, but instead there are “hot spots” where certain obsidian industries are utilised, created and located (Carter, Poupeau et al., 2006 :907). In the Late period, obsidian became a specialised good.

These changes in obsidian have been described as radical changes within both raw materials and procurement strategy and interpreted as being the direct result of agricultural intensification and requiring a better tool kit (Carter, Poupeau et al., 2006: 907). Once again, I argue that this is the agricultural energy feedback system is at work. Hodder explains that the overall pattern for these changes in Çatalhöyük’s stone tools is that they “were needed to do more work, or to work more efficiently, as household tasks multiplied” (Hodder, 2014b: 14). From an energetic perspective, as Çatalhöyük dedicated more time and energy to supporting itself *and* required more energy input towards agriculture, its processes, herding, gathering, foraging, feasting, etcetera, it had to account for such increases in energy input. Having better, more durable, and more efficient tools which could do more, and, expanding networks outside of Çatalhöyük to do so, helped to ease the energetic burden of agriculture, but subsequently changed relationships with obsidian and exchange networks outside of Çatalhöyük.

As Çatalhöyük’s occupation continued and its population grew, there were significant changes in Çatalhöyük’s health, diet, relationships to plants and animals within the household itself (physical and symbolic), religiosity, resource procurement, and material production (Hodder, 2014b). These changes and the archaeological data, as Hodder argues, represent Çatalhöyük’s entanglements between humans, materials, the environment, animals, plants, and labour (Hodder, 2012, Hodder, 2016, Hodder, 2021a). However, these changes and the archaeological data also indicate the presence of the agricultural energy feedback system occurring at Çatalhöyük. There are internal energy mechanisms in place entangled with agriculture which enforce the agricultural energy feedback system at Çatalhöyük. Archaeological evidence demonstrated throughout this chapter subsection, including bioarchaeological, archaeobotanical, zooarchaeological, stone tool, pottery, burial, architectural, and even isotope data further indicate these patterns *and* that the agricultural energy feedback system was indeed occurring at Çatalhöyük (Asouti, 2005a, Atalay and Hastorf, 2006, Ayala, Wainwright et al., 2017, Bogaard, Henton et al., 2014, Charles, Doherty et al., 2014, Doherty, Charles et al., 2008, Filipović, 2014, Jenkins, 2005, Russell and Martin, 2005, Russell, Twiss et al., 2013).

3.4 A WAY FORWARD: ÇATALHÖYÜK’S AGRICULTURAL ENERGY SYSTEM

This chapter subsection summarises the results of the analysis of Çatalhöyük which has demonstrated that the agricultural energy feedback system occurred in the Neolithic at Çatalhöyük (3.3), a claim supported by a range of archaeological evidence. Overall, Çatalhöyük’s need for less labour, greater efficiency in daily processes, and an expansion of resource catchment zones are, I argue, the result of the inner workings of the agricultural energy feedback system. In providing more energy, agriculture at Çatalhöyük facilitated population growth and increased fertility; however, these both require energy *input* from Çatalhöyük’s population to sustain agriculture. Çatalhöyük had to become increasingly more reliant upon agriculture *and* continued to grow; thus, Çatalhöyük dedicated more energy to agriculture to keep the population sustained. Çatalhöyük had to dedicate more time and energy to keeping itself sustained, whilst dedicating energy to agriculture and its processes as well as herding, gathering and foraging, hunting, and feasting. As more resources were required, simultaneously, Çatalhöyük was altering and impacting its own environment, which it *also* had to adjust to forcing Çatalhöyük to expand its resource catchment area. Once Çatalhöyük reached its peak population or its population threshold, its agricultural system had to be made to be more efficient to keep relying upon agriculture. To account for this and make itself more efficient, Çatalhöyük saw changes in diet and nutrition, plant relationships, resource procurement strategies, and even in animal relationships (Hodder, 2014b, Larsen, Knüsel et al., 2019, Pearson, Buitenhuis et al., 2007). While this feedback system was occurring, there is also the issue of the energy *input* required for agriculture's processes. Agriculture's processes are inherently dependent upon one another. Even within Neolithic Çatalhöyük's system, agriculture would have come with the caveat that its agriculutral processes required an energy input and become increasingly dependent upon one another's success to produce and sustain an energetic surplus. This develops a cycle of energy feedback and dependency. Further, agriculture is only successful when its processes are successful; if one agricultural process fails, the energy system fails.

The previous chapter (chapter 2) demonstrated the lack of an energy methodology by which to quantify and model past energy systems, called for a need for an energy methodology utilising archaeological data, methods, analyses, and perspectives, and pointed out issues surrounding past agricultural energy systems. The literary consensus was that agriculture produces significant amounts of energy, may require sedentism, changes social organisation, and, once agriculture took hold, major changes occurred which were unstoppable. It was also the case that literature surrounding society-energy relationships were missing deeper discussions and exploration of the agricultural energy feedback system. This was very much related to not just a lack of energy methodology by which to quantify energy systems in the past, but also, how energy was quantified. Agricultural processes were not contextualised and/or they were not being modelled separately and energetically, both of which would allow for a better understanding of the energy mechanisms within efficiency and energy within agricultural systems. Thus, one of the ways we can begin to better understand the agricultural energy feedback system is by modelling and quantifying a past agricultural energy system, here, Çatalhöyük's agricultural energy system: the energy of its processes, its inputs, its outputs, and even its energetic efficiency.

Figure 16 below represents how one could begin to model Çatalhöyük's agricultural system, indicating energy inputs (energy costs), outputs (energy gains) and energy losses within Çatalhöyük's agricultural system. To function, Çatalhöyük as an entity had to invest energy into multiple processes to grow domestic crops and to extract energy from them. Çatalhöyük must input energy into all agricultural processes. The first agricultural processes to take place before domestic crops can grow are land clearance, tillage, and planting. Once plants grow, the energy from the crops can only be extracted via harvesting, then subsequently threshing, winnowing, sieving, and pounding or grinding, all of which also require energy input from Çatalhöyük peoples. The energy from domestic crops is extracted in the form of grain and returned to Çatalhöyük via curation (here defined as food, further food processing, and cooking) (Atalay and Hastorf, 2006). However, to grow agricultural crops for the next year, a portion of the grain must be stored as seed. This seed energy does not go directly back in to sustaining Çatalhöyük, but instead, goes back into sustaining Çatalhöyük's agricultural system via planting. Agriculture as a system, even at Neolithic Çatalhöyük, comes with the caveat that agricultural proceses require an energy input and becoming increasingly dependent upon one another's success to produce and sustain an energetic surplus. Within agriculture itself, agriculture processes require energy input, and agricultural processes depend upon the success of other agricultural processes. This develops a cycle of energy feedback and dependency.

Understanding this cycle of energy feedback and dependency and how this occurred at Çatalhöyük is crucial. Çatalhöyük is one of the foundational sources of agricultural expansion during the Neolithic; thus, by modelling and understanding what is occurring at Çatalhöyük with regards to energy, agriculture, and population growth, we gain an insight to how these mechanisms played a role in the spread of agriculture during the Neolithic (Barrett, 2011, Barrett, 2016, Barrett, 2019, Shennan, 2018: 77). By using Çatalhöyük as a case study for quantifying, presenting, and assessing a past energy system, which will be developed throughout chapters 4 to 6, this thesis provides an exciting and valuable perspective on modelling society-energy relationships, provides a way to quantify and present energy systems in the past, and help to understand better the relationship between energy, agriculture, and population growth during this crucial time in human history. Quantifying and assessing a past energy system using archaeology, its data, and its methods is not only required but possible. Therefore, the remainder of this thesis (chapters 4-6) will focus on utilising Çatalhöyük's archaeological data to model and present the Çatalhöyük agricultural system, energetically.

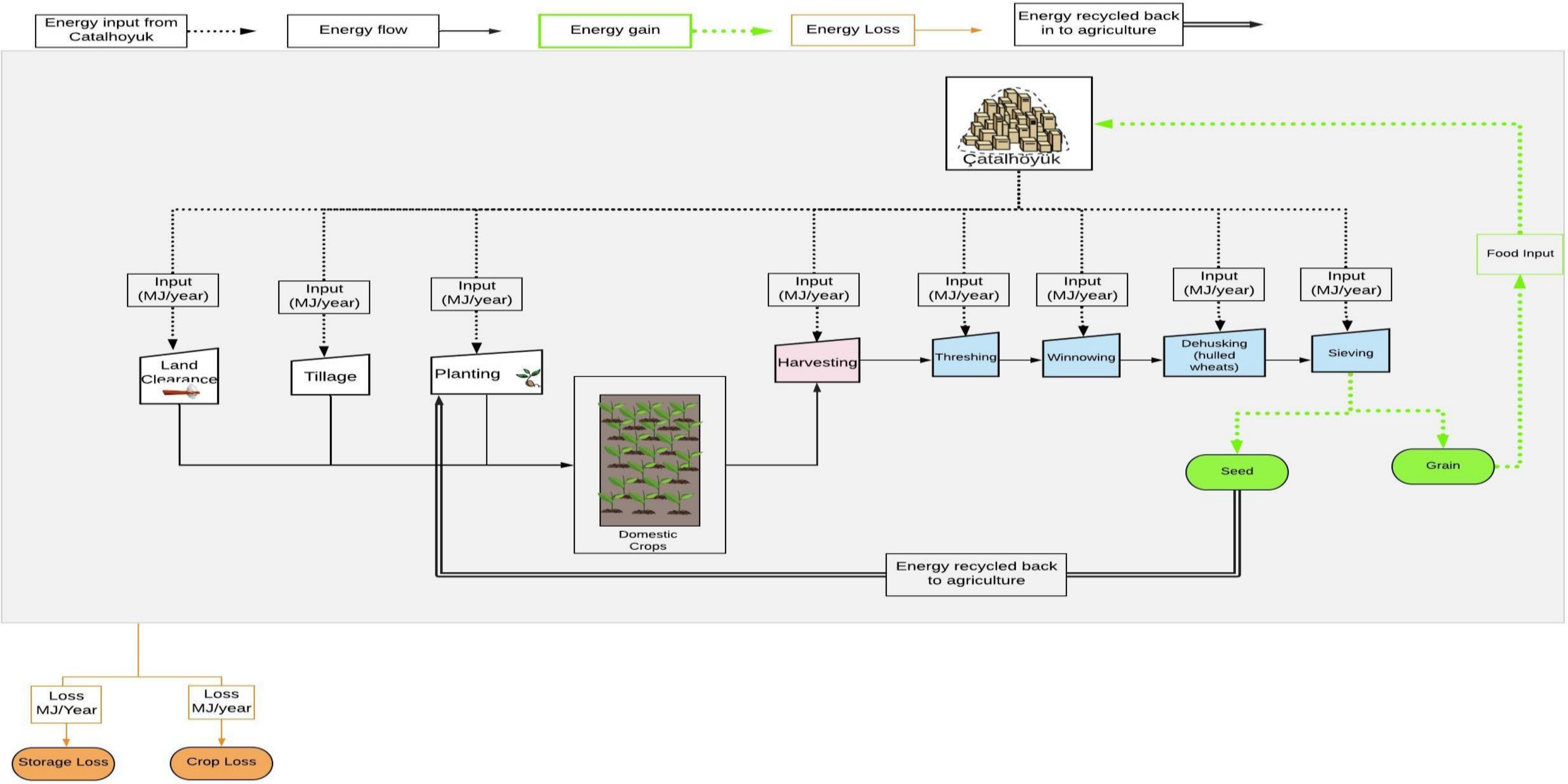


Figure 16: Çatalhöyük Agricultural Energy Diagram indicating energy inputs (energy costs), outputs (energy gains) and energy losses throughout agricultural processes. Çatalhöyük must input energy into agricultural processes before domestic crops can grow, including land clearance, tillage, and planting. Once crops grow, the energy from crops can only be extracted via labour investment in harvesting. To extract the energy from harvested crops, Çatalhöyük must also input energy into threshing, winnowing, sieving, and pounding or grinding. The energy from domestic crops is returned to Çatalhöyük via curation, defined as food, further food processing, and cooking. However, to grow agricultural crops for the next year, a portion of the grain must be stored as seed. This energy does not go directly back in to Çatalhöyük, but instead, goes back into the agricultural system via planting. Finally, there are losses in the form of storage, harvesting, and crop processing which must also be accounted for.

4 CHAPTER 4: METHODOLOGY: CONVERTING ACTIVITIES TO INTO ENERGY

In order to quantify Çatalhöyük's agricultural system energetically, this chapter focuses on establishing and presenting the human work (energy) associated with different activities within the Çatalhöyük agricultural system. The baseline in this thesis is the minimum energy requirement for Çatalhöyük's agricultural system, which includes the amount of land required to support Çatalhöyük's agricultural system, the human energy requirements to support its agriculture and its processes, storage energy, and surplus energy (food, energy output). This chapter produces the framework to create a baseline required for energetically modelling Çatalhöyük's agricultural system.

Establishing an energetic baseline and converting agricultural activities into energy equivalents are fundamental steps toward modelling and presenting the energy of Çatalhöyük's agricultural system. This chapter demonstrates how to apply a modern human energy requirements framework, the 2004 Human Energy Requirements Expert Consultation (henceforth referred to as the HERE consultation) to Çatalhöyük's archaeological data, in order to establish this baseline and convert agricultural activities into energy. This chapter also seeks to bridge the archaeological knowledge gap in understanding past energy systems while demonstrating that quantifying and assessing past energy systems using archaeology and archaeological methods is possible.

To present the Çatalhöyük agricultural system energetically, first, agricultural activities must be converted into their energy equivalents. The methodology employed in this thesis utilises the Food and Agriculture Organisation (FAO), World Health Organisation (WHO), and United Nations University (UNU) 2004 Human Energy Requirements Expert Consultation (henceforth referred to as the HERE consultation) to convert activities into their energy equivalents. The HERE consultation was created to determine and assess populational energetic needs accurately; it is currently employed and supported by the Food and Agriculture Organisation (FAO), World Health Organisation (WHO), United Nations University (UNU), and utilised by modern human energetics specialists (Durnin and Passmore, 1967, James and Schofield, 1990, Passmore and Durnin, 1955, UNU, 1985, UNU, 2004, Vaz, Karaolis et al., 2005). Although designed for modern populations, for this methodology, the HERE consultation is applied to the Çatalhöyük archaeological data.

Initially produced for governments to provide aid for those in need, the HERE consultation presents calculations and methods which aid in determining populational energy requirements (UNU, 2004: 38). The HERE consultation sought to determine and assess populational energetic needs accurately by basing requirements on survival needs and physical activities performed (Henry, 2005, UNU, 2004). Thus, populational energy requirements can be determined by calculating the Basal Metabolic Rate (BMR), Physical Activity Level (PAL), Physical Activity Ratios (PAR) and Total Energy Expenditure (TEE), of a population or group (Table 1 defines the terms and their units). These can be reasonably quantified for Çatalhöyük by drawing directly from archaeological data and, consequently, can aid in providing calculations of past energy requirements.

Table 1: Terms, Units and Definitions Utilised from the Human Energy Requirements Expert Consultation. This table lays out the terms, units, and definitions utilised throughout this chapter section and used to help determine an energetic baseline for Çatalhöyük's agricultural energy system.

Term	**Definition**	**Units**
BMR- Basal Metabolic Rate	The minimum rate of energy expenditure compatible with life. Basal metabolic rate is not to be confused with body mass index (BMI), a heavily contested measurement of metabolic health and **not** used in this analysis (Strings, Ranchod et al., 2016, Tomiyama, Hunger et al., 2016).	Megajoules/time (MJ/time)
PAR- Physical Activity Ratio	The PAR is simply the energy costs of activities. It is a ratio that expresses the energy cost of an individual activity per unit time as a ratio of cost of BMR per unit time. (James and Schofield, 1990: 47-48). Thus, PAR is a minute by minute or hour by hour estimate of the energy cost of a specific physical activity (James and Schofield, 1990 :54). (James and Schofield, 1990, UNU, 1985, UNU, 2004)	Energy spent in an activity for the selected time unit. The energy cost of an activity per time unit usually expressed as a multiple of BMR. It is a ratio, therefore, unitless.
PAL- Physical Activity Level	1. The total energy requirement for a 24 hour period; it is the estimated average degree of activity of the group (James and Schofield, 1990: x, 52-54). 2. PAL is the total energy expenditure (TEE) for 24 hours expressed as a multiple of BMR (the total energy expenditure (TEE) divided by BMR.) 3. Typically, it is expressed as the PAR multiplied by the time allocation of the activity in hours 4. Multiplying the PAL by the BMR gives actual energy requirements. (James and Schofield, 1990, UNU, 1985, UNU, 2004)	The total energy required per day/BMR rate per day
TEE- Total Energy Expenditure	1. The energy spent, on average, in a 24-hour period by an individual or group of individuals. It reflects the average amount of energy spent. 2. When BMR and PAL of a population are known, the mean energy requirement for the population is also known. a. (BMR x PAL)= TEE for the population or group of individuals. 3. TEE for activities can also be determined when the BMR, PAR, and duration of an activity are known. (BMR * PAR * Duration) = TEE of an activity	Megajoules (MJ)

	(James and Schofield, 1990, Lazzer, Busti et al., 2009, UNU, 1985, UNU, 2004)	

Human development and functioning depend on environmental factors, health, diet, and therefore energy intake (Bogin, 1999, Larsen, Hillson et al., 2015). The basal metabolic rate (BMR) is the minimum rate of energy expenditure compatible with life; it can be accurately determined based on the weight or estimated weight of a group of individuals (James and Schofield, 1990: 52, UNU, 2004: 10). Therefore, the basal metabolic rate calculates the minimum energy requirements to sustain a population; calculating the basal metabolic rate is the first step towards determining populational energy requirements.

However, the basal metabolic rate does not account for the extra energy needed for daily physical activities. Therefore, along with the basal metabolic rate, the physical activity level of a population must be known. The physical activity level (PAL) is the total energy expenditure expressed as a multiple of basal metabolic rate; in other words, the physical activity level is the average degree of activity of a group or population (James and Schofield, 1990: x, 52-54, UNU, 2004: 10). When the mean basal metabolic rate and physical activity level of a population are known, the average energy requirements of that population can be calculated, allowing for an accurate energy requirement based on habitual physical activity (UNU, 2004: 37).

To determine the energy requirements of more specific activities, we must utilise the physical activity ratio. The physical activity ratio (PAR) is the energy cost of an activity. When the basal metabolic rate, physical activity ratio, and time are multiplied, it is possible to determine the energy requirements of specific activities based on that population. In sum, determining the basal metabolic rate, physical activity level, and physical activity ratios allows for accurate calculations of the daily total energy expenditure (TEE) and the energy of specific activities, thus, and can help to calculate baseline energy requirements. In Çatalhöyük's case, it is possible to determine both the average populational basal metabolic rate and physical activity level. Both can be reasonably estimated by drawing from routinely collected bioarchaeological data and thus, provide an average energy requirement per person. Further, when physical activity ratios provided by the HERE consultation are amalgamated with accurate time estimates of activities, it is also possible to quantify the energy of different activities which would have occurred in the past.

Therefore, this methodology will be utilised to determine the baseline energy requirements for Çatalhöyük's agricultural energy system. The succeeding subsections focus on applying the HERE consultation to Çatalhöyük's dataset to determine Çatalhöyük's agricultural energy. Section 4.1 explains how the basal metabolic rate at Çatalhöyük was quantified. Section 4.2 describes physical activity levels, how they vary, and how these were calculated for Çatalhöyük. Section 4.3 describes the physical activity ratio, its importance, and how it is used for Çatalhöyük calculations. Section 4.4 describes time allocations for activities and explains the experimental archaeological and ethnographic data from which these time allocations came.

4.1 BASAL METABOLIC RATE: CALCULATING ÇATALHÖYÜK'S BASAL METABOLIC RATE FROM ARCHAEOLOGICAL DATA

Since we do not have an exact representation of the Çatalhöyük population, for this dissertation, it is presumed that the Çatalhöyük bioarchaeological measurements and data are a robust representation of the Çatalhöyük population. Therefore, Çatalhöyük body mass estimates calculated by Hillson, et al. 2013 and Larsen, Hillson et al. 2015 (Table 2, column 2) were used to determine basal metabolic rate.

According to Larsen, Hillson et al. 2015, Çatalhöyük body mass (Table 2, column 2) indicates that the population was relatively normal and suggests that people were "living in a setting that had adequate nutrition and positive circumstances necessary for normal growth and development" (Larsen, Hillson et al., 2015: 50). The bioarchaeological data indicates that the Çatalhöyük population had enough dietary intake to sustain itself. The Çatalhöyük bioarchaeological data also shows that the population was of average size for the Neolithic, sexual dimorphism in body mass was average and similar to today, and sexual dimorphism in stature, overall, was "unremarkable" (Hillson, Larsen et al., 2013: 370-372). Statistically speaking, the size differences between men and women were negligible at Çatalhöyük (Hillson, Larsen et al., 2013: 370-372). Further, the body mass estimates come from a large and robust archaeological sample: a large quantity of well-preserved remains, from both Mellaart and Hodder excavations, from primary, secondary, and primary disturbed depositional contexts, and, from the three major time periods (Early, Middle, Late) (sample size=382) (Hillson, Larsen et al., 2013, Larsen, Hillson et al., 2015). It should be noted that even as population numbers changed over time at Çatalhöyük, there were no significant differences in body mass over time (Hillson, Larsen et al., 2013: 370-372).

Morphometric and mechanical equations for body mass estimates from skeletal remains are customary in bioarchaeology for estimating the mass of fossil hominin groups, hominin specimens, archaeological *Homo sapiens* populations, and even in modern forensic contexts (Elliott, Kurki et al., 2016). These methods of determining body mass from skeletal remains were explicitly created to estimate the average body mass of a population or group and should not be utilised to estimate an *individual's* body mass (Jeanson, Santos et al., 2017: 183.e1, 183.e6-183.e7). Determining an individual's body mass from skeletal elements based on these estimation equations is widely contested, inaccurate, and variable (Elliott, Kurki et al., 2016, Jeanson, Santos et al., 2017, Schug, Gupta et al., 2013). However, when determining the average mass of a group, these estimations are "accurate and reliable enough for estimating the average body mass of a population" (Jeanson, Santos et al., 2017: 183.e5). The Çatalhöyük Research project calculated average body masses for juveniles and adults and from a large sample size; therefore, the stature and body mass estimates from Çatalhöyük are deemed to be accurate and reliable (Auerbach and Ruff, 2004, Hillson, Larsen et al., 2013: 370, Jeanson, Santos et al., 2017, Ruff, Holt et al., 2006). Estimating the stature and body mass from adolescents are also accurate estimates of stature and body mass for the same reasons. It is, therefore, feasible to use the Çatalhöyük body mass estimates to determine the mean basal metabolic rate.

To ensure that we fully represent the Çatalhöyük community without severely overestimating populational energy requirements, the average basal metabolic rate for adolescents (age 1-18)[2] and adults (18-60+), both male and female, were quantified. Large ranges in basal metabolic rate of populations are typically due to differences in basal metabolic rate based on age and sex. Men have a higher basal metabolic rate for their body weight than women (UNU, 2004: 35). Adolescents have a lower basal metabolic rate, but more energy[3] is allocated for growth and development (James and Schofield, 1990: 23, UNU, 2004: 23). Due to the ageing of adolescent skeletal elements, the average body mass of each age range present at

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[2] For this methodology, adolescents include those individuals aged 1-18 years. Body mass estimates for those under age 1 at Çatalhöyük were unavailable.

[3] The energetic difference between adolescents and adults comes more into play with physical activities and is described in the succeeding section.

Çatalhöyük was amalgamated to calculate the average basal metabolic rate. Most bioarchaeological skeletal remains cannot be sexed as adolescents; therefore, basal metabolic rate equations for males and females were used (Schug, Gupta et al., 2013: 3077). If the quantified average basal metabolic rate were based solely upon adults, this would be an extreme overestimation of populational energy needs. By taking the average basal metabolic rate of male and female adolescents and adults, we satisfy the Çatalhöyük community's energy requirement baseline more accurately.

The equations (Table 2, column 3) used for basal metabolic rate were from Schofield 1985 table 1.7, and the 1985 report of another joint expert consultation: Energy and Protein Requirements (UNU, 1985). These are the same equations used by the HERE consultation. Basal metabolic rate calculations are presented in Table 2 below. Based on the archaeological data, the basal metabolic rate rages from 3.7 to 6.9 MJ/day, with an average of 5.8 MJ/day. This mean basal metabolic rate quantified here is used throughout this analysis. As there is a lack of statistically significant differences in body mass over time at Çatalhöyük, the basal metabolic rates quantified can also be used throughout the entire occupation period.

Table 2: Çatalhöyük BMR Calculations (using James and Schofield 1990 equations and Energy and Protein Requirements Expert Consultation). This table presents the BMR values, in megajoules per day, of various parts of the Çatalhöyük population. The BMR was calculated by using equations from the human energy requirements framework and applying Çatalhöyük's bioarchaeological data. Based on this, Çatalhöyük's average BMR is 5.8 megajoules per day.

Age	**Weight** (kg)	**Equations (James and Schofield, 1990 :25, table 1.7, UNU, 1985)**	**BMR** (MJ/day)	**Average BMR** (MJ/day)
Adolescents (1-3)	9.3	BMR Males, 1-3 = 0.255*(kg)-0.226	2.2	3.7
		BMR Females, 1-3 =0.255*(kg)-0.215	2.2	
Adolescents (3-10)	20.6	BMR Males, 3-10 = 0.0949*(kg) +2.07	4.0	
		BMR Females, 3-10 = 0.0941*(kg) +2.09	4.0	
Adolescents (10-18)	36.3	BMR Males, 10-18 =0.0732*(kg)+ 2.72	4.7	
		BMR Females, 10-18 =0.0510*(kg)+ 3.12	5.0	
Adult Male (18-60+)	63.4	BMR Male, 18-29= 0.064*(kg) + 2.84	6.9	5.8
		BMR Male, 30-59= 0.0485*(kg) + 3.67	6.7	
		BMR Male, >60 = 0.0565*(kg)+ 2.04	5.6	
Adult Female (18-60+)	54.8	BMR Female, 18-29= 0.0615*(kg) + 2.08	5.5	
		BMR Female, 30-59= 0.0364*(kg) + 3.47	5.5	
		BMR Female, >60 = 0.0439*(kg)+ 2.49	4.9	

The BMR must be utilised along with a population's physical activity level (PAL) to quantify a population's average energy requirements; this allows for an accurate energy requirement based on habitual physical activity (UNU, 2004 :37). Therefore, the next section focuses on determining Çatalhöyük's physical activity level.

4.2 PHYSICAL ACTIVITY LEVEL: CALCULATING ÇATALHÖYÜK'S PHYSICAL ACTIVITY LEVELS FROM ARCHAEOLOGICAL DATA

The physical activity level (PAL) is the average degree of activity of a group or population (James and Schofield, 1990: x, 52-54, UNU, 2004 :10). Physical activity levels are based on habitual physical activity (UNU, 2004: 23). The HERE consultation classifies lifestyles in relation to habitual physical activity, defined as activities "most often performed by most individuals in the population, over a period of time" (UNU, 2004: 38). Physiologically, there is "no basis for establishing the duration of the time period," however the HERE consultation designates this time as a habitual activity occurring for one month or longer(UNU, 2004: 38). These categories are presented in Table 3 and further explained, below.

A "sedentary or light activity lifestyle" includes people with undemanding occupations requiring minimal physical effort; they spend most of their time sitting or standing; this excludes walking long distances, regular exercise, and significant body movement (UNU, 2004: 39). One example provided by the HERE consultation is that of individuals "in villages with electricity, piped water, and nearby paved roads, who spend most of the time selling produce at home or in the marketplace, or doing light household chores and caring for children in or around their houses" (UNU, 2004: 39). An "active or moderately active lifestyle" includes people with occupations that are not necessarily strenuous but involve more movement and energy expenditure than those with sedentary lifestyles (UNU, 2004: 39). This includes people with "sedentary occupations who regularly spend a certain amount of time in moderate to vigorous physical activities, either the obligatory or the discretionary part of their daily routine" (UNU, 2004 :39). Examples of active or moderately active lifestyles include masons, construction workers, and individuals "who participate in agricultural chores or walk long distances to fetch water and fuelwood" (UNU, 2004: 39). Finally, a "vigorous or vigorously active lifestyle" includes those who regularly engage in strenuous work and leisure activities for extended time periods (UNU, 2004: 39). Examples of lifestyles that are vigorous or vigorously active include those "with non-sedentary occupations who swim or dance an average of two hours each day, or non-mechanised agricultural labourers who work with a machete, hoe or axe for several hours daily and walk long distances over rugged terrains, often carrying heavy loads" (UNU, 2004: 39).

Table 3 Physical Activity Level Lifestyles and Values (from HERE Consultation). This table indicates the Physical Activity level (PAL) lifestyle and values from the HERE consultation. PAL is an accurate and useful estimate for populational energetics. According to the HERE consultation, Çatalhöyük peoples would have led a vigorous or vigorously active lifestyle. Çatalhöyük's own bioarchaeological data also supports this notion.

Category	**PAL Value**	**Definition**
Sedentary or light activity lifestyle	1.40-1.69	People with "occupations that do not demand physical effort, are not required to walk long distances, use motor vehicles for transport, do not exercise or participate in sports regularly, and spend most of leisure time sitting or standing with little body displacement (e.g. talking, reading, watching television, listening to the radio, using computers)" (UNU, 2004: 39).
Active or moderately active lifestyle	1.70-1.99	People with occupations that are not necessarily strenuous but, involve more movement and energy expenditure than those with sedentary lifestyles (UNU, 2004: 39).

Vigorous or vigorously active lifestyle	2.0-2.40	People who regularly engage in strenuous work or in strenuous leisure activities for many hours (UNU, 2004: 39).
Extremely high PAL levels	2.40-4.7	These are rare PAL numbers, and studies indicate that these would be best represented by three weeks of competitive cycling or hauling sledges across the arctic (UNU, 2004: 39).

Physical activity levels are an accurate and helpful estimate for populational energetics. Typically, one would determine the energetics of a group of individuals by studying their activities throughout the day. First, an individual’s basal metabolic rate would be determined, and their activity would be recorded for an entire 24-hour period over a few weeks to months. Activities recorded include everything the person did: what they ate, how much they ate, for how long, and how often, every single activity and its duration, and even how long someone slept. From here, energy requirements would be precisely determined based on basal metabolic rate and activities. However, this process is lengthy and costly; even for governments and societies today, it is unfeasible to complete this level of detail for every individual. Therefore, when this sort of fine-grained study is impossible, human energetics specialists (Passmore and Durnin 1955 and Durnin and Passmore 1967) and the HERE consultation advocate using the physical activity level to estimate group or populational energy requirements accurately. The physical activity level, in sum, is an accurate and plausible way to determine the average daily energy requirements of populations when 24 hour-a-day activity recording is not possible. For Çatalhöyük, daily recording activities is impossible; hence, this physical activity level approach is applied to the Çatalhöyük population and explained below.

Like many agriculturalists today, the Çatalhöyük population underwent seasonal and cyclical change**.** Therefore, the energy requirements of Çatalhöyük throughout the year would change depending on the seasonal energy demands (UNU, 2004: 39). As a result, for this analysis, Çatalhöyük’s physical activity levels can be classified as both moderately and vigorously active. This physical activity level is also supported by Çatalhöyük bioarchaeological data (page 73). Çatalhöyük archaeological evidence also indicates that adolescents and adults met their nutritional requirements, and adolescents had standard growth rates (Larsen, Hillson et al., 2015). This suggests that minimum nutritional requirements were met at Çatalhöyük for both adolescents and adults. As mentioned in section 4.1, the energy requirements for children differ from adults. Unlike adults, children require more energy to grow (James and Schofield, 1990: 23). To accurately estimate adolescents’ total energy requirements, the energy required during this growth must be added; this is equivalent to multiplying the physical activity level of adolescents by 1.01 (UNU, 2004: 23). This additional energy is included in the calculations for adolescents.

It should be noted that, contrary to popular belief, the effect of climate on energy expenditure is minuscule. Only in emergency conditions (i.e. starvation) and extremely low environmental temperatures is more energy needed (James and Schofield, 1990: 3, Passmore and Durnin, 1955: 827). Colder temperatures can increase energy expenditure by 10%; however, this difference is usually due to the *timing* of activities (Durnin and Passmore, 1967, Passmore and Durnin, 1955: 827). The timing of activities is more thoroughly discussed in section 4.4.

Since the average basal metabolic rates were quantified (Table 2), and, we have determined the Çatalhöyük physical activity levels, the average daily total energy expenditure per person at Çatalhöyük can be determined. This is calculated by simply multiplying the basal metabolic rate by the appropriate physical activity level values. These values are presented in Table 4 for both adolescents and adults. Sedentary physical activity levels are also presented in this table to demonstrate the range of energy requirements. The total energy expenditure was based on the mean basal metabolic rate for adults and adolescents and upon moderate and vigorous physical activity levels to account for changes in seasonality and temporal changes in workload and mobility. This allows for a more accurate picture of the daily total energy expenditure for the average individual at Çatalhöyük. The total energy expenditure (9.7 MJ/Day; 2300kcal/day) is presented in both megajoules and kilocalories in Table 4. These values represent the daily total energy expenditure, the amount of energy required to sustain life daily, according to the activity levels at Çatalhöyük. At a minimum, the Çatalhöyük peoples, on average, would have required 9.7 MJ/Day, or 2,300 kilocalories per day.

Table 4 Total Energy Expenditure Values at Çatalhöyük based on various Physical Activity Levels. This table applies BMR, PAL, for sedentary, moderate, and vigorously active PAL's at Çatalhöyük, to show the range of average Total Energy Expenditure (in both megajoules and kilocalories) at Çatalhöyük. By using this data, it is possible to determine the average TEE for the average adult and adolescent at Çatalhöyük, and thus, the average TEE for Çatalhöyük's population, in order to determine the average energy requirements of Çatalhöyük's population.

	Average Adult		**Average Adolescent**	
BMR MJ/day	5.8		3.7	
BMR MJ/hour	0.2		0.1	
BMR MJ/Hour (Average adult, adolescent)	0.4			
	TEE (MJ)	TEE (kcal)[4]	TEE (MJ)	TEE (kcal)
PAL sedentary				
1.4	*8.2*	*2000*	*5.2*	*1200*
1.5	*8.8*	*2100*	*5.6*	*1300*
1.6	*9.4*	*2200*	*6.0*	*1400*
Average Sedentary	*8.8*	*2100*	*5.6*	*1300*
PAL moderate				
1.7	*9.9*	*2400*	*6.3*	*1500*
1.8	*10.5*	*2500*	*6.7*	*1600*
1.9	*11.1*	*2700*	*7.1*	*1700*
Average Moderate	*10.5*	*2500*	*6.7*	*1600*
PAL Vigorous				
2	*11.7*	*2800*	*7.4*	*1800*
2.1	*12.3*	*2900*	*7.8*	*1900*
2.3	*13.4*	*3200*	*8.6*	*2000*

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[4] 1 kilocal is equal to 4184 joules (J) or 0.004184 megajoules (MJ), 1 megajoule (MJ) is equal to 1000000 joules (J)

2.4	*14.0*	*3400*	*8.9*	*2100*
Average Vigorous	*12.9*	*3100*	*8.2*	*2000*
Average TEE all PAL	*10.9*	*2100*	*7.0*	*1700*
Average TEE of Moderate & Vigorous	*11.9*	*2300*	*7.4*	*1800*
Average TEE of Adults + Adolescents (all PAL)	*8.9*	*2100*		
Average TEE of Adults + Adolescents (moderate + vigorous)	*9.7*	*2300*		

By determining the daily total energy expenditure, it is possible to determine the energy requirements of the Çatalhöyük population as a whole (UNU, 2004). This is discussed further in Chapter 5.

4.3 PHYSICAL ACTIVITY RATIOS: BENEFITS AND APPLICATIONS FOR THE ÇATALHÖYÜK ARCHAEOLOGICAL DATA

The physical activity ratio (PAR) is arguably one of the most valuable figures from the HERE consultation. The physical activity ratio expresses the energy cost of an individual activity per unit time as a ratio of cost of the basal metabolic rate per unit time; it is the energy cost of specific activities (James and Schofield, 1990: 47-48). As aforementioned, the energetics of individuals, or a group of individuals, is completed by studying every activity during a 24-hour period, for a few weeks to months. The physical activity ratio was conceived to aid in simplifying this process—if the activities and their duration are known, along with the average basal metabolic rate, then energy costs of activities, based on that population, can be determined; painstaking, costly studies are no longer necessary. This is precisely why human energetics specialists and the HERE consultation determined the physical activity ratios of a plethora of activities ranging from sleeping, tending to animals, grinding grain with a millstone, all the way to brewery work. These physical activity ratio values from the HERE consultation, used for this dissertation, include data assembled by Professor J. V. G. A. Durnin, institute of Physiology, University of Glasgow, Scotland (UNU, 1985, UNU, 2004). The physical activity ratios are based on modern values from various nations and diverse societal and lifestyle types and activities (Durnin and Passmore, 1967, Passmore and Durnin, 1955, UNU, 1985, UNU, 2004). Some of this data comes from Hungary, Russia, Italy, Gambia, Nigeria, Southeast Asia, for example, and includes data from both mechanised and non-mechanised agricultural societies; some activities include office and hard-labour jobs, domestic labour, and even leisure activities (Durnin and Passmore, 1967, Passmore and Durnin, 1955: 818-822).

Physical activity ratios vary by activity, and it should be noted that there is a minuscule difference between the cost of females and males doing the same task. This is because males have a higher basal metabolic rate for their body weight than females, and vigorous activities such as lifting and carrying heavy loads, demand more muscle mass and strength, which are also typically higher among males (UNU, 2004: 35). As a result, the physical activity ratios used and presented below (Table 5) are the average of both females and males.

Utilising the physical activity ratio has four essential benefits for this analysis. First, those who have different body weights, and therefore different total energy expenditures, will have the same physical activity ratio (James and Schofield, 1990: 48). This allows for applying physical activity ratios to different individuals and allows for using the average basal metabolic rate to determine the energy of different activities. Second, if the physical activity ratio of an activity, the duration of that activity, and the basal metabolic rate of individuals performing an activity are known, then the energy of that specified activity can be calculated. Third, energy calculations for a plethora of activities exist. In fact, the physical activity ratios available within the HERE consultation also include activities that would have taken place at Çatalhöyük.

It could be argued that these modern physical activity ratios cannot be used for archaeological datasets; perhaps they are lower or higher than modern, non-mechanised activities for which we have data. However, Passmore and Durnin (1955) and Durnin and Passmore (1967), upon which the HERE consultation consistently relies, state that with human energy requirements, “larger errors are likely to arise from a failure to determine correctly the length of time spent in any activity rather than in any assessment of the metabolic cost of that journey” (Passmore and Durnin, 1955: 802, 830). Therefore, fourthly, if the physical activity ratio is not exact, this will not cause a significant error; accurate time estimates can help account for this error. For this reason, time is the focus of the next section (section 4.4), and there is a thorough time estimation for each agricultural activity at Çatalhöyük.

For this analysis, physical activity ratios are applied to Çatalhöyük as an hour by hour energy cost estimate of a specific physical activity (James and Schofield, 1990 :54, UNU, 2004 :10). The average basal metabolic rate of those performing activities (the Çatalhöyük population) is known, the duration of an activity can be estimated (further discussed in section 4.4), and physical activity ratios for non-mechanised agricultural activities exist; therefore, the energy costs of agricultural activities at Çatalhöyük can be determined. The physical activity ratios for agricultural activities at Çatalhöyük utilised for this dissertation, from Annex 5 of the HERE consultation, are presented below (Table 5) (UNU, 2004: 92-96).

Table 5: Physical Activity Ratios used for Çatalhöyük. This table presents the Physical Activity Ratios (PARs) which are utilised for this analysis. The PARs used for Çatalhöyük were calculated from an average of multiple physical activity ratios. This is further described in the relevant, agricultural process subsections. The PAR for each agricultural activity, how this was combined with archaeological evidence, and from what resources they were drawn is presented and described within each agricultural activity section of this methodology chapter.

Activity	**Physical Activity Ratio Value**	**Reference**
Harvesting	*4.2*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Planting	*3.7*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Land Clearance	*5.7*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Tillage	5.1	(UNU, 2004, Vaz, Karaolis et al., 2005)
Threshing	*5.1*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Winnowing	*2.7*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Pounding/grinding	*5.4*	(UNU, 2004, Vaz, Karaolis et al., 2005)
Sieving/Sifting	*4.3*	(Vaz, Karaolis et al., 2005)

The next step to ascertaining the energy expenditure for Çatalhöyük agricultural activities is to determine the time allocated for each activity. This is the focus of the subsection below.

4.4 DETERMINING TIME ALLOCATION ESTIMATES FOR ÇATALHÖYÜK'S AGRICULTURAL ACTIVITIES

Time spent performing an activity is arguably the most critical aspect of estimating and quantifying human energy expenditure. As stated by Passmore and Durnin 1955, "it is most important to try to obtain reliable figures for the duration of each activity" (Passmore and Durnin, 1955: 802, 830). Thus, it is pivotal to secure how much time activities take; if they are estimates, they must be as accurate as possible.

For this analysis, timings for agricultural activities were drawn from and based on multiple ethnographic and experimental sources: Steensberg 1979, Gregg 1988, Russell 1988, Steensberg 1991, Wright 1994, Ertuĝ-Yaras 1997, Mathieu and Meyer 1997, Meurers- Balke and Lüning 1999, Valamoti et al. 2013, Halstead 2014, and Dietrich et al. 2019. Each of these resources, the sheer interdisciplinarity of the data within them, and the combination of experimental archaeology and ethnographic research have proven to be pivotal for forming this energy methodology. The timings for each agricultural activity gathered and averaged from the above ethnographic and experimental resources are presented in Table 6, below. Timings for each agricultural activity, how this was combined with archaeological evidence, and from what resources they were drawn is presented and described within each agricultural activity section of chapters 5 and 6.

Table 6: Timing of Agricultural Activities from Various Ethnographic and Experimental Archaeological Sources. This table presents the timings used to determine the energy of agricultural activities at Çatalhöyük. The timings for each agricultural activity were gathered and averaged from ethnographic and experimental sources. Timings for each agricultural activity, how this was combined with archaeological evidence, and from what resources they were drawn is presented and described within each agricultural activity section of this methodology chapter.

Activity	**Time**	**Units**	**Reference**
Land Clearance	0.002	ha/hour	(Halstead, 2014: 47, 260-262, 265)
Tillage	0.003	ha/hour	(Halstead, 2014: 41, 48, 118)
Planting	0.004	ha/hour	(Gregg, 1988: 158, Steensberg, 1979: 9)
Harvesting Barley with sickle	0.005	ha/hour	(Halstead, 2014: 105-106, Russell, 1988)
Harvesting Emmer with sickle	0.003	ha/hour	(Halstead, 2014: 105-106, Russell, 1988, Steensberg, 1979)
Harvesting Einkorn with sickle	0.003	ha/hour	(Ertuĝ-Yaras 1997: 452, Halstead, 2014: 105-106, Steensberg, 1979)
Harvesting free threshing wheat with sickle	0.003	ha/hour	(Halstead, 2014: 114, Russell, 1988 :116, Steensberg, 1979)
Threshing	16	kg/hour	(Gregg, 1988: 161-163, Halstead, 2014: 166-168, 170-171, 182)
Winnowing	63	kg/hour	(Halstead, 2014: 169, Russell, 1988)
Dehusking Einkorn	1.8	kg/hour	(Dietrich, Meister et al., 2019: 25, Ertuĝ-Yaras 1997: 233, Ertuğ-Yaras, 2000, Halstead, 2014: 182, Meurers-Balke and Lüning, 1999 , Valamoti, Chondrou et al., 2013, Wright, 1994: 245-257)
Dehusking Emmer	2.4	kg/hour	(Dietrich, Meister et al., 2019, Ertuĝ-Yaras 1997: 233, Ertuğ-Yaras, 2000,

			Meurers-Balke and Lüning, 1999 , Samuel, 2010, Wright, 1994)
Sieving	175	kg/hour	(Halstead, 2014)

4.5 ENERGY CONVERSIONS: CONCLUDING REMARKS

This methodology chapter has demonstrated how to use aspects from the HERE consultation and apply them to archaeological datasets; in this case, Neolithic Çatalhöyük. The HERE consultation provides us with a way to determine and assess populational needs by basing requirements on survival needs and physical activities performed. This was applied to the Çatalhöyük dataset using Çatalhöyük archaeological data, in order to help present the Çatalhöyük agricultural system energetically. Section 4.1 presented the Çatalhöyük basal metabolic rate and demonstrated how Çatalhöyük bioarchaeological data was used to calculate it. Section 4.2 described physical activity levels and designated Çatalhöyük people's lifestyles as moderately to vigorously active, based on bioarchaeological data. Using the Çatalhöyük basal metabolic rate, we determined the total energy equivalent: the average total amount of energy each person at Çatalhöyük would have needed per day. This calculation was, again, based on what the Çatalhöyük bioarchaeological data informs us about habitual activity. Although the basal metabolic rate and physical activity level give us an average energy requirement for individuals at Çatalhöyük, this does not give us information on the energy of individual activities performed. Therefore, Section 4.3 explained the physical activity ratio, its benefits, and its use throughout the rest of this thesis to determine the energy requirements of agricultural activities. Finally, section 4.4 emphasised the importance of time in determining the energy requirements of activities.

Now that the foundation of this energy methodology has been outlined, the succeeding sections of this chapter will focus specifically on determining the baseline energy requirements of the Çatalhöyük agricultural system. The next chapter (5) will demonstrate how this data aids in determining the amount of land needed to sustain the Çatalhöyük population, estimated to be 3000 during its peak occupation (Bernardini and Schachner, 2018). This is crucial, as it sets the foundation for what would have been the minimum energy catchment area to sustain Çatalhöyük's agricultural system. Overall, chapters 5 and 6 focus on determining the energy requirements of various agricultural activities, including land clearance, tillage, planting, harvesting, threshing, winnowing, sieving, and dehusking. Each of the chapter subsections within chapters 5 and 6 will describe how the Çatalhöyük archaeological data, ethnographic data, and experimental archaeological data were combined with the outlined energy methodology to determine the baseline energy of Çatalhöyük's agricultural system. From here, it is possible to determine the total energy expenditure of agricultural activities at Çatalhöyük, and thus, the baseline energy requirements of Çatalhöyük's agricultural system.

5 CHAPTER 5: LAND PREPARATION: LAND REQUIRED, LAND CLEARANCE, TILLAGE, AND SOWING

5.1 INTRODUCTION

Defining the amount of land required to sustain Çatalhöyük is necessary for determining the energy of agricultural activities, and thus, the Çatalhöyük agricultural system. Thus, this chapter presents and describes the relationship between land and energy and quantifies how much land was required for Çatalhöyük. The method by which this is accomplished is the focus of section 5.2. Section 5.3 focuses on determining the amount of land required for Çatalhöyük, and, quantifying the energy of land clearance at Çatalhöyük, section 5.4 focuses on quantifying the energy of tillage for Çatalhöyük, and section 5.5 focuses on quantifying planting at Çatalhöyük, in addition to seeding rate and the amount of storage required.

5.2 THE AMOUNT OF LAND REQUIRED TO SUSTAIN ÇATALHÖYÜK:

A primary energy source is defined as being directly available from the environment and can only be used by humans via extraction (Demirel, 2012: 28-29). The land provides access to primary energy, more specifically for this analysis, energy in the form of plants and animals. Subsistence pathways, like agriculture, are the mechanism by which humans extract energy to sustain themselves. Therefore, any agricultural analysis must include land quantifications, as, of course, agriculture is heavily dependent upon land, its productivity, and its availability.

Land needed for agriculture depends on household size, crop yields, land productivity, and dietary requirements and preferences (Filipović, 2014: 141). Although the exact amount of land required to sustain Çatalhöyük is unknown, estimates can be made from dietary requirements. With regards to diet, according to Larsen, Hillson et al. 2015, body mass estimates indicate that the Çatalhöyük population was "living in a setting that had adequate nutrition and positive circumstances necessary for normal growth and development" (Larsen, Hillson et al., 2015: 50). The growth trajectories of adolescents at Çatalhöyük further evidence this, indicating that early childhood growth was normal and that children were "born into a relatively healthy environment, with adequate resources and access to quality nutrition" (Larsen, Hillson et al., 2015: 48).

Concerning differences in diet, there was no significant difference in diet between males and females at Çatalhöyük (Larsen, Hillson et al., 2015: 50). They had very similar diets, evidenced by stable isotope analyses where "the mean values for men and women are statistically indistinguishable" (Larsen, Hillson et al., 2015). Further, the mean stable isotope values for males and females are indistinguishable throughout the Early, Middle, and Late periods at Çatalhöyük (Larsen, Hillson et al., 2015: 38). For the average individual at Çatalhöyük, the plant diet was primarily centred around emmer, einkorn, bread wheat, naked barley, peas, lentils, bitter vetch, wild mustard, acorn, almond, hackberry, fig, and pistachio (Bogaard, Charles et al., 2013, Pearson, Haddow et al., 2015: 213). This stable isotope data does indicate that males and females ate the same foods, and bioarchaeological research indicates they were physically active and performing similar actions throughout their lives (Pearson and Meskell, 2015: 476). However, the same isotopic research has also indicated that children, adolescents, younger adults, and older adults consumed different foods from one another (Pearson and Meskell, 2015). Diet was based upon age at Çatalhöyük, and there were multiple age-based dietary transitions for individuals at Çatalhöyük (Pearson and Meskell, 2015, Pearson, Haddow et al., 2015). Infants were breastfed, and by three years old, they were fully weaned (Pearson, Haddow et al., 2015: 224). Children aged 5 to 10 years had a different diet than adolescents and adults, suggesting an "adolescent diet" that continued until young adulthood (Pearson, Haddow et al., 2015: 224). Once a Çatalhöyük person reached young adulthood, the diet changed again; this transition was maintained until old age (Pearson, Haddow et al., 2015: 224). These dietary differences are explained as younger adults having access to plants or animals from different parts of the surrounding landscape, and/or they consumed a greater quantity of meat from wild equids and boar; older individuals seemed to have consumed a greater quantity of meat from sheep and cattle (Pearson, Haddow et al., 2015: 224). Although this thesis explicitly focuses on the agricultural aspect of the diet, meat was a major and important component of Çatalhöyük diet, and animal (caprine) herding was crucial to Çatalhöyük's success (Bogaard, Ater et al., 2019, Bogaard, Filipović et al., 2017, Filipović, 2014, Hillson, Larsen et al., 2013: 354, Pearson and Meskell, 2015: 468-472, Pearson, Haddow et al., 2015: 223-224). Future research (further discussed in 7.5), should incorporate the animal-meat contribution to the diet and the energetic aspect of herding flocks. The methodology here within this thesis cannot account for every single dietary change that occurred at Çatalhöyük, nor can it focus on individuals' differences between diets; this is another avenue for future research (discussed in 7.5). It is simply impossible to estimate exactly how many cereals and starches in relation to meat the Çatalhöyük peoples were consuming (Hillson, Larsen et al., 2013: 392). However, we can model a range of dietary reliance on domestic cereals. Thus, this thesis includes calculations assuming 25%, 50%, and 75% of the Çatalhöyük diet relied on domestic cereals. Modelling such a range allows for a fuller, more robust model of potential agricultural scenarios at Çatalhöyük.

Previous land estimates were determined based on nutritional needs by Filipović 2014. Filipović 2014 surmised that cereals comprised 80% of the diet, equal to 2500 kilocalories per person per day for Çatalhöyük (Bogaard, 2004, Filipović, 2014). However, Filipović 2014's calculations were not based on the nutritional requirements representative of the Çatalhöyük population's needs and activities, nor are they based on vital bioarchaeological data. This, therefore, renders Filipović 2014's calculations inadequate for accurate land estimate calculations, although it does allow for a comparison. However, implementing the relevant bioarchaeological data based on activity levels and a range in dietary reliance makes the quantifications below (Table 7) for this analysis more precise baseline calculations. Table 7 (below) presents the daily total energy expenditure (calculated in section 4.2) in both megajoules and kilocalories. Based on the Çatalhöyük data, a person would need 2300 kilocalories per day per year to sustain themselves. Assuming 25% to 75% of the Çatalhöyük diet relies upon domestic cereals, leading to a baseline of 600 to 1800 kilocalories per person per day coming from cereals. This is a reasonable estimate and in tune with what would have been energetically required by Çatalhöyük people's activity levels.

Table 7: Kilocalories of cereals per day calculated based on Çatalhöyük's average total daily energy expenditure (calculated in section 4.2, Table 4). The average daily intake of the Çatalhöyük population, based on activity levels, is 9.7 Megajoules per day, or 2300 kilocalories per day. If 75 percent of the diet is based on domestic cereals, this equates to roughly 1800 kilocalories or 7.5 megajoules per day for each person at Çatalhöyük. If 50 percent of the diet is based on domestic cereals, this equates to 1200 kilocalories or 5.0 megajoules per day for each person at Çatalhöyük. If 25 percent of the diet is based on domestic cereals, this equates to 600 kilocalories or 2.5 megajoules per day for each person at Çatalhöyük.

Average TEE of Population (daily intake required)	9.7 MJ/Day	2300 kcal/day
75% of daily intake is cereals, therefore daily calorific intake on average, per person:	7.5 MJ/Day	1800 kcal/day

50% of daily intake is cereals, therefore daily calorific intake on average, per person:	5.0 MJ/Day	1200 kcal/day
25% of daily intake is cereals, therefore daily calorific intake on average, per person:	2.5 MJ/Day	600 kcal/day

With the calorific amount of cereals required per person, it is possible to multiply this by the Çatalhöyük population estimates and determine the total energy required from crops for Çatalhöyük. This is presented in Figure 17 below. For the remaining diagrams and figures, for the sake of data visualisation, Çatalhöyük's population is represented as starting from a population of 100, peaking at 3000 people, and declining to 500 after its peak, correlated with Figure 10 (Chapter 3).

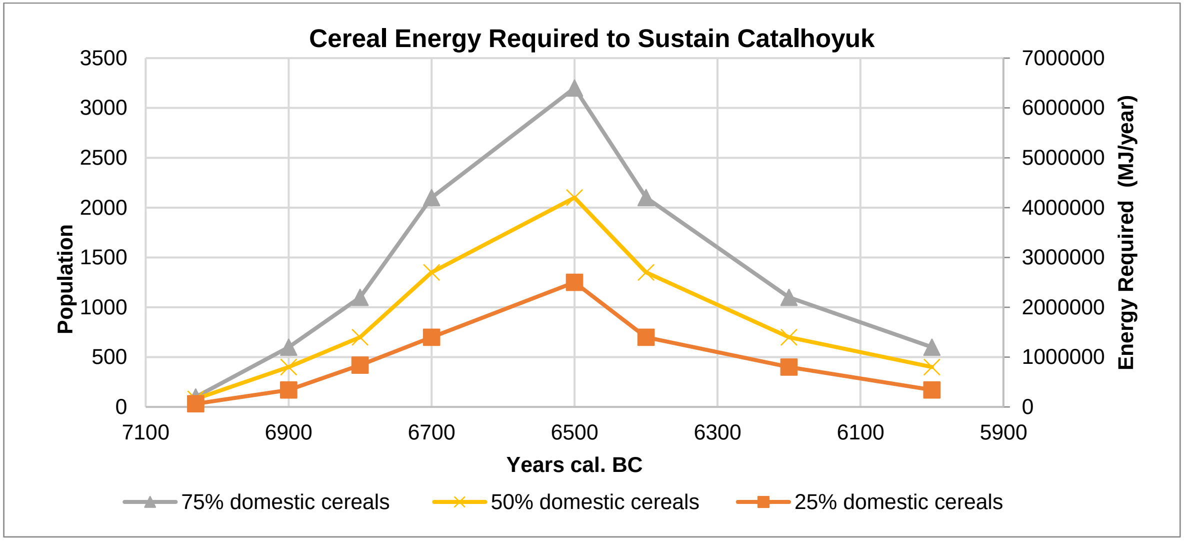

Figure 17: Cereal energy required to sustain Çatalhöyük in Megajoules of cereals per year, originally based off Cessford (2005) estimates, but revised estimates as per Bernardini and Schachner 2018 (a maximum of 3000 people). By converting the daily amount of cereals required to megajoules required per year, it is possible to determine the average amount of cereals required per year based on Çatalhöyük's population and population growth over time. For a population of 100 to 1000 people, which would have been most representative of Çatalhöyük's Early period, 80,000 to 4,200,000 megajoules of cereals were required (25% to 75% domestic cereals, population 100-1000). For Çatalhöyük's Middle period (6700 to 6500 cal. BC) and a population of 2000 to 3000 people, 1,400,000 to 6,400,000 megajoules of cereals are required to sustain Çatalhöyük's population (25% to 75% reliance on domestic cereals. It should be noted that this diagram only presents the amount of ***direct*** *cereal energy received from Çatalhöyük; it does not include the amount of seed energy required for agriculture the next year.*

As populations grow, they require more energy to sustain themselves and extract more energy from their environment. Societies are dependent upon energy extraction, and Çatalhöyük is no exception. Referring to Figure 17, over time, the more that Çatalhöyük's population grows, the more energy from cereals required to sustain it. Moreover, within an agricultural society like Çatalhöyük, as population growth occurs, more land is also required. Thus, by using the amount of energy required from cereals to sustain Çatalhöyük, it is possible to determine the amount of land required to sustain Çatalhöyük's population by utilising the calorific values of crops and crops yields.

As crops differ by calorific value, yield, and crop processing, each crop's land requirements must be determined. This is an essential step for determining the energy of any agricultural system, as crops differ by these factors in addition to crop processing. Furthermore, it is possible that crop production levels differed from one household to another, as crop production is primarily dependent upon factors such as tilling and weeding, manuring, level of agricultural intensity, and even dietary preferences (Filipović, 2014: 142, Jones, Bogaard et al., 1999). Due to these variations[5], to determine the energy of agricultural processes, the land requirements for each crop will be treated separately. Originally, Cessford's (2005) population estimates of 3500-8000 had been used for population estimates at Çatalhöyük; however recent research has indicated that Çatalhöyük's population estimates at its peak were much lower in the range of 2500 ± 500 (Bernardini and Schachner, 2018, Cessford, 2005).. Therefore, this estimate is utilised in this thesis[6] and is used for this methodology (100, 500, 1000, 2000, 3000).

Based on archaeological data, the four most common domestic cereals identified at Çatalhöyük include free-threshing wheat, emmer, einkorn, and barley (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Charles, Doherty et al., 2014). As aforementioned, the NGW (new type glume wheat) appeared at Çatalhöyük during its Middle period and replaced emmer wheat by the Late period (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Russell and Bogaard, 2014). For the sake of modelling, and because we have no calorific or yield data on this NGW, this model will assume NGW is identical to emmer. Although the exact proportions of these cereals cannot be determined, this methodology assumes an even distribution (i.e., 1800 kcal, divided by 4) and holds the equal distribution in the diet as constant over time[7]. The calorific values of free-threshing wheat, barley, emmer (hulled wheat), and einkorn (hulled wheat) are presented in the table below.

Table 8 Calorific values of crops. The calorific values for crops are drawn from multiple, modern, and historical sources and presented in this table in kilocalorie value per kilogram. Barley has the highest calorific value, followed by einkorn, emmer, then free-threshing wheat. Sources of the kilocalorie values are also provided in the table below.

Crop	**Kilocalorie value per kilogram**	**Source**
Wheat	3100	(Filipović, 2014, Gregg, 1988, Ranhotra, Gelroth et al., 1996: 142)
Barley	3500	(United States Department of Agriculture, May 2016)
Emmer	3200	(Ranhotra, Gelroth et al., 1996, United States Department of Agriculture, May 2016)
Einkorn	3400	(Abdel-Aal, Hucl et al., 1995)

Barley has the highest calorific value, followed by einkorn, emmer, then wheat. These calorific values, in kilocalorie per kilogram, can be used to determine the amount of cereals needed to sustain Çatalhöyük's population and help determine the amount of land required to sustain Çatalhöyük based on a 25%-75% reliance on these four domestic cereals. The total amount of cereals required per year to sustain various population estimates is presented in Figure 18 below.

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[5] This variation in crop processing is more thoroughly discussed in succeeding sections.

[6] Originally, estimates and quantifications in this thesis were based on Cessford 2005 estimates, but after thorough discussion with Ian Hodder during the viva, these quantifications were updated to utilise Bernardini and Schachner 2018 population estimates of a maximum of 3000.

[7] This is simply for the sake of the model at hand, but this will be elaborated upon in the discussion.

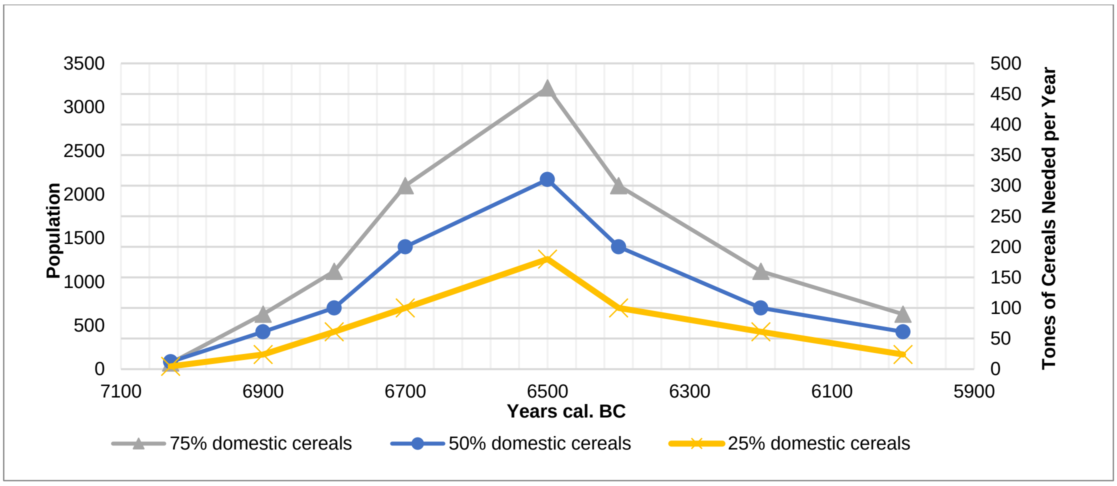

Figure 18 Tonnes of cereals needed per year based off Bernardini and Schachner (2018) Çatalhöyük population estimates (maximum of 3000 people). As Çatalhöyük's population grew over time, the total cereal requirement (total of free-threshing wheat, barley, emmer, einkorn) for Çatalhöyük over time is presented above. For a population of 1000 people, a minimum of 61 to 160 tonnes of cereals would have been required. For 2000 to 3000 people (6700 to 6500 BCE), a range of 100 tonnes to 300 tonnes of cereals would have been required.

Çatalhöyük's bioarchaeological data allowed for an accurate estimate of the average daily energy requirement for the population (Table 4, Table 7) and indicated that the population met its nutritional requirements; therefore, it is feasible to deduce that the Çatalhöyük had enough domestic cereals to sustain itself (Larsen, Hillson et al., 2015). Furthermore, now that the number of cereals needed per year has been calculated (Figure 18), the amount of land required can be determined based on crop yields.

Crop yields, presented as kilogram per hectare of land, allow for land requirement estimations for each crop. Although both the exact yields of Çatalhöyük crops and the precise fertility of Neolithic soils at Çatalhöyük are unknown, it is possible to make approximate calculations based on experimental and ethnographic yields. For this analysis, low, average, and high yield estimates, acquired from Gregg 1988, Halstead 2014, and Filipović 2014, were utilised. Since most of these crops would have been planted in the winter at Çatalhöyük, winter emmer and einkorn values are used instead of spring emmer and einkorn values (Fairbairn, Asouti et al., 2005). These values are presented in the table below; however, a brief explanation of Gregg's 1988 and Halstead's 2014 works is warranted.

Susan Alling Gregg's 1988 work, *Foragers and Farmers,* sought to identify Early Neolithic optimal farming strategies to understand the interaction between foraging and farming populations in the past. She developed a computer simulation to examine various resource combinations developed by drawing from ecological, ethnobotanical, and archaeological evidence (Gregg, 1988). The data within Gregg 1988's work includes various crop yield estimates, planting, harvesting, hunting, gathering activity times, and information about forager and farmer exploitation and resource use schedules and patterns. *Two Oxen Ahead* by Paul Halstead (2014) provides extremely detailed accounts of agricultural processing from his ethnographic field observations. Halstead 2014 provides data on agricultural tasks and a comparative approach to understanding current and past farming practices (Halstead, 2014).

Table 9 Low and High Yield Values of Crops (with sources and data descriptions when necessary). Low, average, and high yield estimates were utilised, acquired from historical and ethnographic sources from Gregg 1988, Halstead 2014, and Filipović 2014. The crop yield values in this table represent winter crops, as Çatalhöyük's domestic cereals would have been winter-planted as opposed to spring-planted. The source of yield values is provided in the table and when relevant, data descriptions.

Crop	**Low Yield (kg/ha)**	**High Yield (kg/ha)**	**Average Yield (kg/ha)**	**Source**	**Data Description**
Wheat	480	1000	740	Filipović 2014:141	Non-manured, continuously cropped; medium yields (comparable to experimental plots cultivated without manuring)
Barley	250	1000	630	Halstead 2014: 240-242	barley, poor land, continuously cropped plots
Emmer	860	1200	100	Gregg 1988; Source within: Statistisch-Topographisches Bureau 1850-1905	
Einkorn	700	970	840	Gregg 1988; Source within: Statistisch-Topographisches Bureau 1850-1905	

Based on the data above, the average yield for domestic crops at Çatalhöyük, based on the data above, is from highest to lowest: emmer, einkorn, free-threshing wheat, and barley. From these yields, it is possible to determine how much land was needed for each crop per year at Çatalhöyük. First, however, we must account for crop losses, processing and storage losses, and seed for the following year's planting. According to ethnographic, experimental, and human energetics requirements research, agricultural losses typically amount to an average of 50%; this includes 20% crop loss, 20% crop processing loss, and 10% seedcorn storage loss, and grain for seedcorn amounts to approximately 20% (Araus, Slafer et al., 2003, Bogaard, 2004, Halstead, 2014, James and Schofield, 1990, Steensberg, 1979, UNU, 2004). Therefore, an additional 70% is required to account for these losses for this analysis. Thus, the total amount of land, including accounting for losses, is presented below in Figure 19, demonstrating the land requirement for each crop, based on average yields and population estimates at Çatalhöyük.

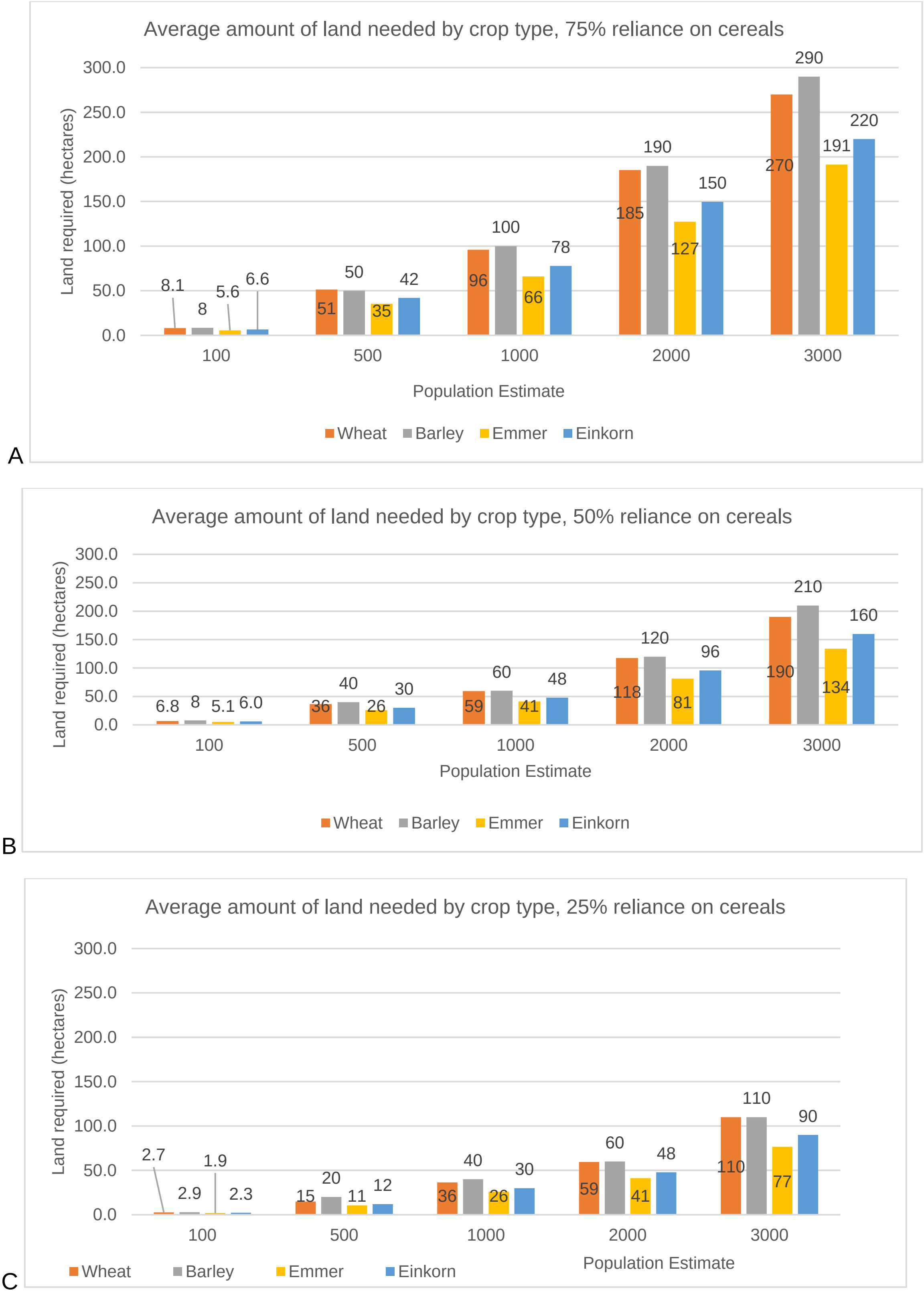

Figure 19: Amount of land required (hectares) required per year by crop type and according to population estimates and percentage of diet (A-75%, B-50%, C-25%). The higher the population and the higher the percentage of the diet, of course, the more land that is required to sustain agriculture. For all population estimates, free-threshing wheat, barley, and einkorn require the most land, whereas emmer requires the least amount of land.

Of course, more cereals are needed as Çatalhöyük's population grows, and, if the reliance upon domestic cereals is higher. Figure 18 and Figure 19 indicate this and emphasise the differences between the area of land needed by crop due to their differing yields. The higher the crop yield, the less land that is required. In energetic terms, the more energy the plant provides per hectare, the less land that is required. Einkorn and barley require the most land yearly, followed by free-threshing wheat; emmer requires the least land yearly. Table 10 below further emphasises this and demonstrates the amount of land required by yield, population, and percent reliance on domestic cereals. Again, the higher the crop yield, the less land that is required. The higher the reliance on domestic cereals, the more land that is required.

Table 10 Total land required to sustain Çatalhöyük's population according to yield and percent reliance on domestic cereals. Table A indicates the amount of land required for a 75% reliance on domestic cereals, Table B shows the amount of land needed for a 50% reliance on domestic cereals, and Table C provides the amount of land required for a 25% reliance on domestic cereals.

A. 75% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield (ha)	48	310	570	1100	1600
Average yield (ha)	29	180	340	650	1000
High yield (ha)	22	140	260	490	730

B. 50% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield (ha)	43	230	360	700	1200
Average yield (ha)	26	130	210	410	700
High yield (ha)	19	100	160	320	520

B. 25% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield (ha)	16	90	230	400	600
Average yield (ha)	10	60	130	210	400
High yield (ha)	7.4	40	100	160	290

Filipović 2014, based off archaeobotanical and ethnographic evidence, determined that a 5km radius would have been sufficient for agricultural production at Çatalhöyük. Filipović 2014 estimates were primarily based on average wheat values instead of more specific estimates of emmer, einkorn, free-threshing wheat, and barley, but they do provide a sound comparison for this analysis (Filipović, 2014: 141, table 7.8). For this analysis, a low-yielding scenario with domestic crops being 25% of the diet requires a radius of 0.3 to 1.4km, 50% requires a radius of 0.4 to 2.0km, and a diet of 75% cereals requires a radius of 0.4km to 2.3km. For average-yielding scenarios, a diet comprised of 25% domestic cereal requires a radius of 0.3km to 1.9km, a diet with 50% domestic cereals requires a radius of 0.3km to1.5km, and a diet of 75% cereals requires a radius of 0.3km to 2.8km. For high-yielding scenarios, a diet comprised of 25% domestic cereal requires a radius of 0.2km to 0.7km, a diet with 50% domestic cereals requires a radius of 0.3km to 1.0km, and a diet of 75% cereals requires a radius of 0.3km to 1.2km.

5.2.1 The Amount of Land Required to Sustain Çatalhöyük: Concluding Remarks

The land estimates above offer a sound baseline for land requirements to sustain Çatalhöyük. They are grounded by ethnographic data, experimental archaeological data, and, most importantly, Çatalhöyük's archaeological data. These land requirements also allow for determining the energy of the Çatalhöyük's agricultural processes, and thus, Çatalhöyük's agricultural system.

Although agriculture provides a way for humans to extract energy from the environment, it requires land and energy extraction from the land in order to do so. Therefore, access to land is a limiting factor in agricultural systems. Further, agricultural processes such as land clearance, tillage, planting, and harvesting are all dependent upon the land, are required to exploit agriculture's energy, and require energy to perform. In the remaining subsections of this chapter, the energy investment of these agricultural processes will be quantified. It will become increasingly clear that Çatalhöyük's Neolithic Agriculture system was energy-intensive.

By investing energy in agriculture, Çatalhöyük became more dependent upon it, and more and more energy was required to keep it going. By providing more energy, agriculture helped to facilitate population growth; however, this population growth also required more energy investment into agricultural processes from the Çatalhöyük peoples. As this occurred, within agriculture itself, agricultural processes simultaneously are dependent upon one another’s success. This develops a cycle of energy feedback and dependency, in which agriculture is only successful when its processes are successful; if any of the processes fail, the agricultural system itself fails.

To understand how this positive energy feedback cycle took place at Çatalhöyük, the energy investment in agricultural processes must be determined. In chapter 2, the lack of energy qualifications of agricultural processes, past and present, was noted as a significant problem. Quantifying and understanding agricultural processes is crucial, as it allows for understanding Çatalhöyük's agricultural energy system and better understandings of the mechanisms within the agricultural energy feedback system, i.e., energy and growth. Further, it is possible to compare agricultural processes on the same scale and understand the intricacies of Çatalhöyük's agricultural energy system. Therefore, the succeeding sections of this chapter focus on demonstrating how to quantify and will quantify the energy of pre-harvesting agricultural processes at Çatalhöyük. Harvesting and post-harvesting agricultural processes are the focus of chapter 6. In utilising archaeological, ethnographic, and experimental archaeological data and the energy methodology outlined in preceding sections, we can assess Çatalhöyük's past agricultural processes energetically.

5.3 LAND PREPARATION: LAND CLEARANCE

All agricultural processes require energy to perform. Quantifying the energy of agricultural processes and understanding their roles are both crucial to quantifying and understanding Çatalhöyük's agricultural energy system. Land clearance is the first step towards extracting energy from agriculture (Figure 16, Figure 20); thus, this chapter section focuses on quantifying the energy of land clearance at Çatalhöyük. Land clearance energy is quantified by utilising the energy methodology outlined in the preceding sections of this chapter, based on the Çatalhöyük land estimates (5.2) and archaeological, ethnographic, and experimental archaeological data.

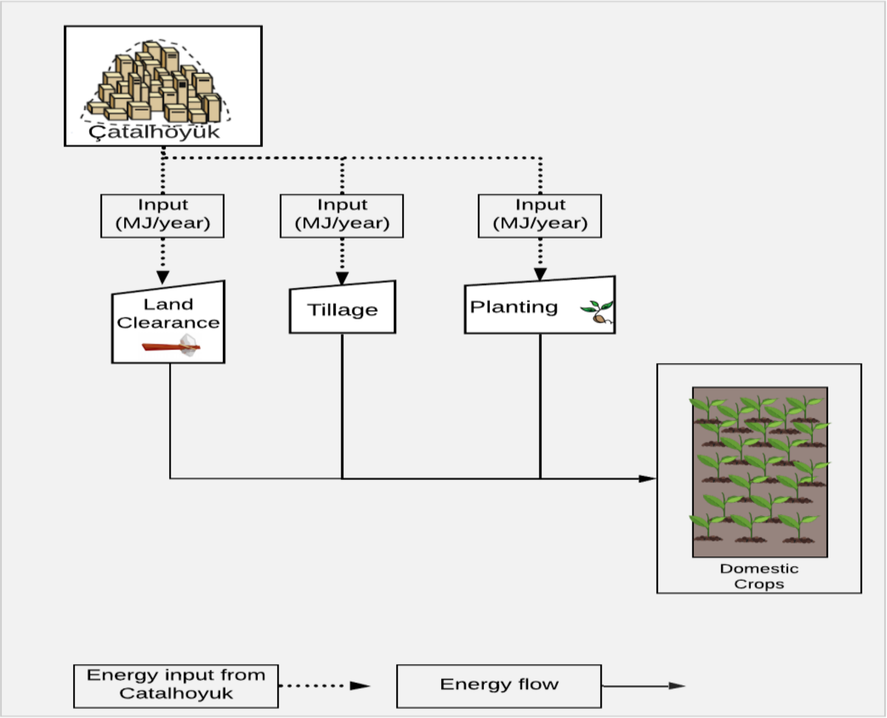

Figure 20 Land Clearance within Çatalhöyük's Agricultural Energy System. This figure demonstrates where land clearance, as an agricultural process, sits within Çatalhöyük's agricultural system. Land clearance is the first step that must occur prior to tillage and planting of domestic crops. Therefore, clearing land for agriculture is a requirement for agriculture to take place and requires an energy input from the Çatalhöyük peoples.

Land clearance includes clearing an area of land to remove boulders, rocks, and native vegetation cover—including trees, weeds, shrubbery, and roots—from the surface (Halstead, 2014: 312, Rappaport, 1971). Clearing native vegetation is crucial for agriculture, as it establishes a suitable soil bed into which seeds can be planted and crops successfully grow (Singh, Cattle et al., 2014). However, removing trees, bushes, stones, and weeds requires a significant energy investment; even today, land clearance is one of the most labour-intensive agricultural processes (Halstead, 2014: 312, Hillman and Davies, 1999: 91, Rappaport, 1971).

Although it is a required step, land clearance has many unintended and long-lasting consequences. Once agricultural land clearance takes place, it alters the environment for generations. More specifically, it "alters the quality and quantity of surface and ground water flows, quality of air, and fish and wildlife habitat," as well as "the physical condition of the topsoil… and nutrient cycling," to the point of no return (Singh, Cattle et al., 2014: 40). Land clearance completely transforms vegetation composition and structure, thereby altering the landscape upon which it takes place (Harris, 1989).

From an energy systems point of view, land clearance and subsequent agriculture indefinitely alter the energy systems of which they are a part. This aspect of land clearance emphasises the point that for humans to benefit from agriculture, they must invest energy into agricultural processes *and* alter the environment and its cycles—the hydrologic, soil, and atmospheric cycles. These consequences and changes in energy flows and systems occurred even from the onset of the "Agricultural Revolution," yet they have been undiscussed in archaeology and are absent from understandings of energy systems today. By quantifying the energy of land clearance, this chapter section will provide one piece of the puzzle in quantifying, modelling, and understanding the agricultural energy feedback system, understanding efficiency and allows for a mechanism to discuss the relationship between energy, settlement growth and subsistence pathways.

The succeeding sections of this chapter section offer a description of how the Çatalhöyük environment factors into land clearance quantifications, presents time investment required for Çatalhöyük's land clearance and how ethnographic, archaeological, and experimental archaeological data were used to determine these time estimates (5.3.1), and, the energy of Çatalhöyük's land clearance process is quantified (5.3.2).

5.3.1 Measuring time spent on land clearance at Çatalhöyük

Knowing and understanding Çatalhöyük's immediate and surrounding landscape is crucial to understanding and quantifying Çatalhöyük's land clearance energy. Çatalhöyük's regional and local environment was discussed in 3.2, and the amount of land required for agriculture to take place at Çatalhöyük was determined in section 5.2 (see Table 10). The land which would have been required to sustain agriculture at Çatalhöyük had to be cleared to remove boulders, rocks, and vegetation. Creating a suitable soil bed for seeds is crucial for crops to grow successfully. Removing trees, bushes, stones, weeds, and grasses had to occur and would have required a significant energy investment. To determine this energy investment ethnographic and experimental archaeological literature must be used to determine land clearance times.

As outlined in 4.4 time estimates are crucial to determining the energy required to agricultural activities, including land clearance. Archaeobotanical, ethnographic, and experimental archaeological data are sources that can aid in determining accurate land clearance estimates for Çatalhöyük. This chapter section will present how these data sources were used to quantify land clearance time estimates.

Land clearance itself depends on the type of land, soils, and vegetation that must be cleared. It is not possible to identify the exact type of land that would have been cleared for Çatalhöyük; however, we can utilise what is known about Çatalhöyük's environment (3.2) and ethnographic data on traditional (non-mechanised) agriculture to determine the time it would have taken for land to be cleared, and as a result, can determine the energy required to clear land for Çatalhöyük. Time estimates (Table 11) for land clearance were obtained from Halstead 2014's ethnographic accounts of non-mechanised land clearance and are presented below.

Table 11: Time estimates for land clearance with descriptions of the type of land clearance activity, the estimated time to perform the activity in hectares per day and hectares per hour, and references for the time estimates. These time estimates range from clearing young light woodlands, rocks, and undershrub, to felling trees and clearing overgrown fields.

Action	**Hectares/day**	**Hectares/hour**	**Source**
Manual labour: clearance of young, light woodland (roots, trees, rocks, etc.)	0.008	0.001	Halstead 2014: 47
Manual labour (general clearance)	0.02	0.002	Halstead 2014: 262
Manual labour: clearing rocks, shrubs, undershrub's	0.03	0.003	Halstead 2014: 265

Young adults clearing land manually	0.008	0.001	Halstead 2014: 260-261
Manually clearing and removing stumps in a wooded area	0.008	0.002	Halstead 2014: 261
Felling trees, removing useful wood, grubbing up stumps	0.006	0.0007	Halstead 2014: 262
Clearing an overgrown field	0.003	0.0004	Halstead 2014: 265
Stone removal by hand	0.05	0.006	Halstead 2014: 265
Average Clearance Time	0.02	0.002	

The time estimates in the table above range from clearing young light woodlands, rocks and undershrub to felling trees and clearing overgrown fields (Halstead, 2014). Although the tools used for land clearance were not specified, it is assumed that modern iron implements were used to accomplish these tasks—iron sickles, sheaths, shovels, axes, and hoes. Of course, at Neolithic Çatalhöyük, stone and wooden implements would have been used, especially sickles. Sickles are found all over Çatalhöyük and in various contexts; sickle elements, sickle handles, and other sickle tools have been identified from Çatalhöyük's earliest occupation levels (Atalay and Hastorf, 2006: 294, Carter, Conolly et al., 2005). Sickles[8] could have been used for clearing bushes, grasses, or even roots. Adzes and axes could have been used to help clear land, potentially to fell trees, clear stumps, undershrub, and light woodlands. Both are present throughout Çatalhöyük's archaeological assemblage, although adzes are rarer than axes (Baysal and Wright, 2005, Brady, 2020, Mellaart, 1967, Wright, 2013, Wright, 2014, Özbek, 2009). Most axes are made from a green diabase/dolerite/metabasalt, a hard, durable material (Wright, 2013: 383). Axes were commonly used and manufactured at Çatalhöyük, although they are rare before Level South K (Early period, "pre-peak", 7100-6700); during Çatalhöyük's Middle and Late Periods, however, they are quite common (Wright, 2013). Moreover, axe pre-forms are present in a range of houses, further indicating that axes and axe-making were "unspecialised" and "ubiquitous" throughout Çatalhöyük; in other words, Çatalhöyük households controlled their own axe production, and axes were not a prestige item (Wright, 2014: 413). Small axes and celts would be inappropriate for felling larger trees or shrubs; however, medium to larger sized axes, especially with having a Mohs hardness scale of 7, could have been used (Wright, 2013, Wright, 2014).

With regards to sickle use, ethnographic and experimental archaeological data on harvesting based on crop type and tools used (further discussed in 6.1.1) indicates that cutting via flint sickle, which would have also been utilised for clearing grasses and shrubbery, takes an average of 0.003 hectares per hour (Table 23). This estimate fits within the land clearance times provided in Table 11. Ethnographically, it has been documented that land clearance and harvesting are the more laborious and time-consuming agricultural processes (Halstead, 2014, Rappaport, 1971). These time estimates are similar to one another, which corresponds with this, therefore, these time estimates are appropriate for this analysis and methodology.

Regarding ethnographic and experimental archaeological data, it is worth taking note of the data from which the data in this chapter section derives. Steensberg's 1991 piece, *Hafting of a Stone Axe-Adze and Its Use in the Fire-Clearance Husbandry of Papua New Guinea,*

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[8] Sickles are more thoroughly discussed in section 6.1.1.

presented a detailed ethnographic account of the process of fire-clearance in Papua New Guinea, most important for this analysis, the process of creating, hafting a stone axe-adze for tree felling. For this analysis, the most crucial aspect was that it is feasible and possible for stone axe-adzes to fell trees (Steensberg, 1991). Further, Steensberg's work provides a detailed, ethnographic account of the process of hafting a stone axe, in which his informant Irari Hipuya utilised a hafted stone-axe to successfully fell a tree with a 17cm diameter in around 7 minutes (Steensberg, 1991: 240-241). Similarly, Mathieu and Meyer 1997's, *Comparing Axe Heads of Stone, Bronze, and Steel: Studies in Experimental Archaeology,* presented results from a thorough experimental archaeology project which investigated the efficiency of stone, bronze, and steel axes with tree type, tree diameter, axe type, handle length, blade width, and axe weight (Mathieu and Meyer, 1997). For trees less than 10cm in diameter, irrespective of the type of axe used, there was not a significant difference between the efficiency of the axes; once a tree reaches 20 centimetres or higher, however, there is a significant difference between stone, bronze, and steel axes (Mathieu and Meyer, 1997: 348-349). Although we cannot determine the exact diameter of every tree or root cleared at Çatalhöyük, because the differences in axe efficiency are only significant with trees more than 20 centimetres in diameter, the average land clearance time provided is a solid estimate for this analysis.

It should be noted that land clearance is very much a "one-off" agricultural activity, as in, it does not have to be completed every single year. In fact, ethnographic research indicates that once land is cleared, it does not usually have to be cleared for at least another decade (Halstead, 2014). Unless the family or the population needs more land, or, that plot of land becomes too overgrown, there is no need to "re-clear" the land (Halstead, 2014). Therefore, the presumption for land clearance at Çatalhöyük is, once the land was cleared once, this did not have to occur again. To prevent double accounting for land which had already been cleared, Çatalhöyük's land clearance hours (and energy) for 500 people *does not* include the land that would have already been cleared for 100 people, the land clearance quantifications for 1000 people does not include that of 500 people, and so on. Further, after Çatalhöyük's population declined in the Late to Final periods from 3000 to 500 people, it is assumed that land for 2000 and 1000 people did not need to be cleared again. This is to ensure that land is not double accounted. Thus, there was no land clearance required for a population of 2000 and 1000 people. However, there *would* be land clearance required for 500 people, as this amount of land is greater than what would have been left over from previous land clearances.

Having the average time needed for land clearance, it is now possible to determine how much time was required to clear land for Çatalhöyük. By dividing the average amount of land needed in hectares (Figure 19, Table 10) by the land clearance time in hectares per hour, the land clearance time in hours can be quantified. These quantifications are presented in the tables below and based on various crop yields.

Table 12 Land Clearance Hours Required at Çatalhöyük. Time dedicated to land clearance depended upon the scale of population growth, crop yield, and percent reliance on domestic cereals. The smaller the population, the less additional land that must be cleared and thus, the less time which must be dedicated to land clearance; the larger the population, the more land that must be cleared and thus, more time must be dedicated to land clearance. Furthermore, with low-yield scenarios, more land must be cleared. For high-yield scenarios less land must be cleared. The higher the reliance on domestic cereals, the more land that must be cleared. Finally, for this model, there was no land clearance required for a population of 2000 and 1000 people. However, land clearance was required for a population of 500 people, as this amount of land is greater than what would have been available from previous land clearances.

A. 75% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500

Low yield	25000	140000	140000	270000	270000	0	0	160000
Average yield	15000	76000	83000	160000	160000	0	0	90000
High yield	11000	60000	61000	120000	120000	0	0	69000

B. 50% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500
Low yield	22000	95000	66000	180000	240000	0	0	120000
Average yield	13000	54000	39000	110000	140000	0	0	70000
High yield	9900	41000	32000	81000	100000	0	0	50000

A. 25% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500
Low yield	8700	36000	71000	66000	150000	0	0	40000
Average yield	5100	24000	38000	39000	92000	0	0	29000
High yield	3700	17000	30000	32000	67000	0	0	21000

Table 13 Extra land required to sustain Çatalhöyük's population: For this model, it is assumed that once land is cleared, it does not have to be cleared again. Therefore, for a population of 100 people, the initial land required to be cleared ranges from 7.4 to 48 hectares, depending on yield and percent reliance on domestic cereals.

A. 75% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500
	Initial land required (ha)	Extra land required (ha)						
Low yield	48	260	260	530	500	0	0	260
Average yield	29	150	160	310	350	0	0	150
High yield	22	120	120	230	240	0	0	120

B. 50% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500
	Initial land required (ha)	Extra land required (ha)						
Low yield	43	190	130	340	500	0	0	190
Average yield	26	100	80	200	290	0	0	100
High yield	19	80	60	160	200	0	0	80

C. 25% reliance on domestic cereals

Population	100	500	1000	2000	3000	2000	1000	500
	Initial land required (ha)	Extra land required (ha)						
Low yield	16	74	140	170	200	0	0	74
Average yield	10	50	70	80	190	0	0	50
High yield	7.4	33	60	60	130	0	0	33

Referring to Table 12, Çatalhöyük, with a 75% reliance on domestic cereals would have had to dedicate 11,000 to 270,000 hours to land clearance. With a 50% reliance on domestic cereals, land clearance hours would range from 9,900 to 240,000 hours, and, with a 25% reliance on domestic cereals, land clearance hours required range from 3700 to 150,000 hours. As Çatalhöyük's population grows, more land must be cleared. Again, the presumption for land clearance at Çatalhöyük is, once the land was cleared once, this did not have to occur again. The land being cleared for 500 people *does not* include the land that would have already been cleared for 100 people; the land cleared for 1000 people does not include that of 500 people, etcetera. Therefore, the larger the population jump, the more land that must be cleared, as further demonstrated by Table 13. On the other hand, after Çatalhöyük's population decline during its Late and Final Periods, for this model, there is no land clearance energy required for a population of 2000 and 1000 people, as this amount of land was already cleared during its peak population.

Initially, at a population of 100, 16 to 48 hectares are required for low yields, 10 to 29 hectares of land are required for average yields, and 7 to 22 hectares of land are required within high yield scenarios. When Çatalhöyük's population reaches 500, a jump of 400 people, an additional 74 to 260 hectares are required for low yields, 50 to 150 hectares for average yields, and only 33 to 120 hectares with higher yields. When Çatalhöyük's population reaches 2000, a jump of 1500 people, more land is required to be cleared: 170 to 530 hectares (low), 70 to 160 hectares (average), and 60 to 260 hectares for high yields. With a population of 3000 people, at minimum 130 hectares to 500 hectares are required for Çatalhöyük's population. Finally, land clearance is not required again until Çatalhöyük's population decreases back to 500 people, where 33 to 260 hectares are required depending on the yield scenario and how much of the diet is reliant on domestic cereals. Land clearance depends on the population at hand, how much of the diet is reliant on cereals, and crop yield. With low-yields, more land is needed and more time must be dedicated to clearing it, whereas with high-yields, less land is needed. Further, when there is a lower reliance on domestic cereals, less land is required. With 3000 people, Çatalhöyük's maximum population estimate, the amount of land required is quite significant, even with a 25% reliance on domestic cereals.

Land clearance is a laborious and time-consuming activity. Ethnographically, land clearance can actually take several years for individuals to complete:

> "the task facing each household varied greatly, as did the workforce: some men worked alone others with grown sons or brothers, and sometimes groups of neighbours collaborated…those dependent on household labor took several years [to clear plots of land]…. Anestis' father single-handedly brought into cultivation about 0.3 ha per year, taking 11 years to clear 3 hectares" (Halstead, 2014: 263).

Land clearance is heavily dependent on the labour force, how much time is available, the state of the plot of land (heavily overgrown, trees needing to be felled, for example), seasonality workload, and even travel time to and from plots of land (Halstead, 2014). Therefore, before determining Çatalhöyük's land clearance energy, a brief discussion on how the physical activity ratio of land clearance was determined must occur.

As aforementioned, land clearance includes clearing boulders, rocks and native vegetation such as trees, weeds, bushes, from the ground surface (Halstead, 2014: 312, Rappaport, 1971). Therefore, the PAR of land clearance is, and should be, a compilation of activities related to land clearance. The PAR values used for Çatalhöyük's land clearance were calculated from an average of multiple, land clearance related PARs. This is presented below in Table 14.

Table 14: Physical Activity Ratios utilised to determine the average Land Clearance Physical Activity Ratio. Activities include digging, land clearing, bending and digging, cutting trees, digging the ground, hoeing (as in, earthing up root crops and weeding or clearing root stumps), and clearing shrubbery and dry grass. The average PAR for all of these activities is 5.7, therefore, this is the PAR for land clearance for this analysis.

Activity	**Physical Activity Ratio Value**	**Reference**
Digging	5.7	(Vaz, Karaolis et al., 2005)
Land Clearing	6.2	(Vaz, Karaolis et al., 2005)
Bending/Digging	4.7	(Vaz, Karaolis et al., 2005)
Dig ground	5.5	(Vaz, Karaolis et al., 2005)
Cut tree	5.4	(Vaz, Karaolis et al., 2005)
Dig ground	5.0	(Vaz, Karaolis et al., 2005)
Hoeing, short spade for earthing up root crops and weeding/clearing root stumps	4.3	(Vaz, Karaolis et al., 2005)
Tree felling	8.0	(Vaz, Karaolis et al., 2005)
Clearing shrub and dry grass	6.3	(Vaz, Karaolis et al., 2005)
Digging	5.6	(UNU, 1985, UNU, 2004)
Digging	5.7	(UNU, 1985, UNU, 2004)
Land Clearance Çatalhöyük (average PAR)	***5.7***	

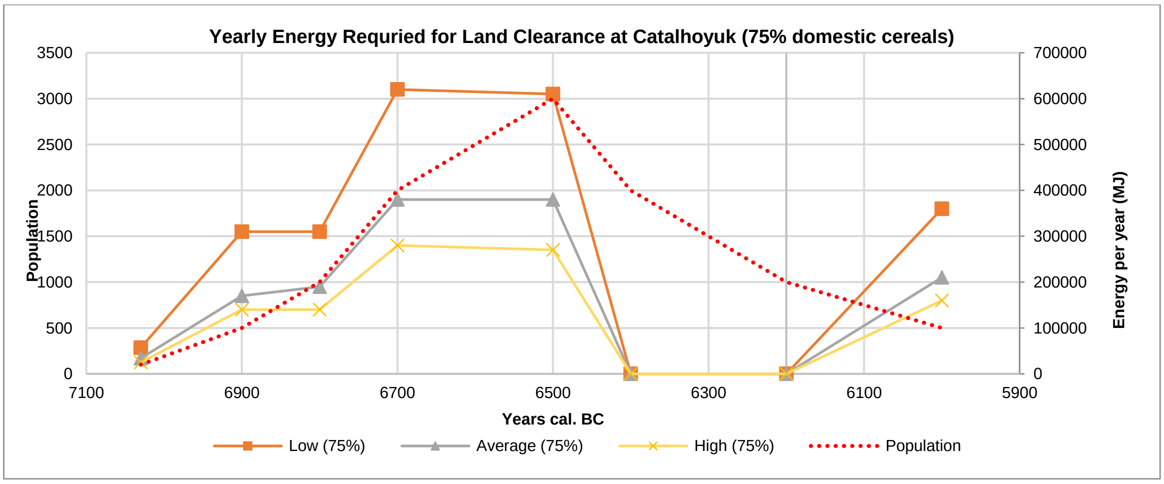
The PARs for land clearance related activities range from 4.3, which includes hoeing, earthing up root crops and weeding or clearing root stumps, to as large as 8.0 for tree felling (Vaz, Karaolis et al., 2005). As there is no way to determine the exact land clearance activities taking place at Çatalhöyük, utilising the average of these activities is the most appropriate way forward.

Having calculated the amount of time land clearance required, it is now possible to quantify Çatalhöyük's land clearance energy by multiplying the average basal metabolic rate (Table 2), the physical activity ratio of land clearance (Table 5, Table 14), and the time allocated for clearing land (Table 12). Land clearance energy is presented and discussed below.

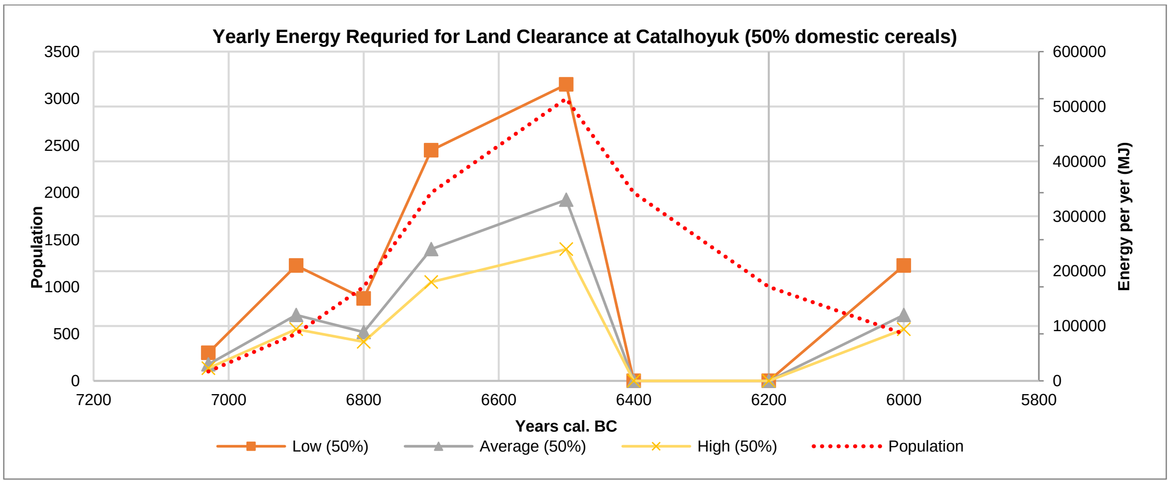
5.3.2 Land Clearance energy

By drawing from Çatalhöyük's geomorphological, paleoenvironmental, archaeobotanical, zooarchaeological, and stable isotopic research (chapter 3) it was determined that Çatalhöyük's diverse environmental landscape would have allowed for agriculture to take place along with herding, hunting, fishing, and gathering (3.2). Section 5.3.1 utilised ethnographic, experimental, archaeological, and Çatalhöyük's stone tool data to determine an appropriate time estimate for land clearance. This allowed for determining a baseline for land clearance time in hours. With this, it is now possible to quantify Çatalhöyük's land clearance energy. To determine the energy of clearing land, we must multiply the average basal metabolic rate (Table 2) with the physical activity ratio of land clearance (Table 5, Table 14) and the time allocated for clearing land (Table 12)

Referring to Figure 21 A, Çatalhöyük would have had to devote 25,000 to 620,000 megajoules of energy to land clearance, assuming a 75% diet reliant upon domestic cereals. Figure 21 B shows, assuming a 50% diet reliant upon domestic cereals, that Çatalhöyük would have had to devote 23,000 to 540,000 megajoules of energy to land clearance. Finally, Figure 21 C indicates Çatalhöyük's land clearance energy with a 25% reliance upon domestic cereals would have required 9000 to 340,000 megajoules of energy. Concerning the shapes of the figures, the peaks and valleys reflect the additional land required based on population and yield, as previously explained in Table 10, Table 12 and Table 13. Land clearance, in essence, scales with the rate of population growth. When the rate in population growth is less than one, Çatalhöyük's population must invest less energy into land clearance the next year than for the previous year. When the rate in population growth is greater than one, the opposite occurs: Çatalhöyük's population invests *more* energy into land clearance than the previous year. However, after Çatalhöyük's population decline, the Çatalhöyük peoples would not have had to dedicate energy to land clearance again until they reached a population of 500. Figure 21 also demonstrates that land clearance is also dependent upon yield yields; with low-yields more land is needed to grow crops, and thus more land must be cleared overall, whereas with high-yields, less land is needed to grow crops and therefore less land is cleared, and less energy input is required. Thus, overall, the more people there are and the more land that is needed, the more energy the Çatalhöyük population must dedicate to clearing that land. Further, the higher the reliance on domestic cereals, the more energy that must be dedicated to sustaining agriculture. Once Çatalhöyük reaches 3000 people regardless of the reliance of domestic cereals, land clearance requires a substantial amount of energy from Çatalhöyük's population.



A



B

C:

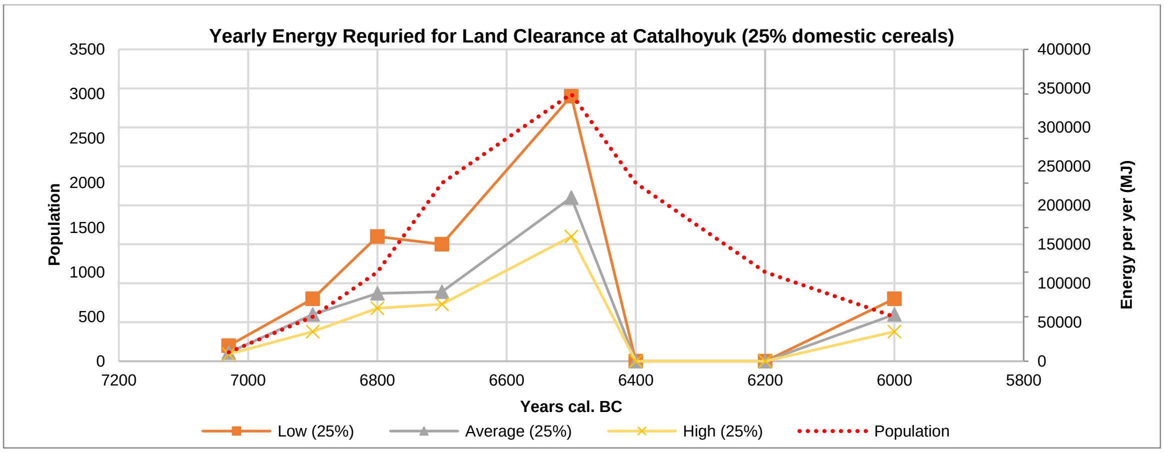


Figure 21 Land Clearance Energy Required for Çatalhöyük in Megajoules per year: Figures A, B, and C energy input for land clearance which would have been required to sustain agriculture at Çatalhöyük, for low, average, and high yielding crops laid upon Çatalhöyük's population growth over time (dotted line). More specifically, figure A presents the energy input with a diet based on 75% cereals. Figure B indicates the energy input for land clearance with a diet based on 50% domestic cereals. Finally, figure C shows Çatalhöyük's input for land clearance, with a diet based on 25% cereals. With a diet more reliant upon domestic cereals, more energy is required to sustain agriculture. Further, energy input into land clearance by Çatalhöyük would have depended upon the scale of population growth, and crop yield. The smaller the population jump, the less additional land that must be cleared and thus, the less energy which must be input to land clearance; the larger the population jump, the more land that must be cleared and thus, more energy must be dedicated to land clearance. Furthermore, with low crop yields, more land must be cleared. For high yields, less land must be cleared.

As land clearance is only the first "step" in Çatalhöyük agriculture, the energy of additional agricultural processes must be determined to understand the system in its entirety.

5.4 TILLAGE : "THE BACKBREAKING TOIL OF MANUAL CULTIVATION"

Tilling, tillage, or manual ploughing, includes mixing topsoil and subsoil layers by stirring, overturning, and digging soil; examples of tilling include picking, shovelling, hoeing, and raking soils before planting (Halstead, 2014, Pollock, 2002: 15, Van Alfen, 2014: 143). The act of mixing and overturning soil helps to break down soil structure, stimulates the mineralisation of organic matter, and accelerates leaf litter decomposition, thereby modifying soil texture, structure, and aiding in fertility (Harris, 1989, Van Alfen, 2014: 143, 191). Tillage allows for the soil to absorb water more easily, helps limit soil erosion, integrates stubble straw or leaf litter, thereby enrichening the soil, aerates the soil, destroys weeds, and decreases the chances of insect infestation (Halstead, 2014: 261-268, Van Alfen, 2014: 101, 202). By mixing leaf litter and soil layers, the seedbed for planting crops improves, which makes for successful planting (Halstead, 2014: 261).

Figure 22 below demonstrates that tillage is one of the earlier steps within Çatalhöyük's agricultural system. Tillage often takes place after land clearance but, prior to planting crops. By providing an adequate seedbed and aiding in structure and fertility, tillage is an essential step in agriculture, and the rest of the agricultural process is dependent upon it. If tillage is inadequate, successful planting cannot occur; if planting is unsuccessful, then the harvest, too, is unsuccessful; tillage is, in sum, crucial to agriculture.

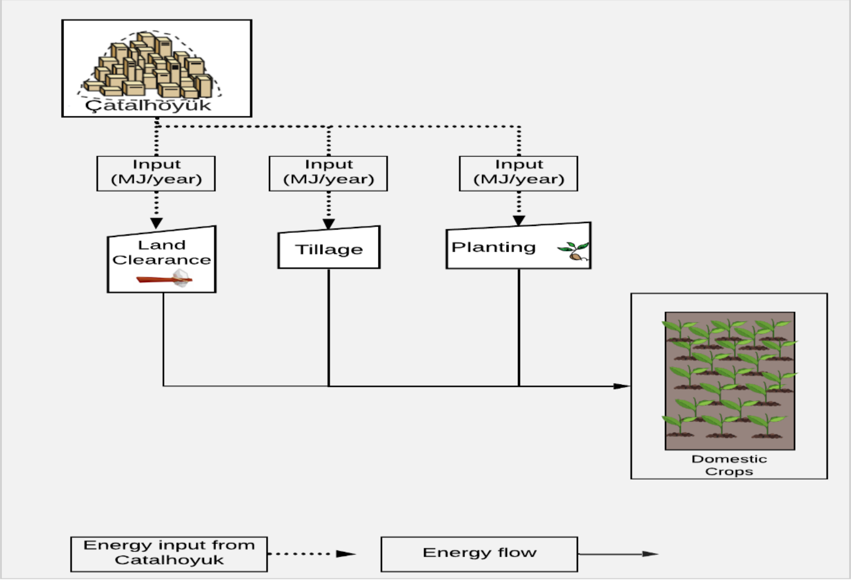


Figure 22 Tillage within Çatalhöyük's Agricultural Energy System. This figure demonstrates where tillage, as an agricultural process, sits within Çatalhöyük's agricultural system. Tillage takes place after land clearance but prior to the planting of domestic crops. Tillage is crucial to agriculture and must take place to ensure plants have an adequate seedbed in which to grow. Tillage also requires an energy input from the Çatalhöyük peoples for it to take place.

The timing of tillage is also important for agriculture's success, as it depends on weather and ground conditions (Halstead, 2014: 46). The ground cannot be too hard and dry, or too soft and wet; tillage must occur after it rains, but not after a heavy rain, and must be completed before the ground freezes (Bogaard, 2004: 142, Halstead, 1987). Ill-timed tillage can be a significant problem, as it creates soil conditions hostile for crop growth (Halstead, 2014: 46). If tillage is unsuccessful, agricultural processes that follow it will also be unsuccessful.

Similar to land clearance, tillage is a required step with unintended and long-lasting consequences, especially if done incorrectly or too often. Some of the longer-term issues with tillage include exposing topsoil to wind and water erosion, recompacting topsoil, reducing the strength and trafficability of soil, especially if it is too wet, disruption of macrofauna (i.e. earthworms), an overall decrease in soil microbial life and organic matter, and quick soil carbon release (Halstead, 2014: 46-47, 261-268, Van Alfen, 2014: 101, 191-193, van den Akker and Soane, 2005). Thus, the potential for damage caused by tillage is great, and, overall, the entire soil cycle and the hydrologic cycle is altered as a consequence of tilling.

For this analysis, tillage is quantified by utilising the energy methodology outlined in this chapter's preceding sections, based on the Çatalhöyük land estimates, and archaeological, ethnographic, and experimental archaeological data. The succeeding subsections this chapter offer a description of how tillage would have taken place at Çatalhöyük and the time investment required for Çatalhöyük's tillage, all of which will be supported by archaeological, experimental archaeological, and ethnographic data.

5.4.1 Measuring time spent on tillage at Çatalhöyük

Archaeobotanical, ethnographic, and experimental archaeological data are sources which can aid in determining tillage estimates for Çatalhöyük. This chapter subsection presents how these data sources, in addition to the energy methodology previously outlined, are used to quantify tillage time estimates.

Çatalhöyük archaeobotanical evidence (i.e. taxa present, weed flora, and flowering data) indicates that most Çatalhöyük crops would have been autumn-sown and were "intensively cultivated, permanent, dry" fields (Fairbairn, Asouti et al., 2005, Filipović, 2014: 132-133). Çatalhöyük's agricultural system was based upon manual cultivation and "productive conditions were probably maintained to varying degrees by thorough tillage, hand-weeding, and manuring (with sheep dung) and/or middening" (Bogaard, Ater et al., 2019: 105). To have intensively cultivated fields, the people of this early hoe-farming society had to adequately till soils. Even today, intensive cultivation requires thorough tillage and even weeding (Filipović, 2014, Halstead, 1987). Tillage at Çatalhöyük would have been hand tilled or manually tilled.

Manual tillage is laborious and takes a significant amount of time; even ethnographic accounts attest to this, "tribulations of the plowman paled into insignificance alongside the backbreaking toil of manual cultivation" (Halstead, 2014: 47). Land cultivated manually "depends on the number of workers, the strength of the manual laborers, much like that of draft animals… They're liable to seasonal variation especially if nutritional standards are low" (Halstead, 2014: 46). Thus, tillage is heavily dependent upon labour force, especially a healthy one. Tillage also depends upon the soil type, how wet or dry it is, what season it takes place, and the implement being used to till (Halstead, 2014).

Stone, wooden, bone, and antler implements could and would have been used for tillage at Çatalhöyük (Bogaard, 2004). In fact, a quartzite hoe, similar to those in other Neolithic sites, has been identified at Çatalhöyük, and the Çatalhöyük team is positive that it is indeed a stone hoe (Milner, Hammerstedt et al., 2010, Wright, 2013: 403). This quartzite hoe was found along with a perforated basalt weight (a possible digging stick weight), which together have been interpreted as a farmer's toolkit (Wright, 2013). Hoes have also been found within other houses at Çatalhöyük, even though they make up only a small percentage of the site's stone tool assemblage (Wright, 2013). Tillage tools do not necessarily have to be stone hoes, but instead can be long, heavy sticks, digging sticks, or even wooden paddle spades (Steensberg, 1976: 45-46). Furthermore, hand tillage with an antler or wooden hoe works just as well as small-scale ard ploughing (Bogaard, 2004: 142). Therefore, it was feasible for Çatalhöyük peoples to till plots of land with either stone, antler, or wooden implements.

Regardless of tool type, although manual tilling is laborious, it is feasible for a household to survive on manually tilled fields (Halstead, 2014: 47). Ethnographic research has indicated that tillage by hand is "time consuming and laborious" but the results are "very satisfactory" (Hajnalová and Dreslerová, 2010: 176). One of the reasons why tillage takes so much labour is that a plot of land must be tilled multiple times prior to planting. Recently cleared land must be tilled at least three times to break up soil clods, before seeds are planted (Halstead, 2014, Hillman, 1984). Typically, for fields being used for agriculture, there is a first tillage to "break" or "cut" the stubble, followed by two more tills before planting: one to mix fertiliser or leaf litter, and another to set the seedbed (Halstead, 2014: 34). Accounts from Rome suggest four tillage events, one of which does not always need to occur but instead depends on whether or not a field is fallow (Halstead, 2014: 34). Ethnographic research in Anatolia has also shown that tillage must occur at least two to three times before planting (Hillman, 1984: 116). Although there is no way to delineate how many times tillage would have taken place at Çatalhöyük or whether some fields were left to fallow, for this analysis, it is postulated that tillage was completed 3 times, regardless of whether it would have been recently or previously cleared land.

Having designated how many times land would have been tilled at Çatalhöyük, the amount of time that hand tillage would have taken can be determined. Time estimates for hand tillage are available from ethnographic sources and utilised for this analysis; in this case, Halstead 2014's ethnographic accounts of non-mechanised tillage are utilised and presented in Table 15 below.

Table 15: Time estimates for tillage with descriptions of the type of tillage activity, the estimated time needed to perform the activity in hectares per hour, and references for the time estimates. The estimates range from general hand tillage, hand tillage with a flint sickle, hand tillage variability in soils and a composite workforce, from Mesopotamia texts on hoeing, and 19th century Greece using a mattock or hoe.

Action	**Hectares/hour**	**Source**
Hand tillage, general	0.002	Halstead 2014: 118
Hand tillage with a flint sickle	0.004	Halstead 2014: 118
Hand tillage estimate, given variability in soils and composite work force	0.002	Halstead 2014: 41
Mesopotamia texts, hoeing	0.0016	Halstead 2014: 41
19th century Greece, using a mattock/hoe	0.004	Halstead 2014, Psikkogios 1987: 34
Average Clearance Time	0.003	

Referring to the table above, the tillage activities range from general hand tillage, hand tillage with a flint sickle, ethnographic accounts of hand tillage, and even tillage using a mattock or hoe in 19th century Greece. Tillage time estimates range from a minimum of 0.0016 to 0.004 hectares per hour; the average of these, 0.003, was utilised for this analysis. Although the tools used for tillage were not always specified, the average tillage time utilised here (0.003 hectares per hour) is not significantly different from hand tillage with a flint tool. Further, experimental archaeological research indicates that even chert hoes can be used effectively with tillage, digging, and excavating, as long as the soils are not too rocky (Milner, Hammerstedt et al., 2010). Therefore, these tillage rates are adequate for quantifying the tillage requirement for Çatalhöyük. The required tillage time in hours is presented in Table 16 below.

Table 16: Tillage Hours required based on Çatalhöyük population and crop yield: As Çatalhöyük's population increases, time dedicated to tillage also increases, i.e., tillage scales with population. Regarding crop yield, low yielding crops require more tillage time, as more land is required to grow enough crops to sustain Çatalhöyük's population. Conversely, high yielding crops require less tillage time, as less land is required to grow crops to sustain Çatalhöyük's population.

A: Tillage Hours required for a diet based on 75% cereals

Population	100	500	1000	2000	3000
Low yield	96000	630000	1100000	2200000	3300000
Average yield	69000	390000	660000	1300000	1800000
High yield	45000	280000	510000	990000	1500000

B: Tillage Hours required for a diet based on 50% cereals

Population	100	500	1000	2000	3000
Low yield	87000	450000	800000	1400000	2400000
Average yield	60000	300000	400000	800000	1300000
High yield	39000	200000	330000	630000	1000000

C: Tillage Hours required for a diet based on 25% cereals

Population	100	500	1000	2000	3000
Low yield	33000	180000	500000	700000	1200000
Average yield	24000	120000	270000	400000	800000
High yield	15000	80000	180000	330000	600000

Table 16A demonstrates that with a diet comprised of 75% domestic cereals, Çatalhöyük had to dedicate 45,000 to 3,400,000 hours to tillage. Table 16B indicates the amount of tillage hours required for a diet comprised of 50% cereals, which was 39,000 to 2,400,000 hours. Table 16C demonstrates that with a diet comprised of 25% domestic cereals, Çatalhöyük had to dedicate 15,000 to 1,200,000 hours to tillage. Overall, as Çatalhöyük's population grows, more and more land must be tilled, depending upon labour force and yield; more people require more resources and more land. Further, the amount of land needed also depends upon yield; with low yields, more land is needed to grow crops for Çatalhöyük's population and therefore must be tilled, whereas with high yields, less land is needed to grow crops to sustain Çatalhöyük, and therefore, less land must be tilled. Unlike land clearance, tillage must take place every year. Thus, for Çatalhöyük’s population growth from 500, 1000, to 2000, tillage hours would be the same when its population decreased. In other words, tillage for 500, 1000, and 2000 people is the same regardless of if it occurs during Çatalhöyük’s growth or decline, as the amount of land required to sustain these population numbers would not have changed, according to this model.

Tillage is a laborious and time-consuming activity. It is heavily dependent upon labour force, time available to till, the types of soils at hand, and the time of year it takes place. Tillage also includes activities such as raking, hoeing, and full-on digging. Therefore, before proceeding on to determine Çatalhöyük's tillage energy, a brief discussion on how the PAR of tillage was determined must take place.

As mentioned, tillage includes hoeing, stirring, overturning, and digging the soil, including the physical actions of picking, digging, and hoeing. Therefore, the PAR values used for Çatalhöyük's tillage were calculated from an average of multiple tillage-related PARs. These are presented below in Table 17.

Table 17: Physical Activity Ratios utilised to determine the average tillage PAR. Tillage activities which would have taken place at Çatalhöyük include ploughing, bending while digging, hoeing, and standing whilst hoeing. The average PAR for all of these activities is 5.1, therefore, this is the designated PAR for tillage in this analysis. It should be noted that ploughing in this case is not machine-based ploughing; it is manual ploughing, by hand and with tools.

Activity	**Physical Activity Ratio Value**	**Reference**
Ploughing	6.14	(Vaz, Karaolis et al., 2005)

Ploughing	5.17	(Vaz, Karaolis et al., 2005)
Ploughing	5.79	(Vaz, Karaolis et al., 2005)
Ploughing	5.4	(Vaz, Karaolis et al., 2005)
Ploughing	6.9	(Vaz, Karaolis et al., 2005)
Bending/Digging	4.7	(Vaz, Karaolis et al., 2005)
Hoeing	3.59	(Vaz, Karaolis et al., 2005)
Hoeing	4.87	(Vaz, Karaolis et al., 2005)
Hoeing	6.48	(Vaz, Karaolis et al., 2005)
Hoeing	4.75	(Vaz, Karaolis et al., 2005)
Hoeing	4.57	(Vaz, Karaolis et al., 2005)
Standing, Hoeing	4.66	(Vaz, Karaolis et al., 2005)
Hoeing	3.6-4.6	(UNU, 1985, UNU, 2004)
Hoeing	4.2	(UNU, 1985, UNU, 2004)
Hoeing	4.5	(UNU, 1985, UNU, 2004)
Hoeing	4.7, 4.7-6.5	(UNU, 1985, UNU, 2004)
Tillage Çatalhöyük (average PAR)	***5.1***	

The PAR for tillage related activities ranges from 3.6 for hoeing, to 6.9, for ploughing (UNU, 1985, UNU, 2004, Vaz, Karaolis et al., 2005). In the table above, ploughing refers to hand-ploughing or manual ploughing, not machine-based ploughing or animal-based ploughing. As there is no way to designate the exact tillage activity taking place at Çatalhöyük, utilising the average of these activities is the most appropriate way forward; therefore, for this analysis, the tillage PAR utilised is 5.1.

Having calculated the average tillage rate and average PAR for tillage, it is now possible to quantify Çatalhöyük's tillage energy by multiplying the hours required for tillage, the average basal metabolic rate (Table 2), and the PAR of tillage (Table 5, Table 17), and the time allocated for tillage (Table 16). Tillage energy is presented and discussed below.

5.4.2 Tillage Energy at Çatalhöyük

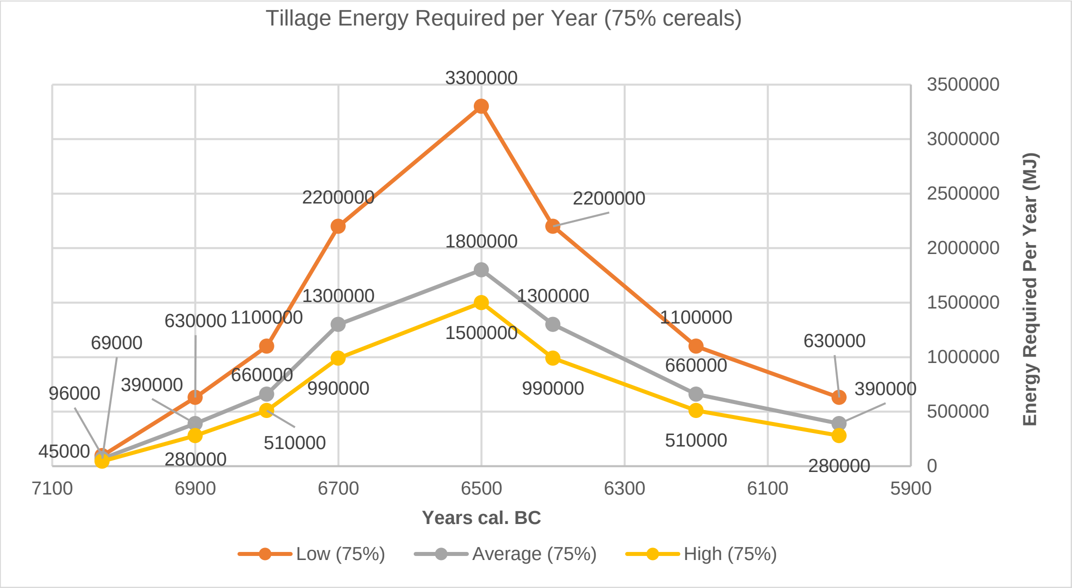
From an energy systems point of view, tillage is required for agriculture to take place; it indefinitely alters the energy system of which it is a part and requires energy to perform. The act of tillage again emphasises the point that for people to benefit from agriculture, they must invest energy into agriculture whilst altering the environment. Such consequences and changes in energy flows and systems occurred even from the onset of the "Agricultural Revolution," yet they have been undiscussed at Çatalhöyük and within archaeology more generally and are absent from our current understandings of energy systems. By quantifying the energy of tilling at Çatalhöyük, this chapter subsection will provide one aspect of quantifying, modelling, and understanding Çatalhöyük's agricultural system, the agricultural energy feedback system at Çatalhöyük, and allows for a mechanism by which to discuss the relationship between energy, settlement growth, and subsistence pathways.

It has been established throughout this subsection that tillage is an essential aspect of agriculture, as many other agricultural processes depend upon it. If tillage is inadequate, successful planting cannot occur; if successful planting cannot occur, then a successful harvest is impossible. Section 5.4.1 established tillage rate, the time required for tillage at Çatalhöyük, and the PAR of tillage by utilising experimental archaeological data, ethnographic data, and Çatalhöyük's own archaeobotanical and stone tool data. This chapter subsection also demonstrated that manual tillage was indeed possible at Çatalhöyük. Overall, tillage is a time consuming and laborious process; therefore, it is expected that it will require a significant amount of energy to perform. To determine the energy of tillage at Çatalhöyük, the average basal metabolic rate (Table 2), the physical activity ratio of tillage (Table 5, Table 17) and the time allocated for tillage must be multiplied. Before tillage energy can be quantified, however, a brief discussion on manuring must take place.

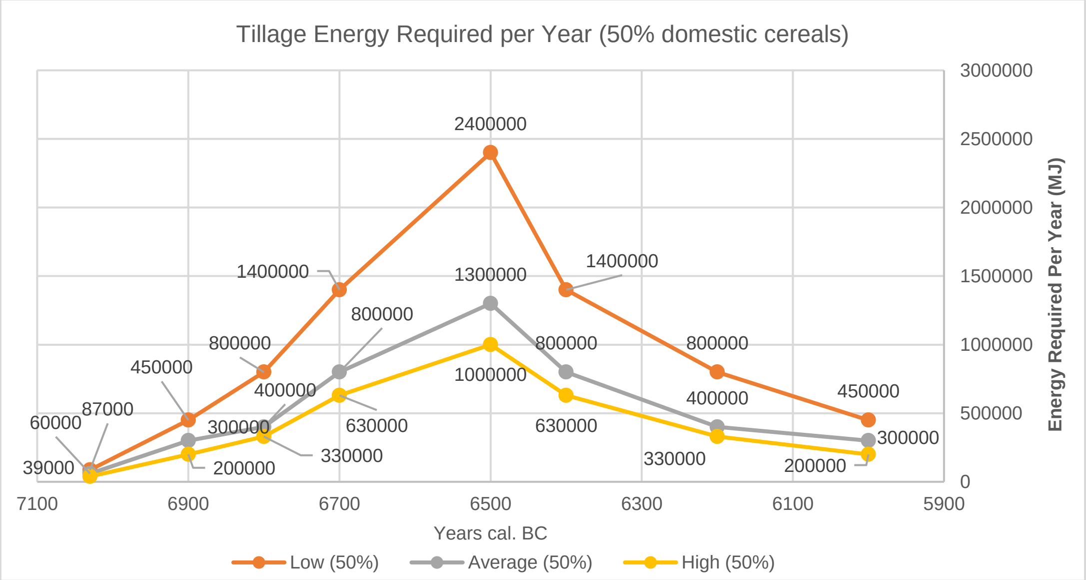
The tillage calculations in this analysis do not account for manuring, but it is the hope that one day, it will. At Çatalhöyük, It is possible that caprine dung helped to fertilise Çatalhöyük crops, especially in the form of herding on stubbled fields (Bogaard and Isaakidou, 2010). There is ample evidence of the use and presence of animal dung throughout Çatalhöyük, especially as a fuel in the form of dung cakes (Fairbairn, Near et al., 2005, Filipović, 2014: 1, 121, 145 , Rosen, 2005). Evidence of manure as fertiliser, however, is harder to come by. Intensive coring data throughout Çatalhöyük indicates that nitrogen levels do increase throughout Çatalhöyük's occupation, which could be interpreted as the result of onsite penning, manuring, and middening (Ayala, Wainwright et al., 2017). However, it could also be due to other environmental reasons, for example, Ayala et al. 2017 explains that the drying and rewetting of soils, due to a change in river channel for example or changes due to clay extraction both would kill microbes, thereby raising nitrogen levels (Ayala, Wainwright et al., 2017). Therefore, for this analysis, manuring is not included. Further, it is also feasible that manure was not required at Çatalhöyük. Tillage aids significantly in fertilising the soil, especially in that it overturns leaf litter. Leaf litter on its own can often act as a sort of "manure," enriching the soil whilst also preventing weed growth (Halstead, 2014). Halstead's ethnographic work in Greece found that yields for fields without manure but alternating fallow had high yields for 3-5 years and where trees left thick leaf mould, high yields lasted for a decade (Halstead, 2014: 262-265). Unlike manure from animals, which facilitates weed growth due to animals consuming weeds or tracking them in, leaf litter *inhibits* weed growth and adequately fertilises the soil (Halstead, 2014: 262). Finally, although manually cultivated fields require more labour they often have better and more consistent yields (Bogaard, 2004, Halstead, 2014: 268). Therefore, for this analysis, manuring is not included. However, if manuring was included, this may require less tilling because it may provide higher yields, therefore, the energy input of tillage would decrease, rather than increase.

Referring to Figure 23, Çatalhöyük would have had to dedicate 45,000 to 3,300,000 megajoules of energy per year to tillage, with a diet comprised of 75% domestic cereals. With a diet comprised of 50% domestic cereals, Çatalhöyük would have had to dedicate 39,000 to 2,400,000 megajoules of energy per year to tillage. With a diet of 25% domestic cereals, Çatalhöyük would have had to dedicate 15,000 to 1,200,000 megajoules of energy per year to tillage. As Çatalhöyük grows over time, more land must be tilled to plant and grow crops, and therefore, Çatalhöyük must dedicate more energy to tillage. Further, the more Çatalhöyük's diet is reliant upon domestic cereals, the more energy it must dedicate to agriculture's processes; tillage is a sure indicator of this. Further, tillage scales directly with population and is dependent upon yield. More land must be tilled with low-yields, as low yields require more land to grow, whereas, with high-yields, less tillage is required, as less land is needed to grow crops. Overall, the more Çatalhöyük grows, the more land Çatalhöyük needs, the more land that must be tilled, and the more energy that must be dedicated to tilling that land to sustain agriculture.

A:


Tillage Energy Required per Year (75% cereals)
3300000
2200000
2200000
1800000
1300000
1300000
630000
1100000
1100000
69000
1500000
660000
660000
630000
990000
990000
96000
390000
390000
510000
510000
45000
280000
280000
7100
6900
6700
6500
6300
6100
5900
Years cal. BC
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
Energy Required Per Year (MJ)
Low (75%)
Average (75%)
High (75%)

B:


Tillage Energy Required per Year (50% domestic cereals)
2400000
1400000
1300000
1400000
800000
800000
800000
800000
450000
1000000
400000
400000
87000
450000
60000
300000
630000
630000
300000
39000
200000
330000
330000
200000
7100
6900
6700
6500
6300
6100
5900
Years cal. BC
3000000
2500000
2000000
1500000
1000000
500000
0
Energy Required Per Year (MJ)
Low (50%)
Average (50%)
High (50%)

C:

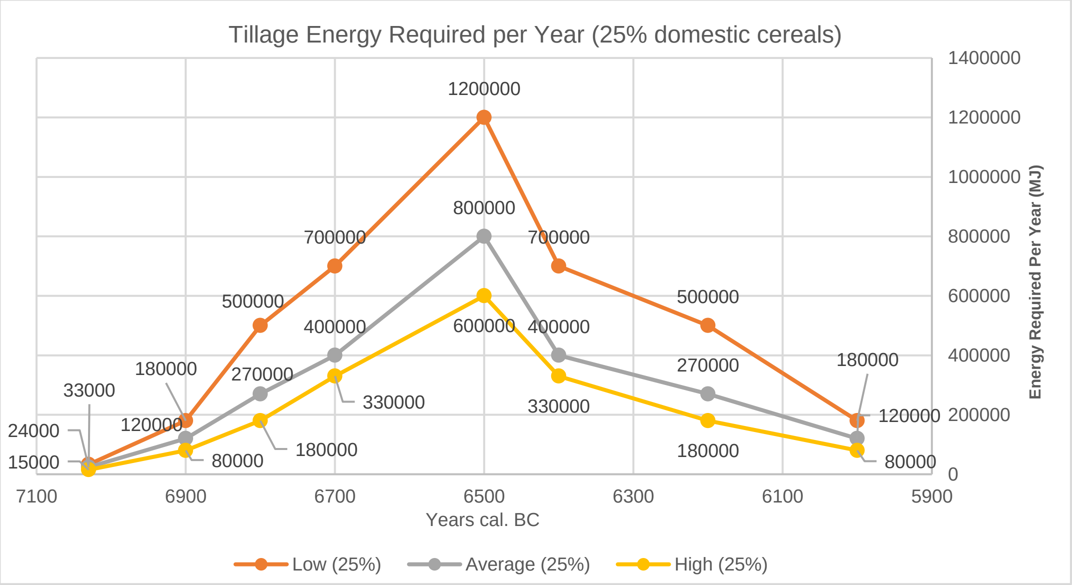

Tillage Energy Required per Year (25% domestic cereals)
1200000
800000
700000
700000
500000
500000
400000
600000
400000
33000
180000
270000
270000
180000
330000
330000
24000
120000
120000
15000
80000
180000
180000
80000
7100
6900
6700
6500
6300
6100
5900
Years cal. BC
1400000
1200000
1000000
800000
600000
400000
200000
0
Energy Required Per Year (MJ)
Low (25%)
Average (25%)
High (25%)

Figure 23 Tillage Energy Required for Çatalhöyük in Megajoules per year. Figure A represents tillage energy required with a 75% reliance on domestic cereals, Figure B represents tillage energy required with a 50% reliance on domestic cereals, Figure C represents tillage energy required with a 25% reliance on domestic cereals. Each figure shows the energy input for tillage which would have been required to sustain agriculture at Çatalhöyük, for low, average, and high yielding crops. Tillage energy scales with population. As Çatalhöyük's population grows, more land is needed to keep it sustained; therefore, more land must be tilled. Further, with low crop yields, or poor soil fertility, tillage energy is very high. This is because if crops are low yielding, more land is needed to plant more crops to sustain Çatalhöyük. For high yields, tillage energy is lower. High yielding crops require less land, and therefore, less land is required to keep Çatalhöyük sustained. Finally, the higher the reliance upon domestic cereals, the more land that needs to be tilled, as more land is required to sustain the diet.

Comparing land clearance to tillage, tillage is around 1.5 to 5.5 times more energy-intensive than land clearance, depending upon the yield and percentage of diet (Figure 21 A-C). Although both land clearance and tillage depend on labour force, population, yield, and both include digging or hoeing, land clearance is not an activity that occurs every single year or multiple times per year. That is, land clearance is a "one-off" activity; once the land is cleared, it does not have to be cleared for at least another decade (Halstead, 2014). On the other hand, tillage must occur at least three times throughout the year (Halstead, 2014, Hillman, 1984). Once to "break" or "cut" the stubble from either the previous year's crop or recently cleared land, followed by two more tills before planting: one to mix fertiliser or leaf litter, and another to set the seedbed (Halstead, 2014: 34). This must occur for recently cleared land as well as the land upon which crops are grown. Furthermore, although tillage has a lower PAR than land clearance, due to it occurring three times throughout the year, it is, overall, more energy intensive than land clearance.

5.5 PLANTING/SOWING

Planting, otherwise known as sowing, is the act of inserting seeds into the soil via hoeing or digging to allow them to germinate and grow. Sowing the crop is one of the most critical tasks. The timing of sowing is pivotal as seeds must be sown before freezing sets in for autumn-sown crops or when the ground begins to thaw for spring-sown; otherwise, yields are low or worse, the crop fails (Russell and Bogaard, 2014: 65-66). To plant seeds, seedcorn must be prepared in advance. Preparing seedcorn for the next year's crop in and of itself is a process: "not only do people have to prepare storage locations, they also have to orient their lives to gather and process the foods into a storable form" (Hastorf, 2017: 107). Figure 24 below demonstrates the planting and seed storing process.

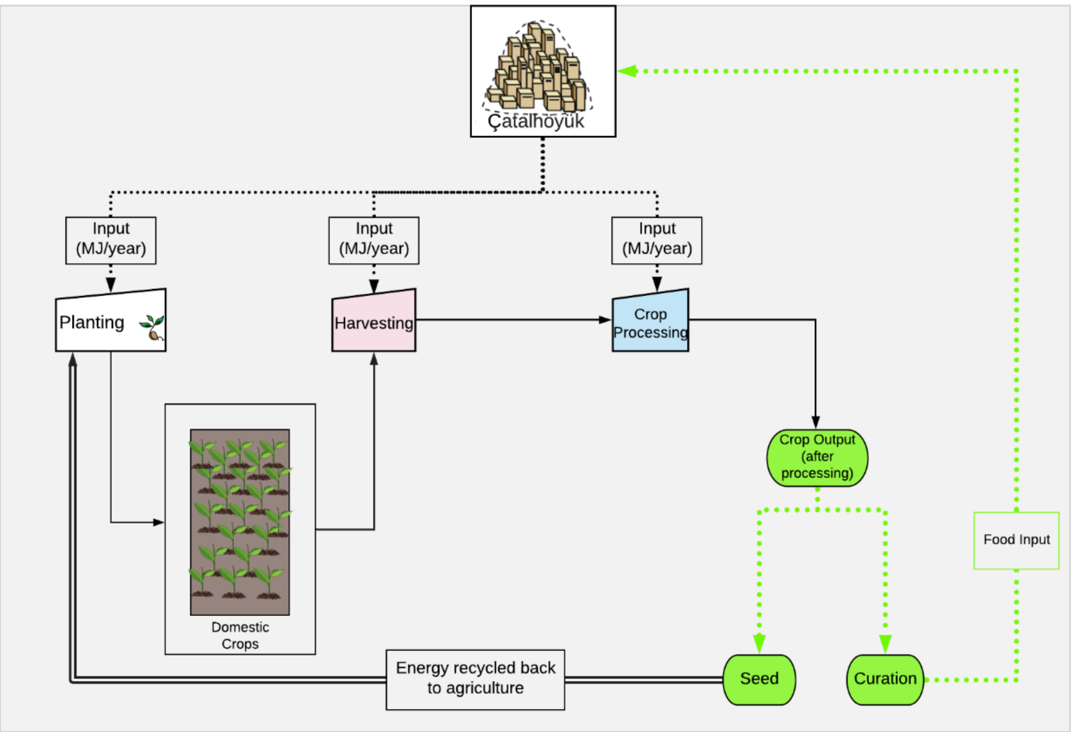


Figure 24 Planting and Seed Storage within Çatalhöyük's Agricultural Energy System. This figure demonstrates where planting and seed storage, as agricultural processes, take place within Çatalhöyük's agricultural energy system. Planting itself requires energy input from the Çatalhöyük population in addition to requiring the successful storage of seeds. Once a crop is harvested, the crop must be semi-processed before it is stored as seed. Once seedcorn is prepared and stored, the energy of the stored seedcorn does not go directly to Çatalhöyük's population, but instead, is recycled back in to Çatalhöyük's agricultural system to sustain agriculture. This aspect of planting emphasises the agricultural feedback cycle, especially in that for humans to benefit from agriculture, they must continuously invest energy into its agricultural processes for agriculture to occur. This also emphasises the point that agricultural processes are dependent upon one another's success. Successful planting cannot occur unless there is adequate tillage or a successful harvest to produce the next year's seedcorn. Similarly, a successful harvest cannot take place unless there is successful planting and seedcorn storage.

Once a crop is harvested, the crop must be, for hulled species, threshed and winnowed prior to storage, and for free-threshing species, must be threshed, winnowed, and sieved before it is stored as seed (further discussed in section 6.2). In order to store seedcorn, unlike grain for food, seedcorn grain cannot be dehusked (pounded or ground), as it makes it unviable for planting (Halstead, 2014: 138). For this model, once the seedcorn is prepared and stored, the energy of the stored seedcorn does not go directly to Çatalhöyük's population, but instead, is recycled back into Çatalhöyük's agricultural system to sustain agriculture. This aspect of planting emphasises the agricultural energy feedback system.

Although typically thought of as simply putting seeds into the ground, overall, the act of planting is far more complicated and entangled with other agricultural processes. If crop yields are too low or crops fail, there may not be enough seedcorn for the next year's crop. If the seedcorn is processed incorrectly or inadequately stored, there could be limited to no seedcorn for the following year's crop, thereby affecting the next year's crop and food output. Planting is one of the agricultural processes upon which other agricultural processes are dependent and vice versa. This demonstrates another aspect of the agricultural energy feedback system, especially regarding dependency: agricultural processes depend upon the success of other agricultural processes. One simply cannot have a successful harvest without successful, viable seedcorn and successful planting. Harvesting, storage, curation, and agriculture are inherently dependent upon viable seedcorn and successful planting. Agriculture's processes, including planting, are dependent upon one another's success. Therefore, determining the amount of energy planting requires and how much seedcorn is required to sustain Çatalhöyük are key aspects quantifying, modelling, and understanding Çatalhöyük's agricultural system, the agricultural energy feedback system at Çatalhöyük, and will allow for a mechanism by which to discuss the relationship between energy, settlement growth, and subsistence pathways.

Çatalhöyük archaeobotanical evidence such as the arable taxa present, weed flora, and flowering information, indicates that most Çatalhöyük crops would have been autumn-sown and were "intensively cultivated, permanent, dry" fields (Fairbairn, Asouti et al., 2005, Filipović, 2014: 132-133). In order to have permanent, intensively cultivated fields for annually sowed crops, it is a requirement for Çatalhöyük peoples to have adequate supplies of seed corn (Russell and Bogaard, 2014: 64). Therefore, determining the planting energy and amount of seedcorn is a key aspect of determining the baseline energy requirements for Çatalhöyük's agricultural system.

To determine the energy of planting and seedcorn requirements, we must account for the method of planting seedcorn (i.e., broadcasting, dibbling, and/or row-sowing), the storage required for seedcorn and the storage available at Çatalhöyük. This is discussed throughout 5.5.1, which relies heavily upon previously quantified land requirements, cereal requirements, BMR, PAR, and Çatalhöyük's archaeological and archaeobotanical evidence. Section 5.5.2 discusses how ethnographic resources and experimental archaeology research were utilised to determine seeding rates. Section 5.5.3 presents the energy of Çatalhöyük's planting and seed storage and concludes the planting energy subsection.

5.5.1 Seedcorn and storage at Çatalhöyük

Although we cannot pinpoint the exact method by which Çatalhöyük peoples sowed crops, it is still possible to make sound inferences and quantify Çatalhöyük's planting energy and seedcorn requirements by utilising ethnographic data, experimental archaeology, and archaeological data. Regarding planting method, for traditional non-mechanised agriculture, there are three primary ways of sowing seeds: broadcasting, dibbling, and row-sowing (i.e., furrowing) (Gregg, 1988, Halstead, 2014, Steensberg, 1979). These planting methods differ by efficiency, amount of seed needed, land, sowing season, and even affect weed growth (Halstead, 2014). Definitions, these differences, and how these were applied to Çatalhöyük to inform seedcorn and storage requirements are discussed throughout this subsection.

There are multiple ways to plant seeds. Broadcasting is the act of tossing the seeds densely over a field by hand (Halstead, 2014: 28). Dibbling is the act of sowing by dropping seeds into small holes and covering the seeds with soil using a foot or a tool (Halstead, 2014: 28-29). Row-sowing is completed by digging a lengthwise trench and covering the seeds with soil using a foot or tool (Halstead, 2014: 28-29). Both dibbling and row-sowing require less seed than broadcasting, ensure an even seed distribution, and cover the ground more reliably than broadcasting (Halstead, 2014: 28-30, 263). Dibbling and row-sowing are more efficient than broadcasting as they require less seed and allow for higher seed-yield ratios (Bogaard, 2004: 29). However, dibbling and row-sowing allow for more space between the plants, thereby facilitating weed growth that may out-compete crops and lead to lower yields (Halstead, 2014: 30). Row-sowing is the norm for summer crops, whereas broadcasting is more typical of autumn-sown crops (Halstead, 2014: 28-29). Ethnographically, dibbling is typically only practised by hand on small plots of land up to 34m^{2,} whereas broadcasting is typically practised, in traditional agriculture, on larger fields from 0.1 to 0.2 hectares (1000-2000m^2) (Halstead, 2014: 29). Broadcasting helps prevent weed growth and is the quickest method of sowing (Halstead, 2014: 28-29).

Dibbling, row-sowing, and broadcasting rates vary regarding the amount of seed needed per hectare, otherwise known as the seed yield or seed yield ratio (Evans, 1993). The seed yield ratio is defined as "the product of the number of grains per unit land area and the average grain weight" (Araus, Slafer et al., 2003: 684). The seed yield ratio is the amount of seed needed to plant per unit of land area, and this ratio differs depending on how seeds are planted and the yield of the crop (Araus, Slafer et al., 2003, Evans, 1993). For this analysis, low, average, and high crop yields were quantified for emmer, einkorn, free-threshing wheat, and barley (Table 9); however, it is impossible to pinpoint the seed ratio based on crop yield for Çatalhöyük's crops. Therefore, for this analysis, the seed yield ratio is based upon the type of planting. For dibbling and row-sowing, the seed yield ratio is usually 10:1; in other words, only 10% of the seed produced must be used for planting the following year (Bogaard, 2004, Halstead, 1987, Halstead, 1990, Halstead, 1995, Sigaut, 1975, Sigaut, 1988). For broadcasting, this ratio is typically 5:1, or 20% of the seed produced must be used for planting the next year (Bogaard, 2004). In his experiments on Neolithic agriculture, Steenberg's seed yield ratios were 20:1, which is quite high (Bogaard, 2004, Steensberg, 1979). Others have used much lower seed-yield ratios and applied them to past agricultural contexts (see Table 18), closer to 3:1, 4:1, or 5:1 (Bogaard, 2004: 41). Although broadcasting is the most likely method of planting, weeds are present throughout the Çatalhöyük bioarchaeological assemblage, which could suggest dibbling or row-sowing(Filipović, 2014).

Ethnographically, the ways einkorn, emmer, wheat, and barley are planted depends on the yield, what the crop is used for (i.e., fodder or human sustenance), and even on the family's preference; both Halstead and Ertuğ-Yaras works heavily emphasise this (Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000, Halstead, 2014). It is simply unfeasible to determine how individual crops could have been planted, based on individual needs or wants, for Çatalhöyük. Therefore, this model assumes that the planting process of einkorn, emmer, free-threshing wheat, and barley is the same. The average of broadcasting, dibbling, row-sowing and lower seed-yield ratios, equal to 20%, is used for this analysis (Table 18, below). In other words, no matter what the population is, 20% of the grain produced is saved per year. This is a constant in this energy model.

Table 18: Percentage of Seed to be Stored for the Next Year's Crop. The table below presents the seeding ratio, the percentage of seed to be saved, and the reference from which these ratios and percentages came. For this analysis, the average of these ratios, 20% of the seed to be saved as seedcorn to plant the next year's crop, was used.

Ratio	% of seed to be saved	Reference
5:1	20	Araus et al. 2003; Bogaard 2004
3:1	33	Bogaard 2004
4:1	25	Bogaard 2004
10:1	10	Araus et al. 2003; Bogaard 2004
Average used for this analysis	20	Average of the above

Applying the 20% of grain saved as seedcorn to Çatalhöyük's cereal requirement calculations, the amount of seed required to plant the next year's crop at Çatalhöyük to sustain itself with a 75%, 50% and 25% reliance upon domestic cereals is presented below. With a 75% reliance upon domestic cereals, 2,600 (population 100) to 92,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19, A).

With a 50% reliance upon domestic cereals 2,400 (population 100) to 62,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19,B). Finally, with a 25% reliance on domestic cereals, 920 kilograms (population 100) to 36,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19, C)

Table 19: Amount of cereals (kg) needed for the following year's crop at Çatalhöyük, and storage requirements. This table presents the amount of cereals that would have needed to be stored for the following year's crop, based on population and crop type. It also presents the total seedcorn required for Çatalhöyük and the storage required per household, based on a 75% (A), 50% (B), and 25% (C) reliance upon domestic cereals.

A: 75% reliance on domestic cereals

Population	**100**	**500**	**1000**	**2000**	**3000**
Wheat (kg)	700	4600	16000	24000	40000
Barley (kg)	620	4000	14000	22000	35000
Emmer (kg)	680	4400	16000	24000	38000
Einkorn (kg)	640	4200	15000	22000	36000
Total required (kg)	2600	17000	32000	61000	92000
Total seedcorn storage required (litres)	2600	17000	32000	61000	92000
Storage required per household	100	140	130	120	120

B: 50% reliance on domestic cereals

Population	**100**	**500**	**1000**	**2000**	**3000**
Wheat (kg)	640	3200	5200	10000	16000
Barley (kg)	580	2800	4600	9200	14000
Emmer (kg)	620	3200	5000	10000	16000
Einkorn (kg)	580	3000	4800	9400	16000
Total required (kg)	2400	12000	20000	39000	62000
Total seedcorn storage required (litres)	2400	12000	20000	39000	62000
Storage required per household	96	96	80	78	83

C: 25% reliance on domestic cereals

Population	**100**	**500**	**1000**	**2000**	**3000**

Wheat (kg)	240	1200	3200	5200	10000
Barley (kg)	220	1200	2800	4600	8000
Emmer (kg)	240	1200	3200	5000	10000
Einkorn (kg)	220	1200	3000	4800	8000
Total required (kg)	920	4800	12000	20000	36000
Total seedcorn storage required (litres)	920	4800	12000	20000	36000
Storage required per household	37	38	48	40	48

Typically, to determine storage capacity, one would determine the average size of individual grains to determine the density to backtrack storage capacity requirements (Araus, Slafer et al., 2003). Unfortunately, that is simply not possible to determine at Çatalhöyük or for many archaeological sites (Araus, Slafer et al., 2003). The only way to complete this would be by determining the individual seed grain weight from archaeobotanical assemblages; even this is an issue due to the burning of seeds, which reduces seed weight and other preservation issues (Araus, Slafer et al., 2003). However, assuming a one-to-one ratio of kilograms to litres, it is possible to estimate storage requirements for seed storage. With a 75% reliance upon domestic cereals, 2,600 (population 100) to 92,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19, A). With a 50% reliance upon domestic cereals 2,400 (population 100) to 62,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19,B). Finally, with a 25% reliance on domestic cereals, 920 kilograms (population 100) to 36,000 kilograms (population 3000) of cereals had to be stored to plant the next year's cereals (Table 19, C).

Although it is an overestimation, applying this rate, all of the seedcorn would have required an average of 37 litres (25% reliance on domestic cereals)-140 litres (75% reliance on domestic cereals) of storage per family (assuming five people per household). Having determined the amount of storage that would have been necessary for Çatalhöyük's seedcorn, we must now assess whether this seedcorn could have been stored within Çatalhöyük households. Storage was required at Çatalhöyük for intensive cultivation on annually sowed, permanent plots to take place and there is ample, direct evidence of storage at Çatalhöyük. It was indeed possible for Çatalhöyük peoples to adequately store this amount of seedcorn whether this was a 75%, 50% or 25% dietary reliance on domestic cereals, with 20% of produced seed being stored for planting the next year.

Although there is no evidence of communal plant storage at Çatalhöyük, there is evidence of small-scale permanent and moveable storage within Çatalhöyük houses (Bogaard, Charles et al., 2009, Filipović, 2014: 133, Twiss, Bogaard et al., 2009). Every excavated building at Çatalhöyük contains some sort of permanent storage, and some buildings even have direct evidence of additional storage containers such as wood, reed, or hide baskets (Cessford, 2007, Farid, 2007, Hastorf, 2017: 113, Mellaart, 1963). For example, in building 52, space 93 has a row of mud bins that adjoin two walls with evidence of barley, peas, almonds, and wheat in addition to animal bone and horn tools (Bogaard, Charles et al., 2009, Hastorf, 2017: 114). In another building, building 5, space 157 was lined with six bins with thick clay packing, which would have helped keep out mice and insects (Atalay and Hastorf, 2005, Atalay and Hastorf, 2006, Bogaard, Charles et al., 2009, Hastorf, 2017). In one of these bins was a mix of wheat and barley covered with woven mats; in front of another bin, wheat phytoliths were present (interpreted as spillage or grain retrieval), and there were other domestic plants, processing tools, and female clay figurines present (Atalay and Hastorf, 2005, Atalay and Hastorf, 2006, Bogaard, Charles et al., 2009, Hastorf, 2017: 114-115).

Most of the direct evidence of storage at Çatalhöyük includes permanent storage in the form of clay bins, many of which were lined with lime plaster (Atalay and Hastorf, 2006, Bogaard, Charles et al., 2009, Hastorf, 2017, Russell and Bogaard, 2014). If only the bin volumes of the permanent clay bins are included in determining storage space, the average storage capacity is just over 1000 litres per household, although it should be noted that the storage range for houses at Çatalhöyük spans from several hundred litres to over 2000 litres (Bogaard, Charles et al., 2009, Russell and Bogaard, 2014: 70). These storage estimates also correspond with local ethnographic estimates of stored plant staples kept by families over one year, including the number of cereals for everyday consumption (Russell and Bogaard, 2014: 70). Halstead's ethnographic accounts also emphasise that one family requires 1000 to 1500 kilograms of grain per year, which would require 1300 to 3000 litres of dry storage; a domestic storage facility in Crete stored up to 2200 litres of grain which farmers stated would allow for 1 to 2 years of grain for a family (Halstead, 2014: 162-163). Overall, ethnographic data indicates that with regards to seedcorn storage, 1000 litres to 2000 litres is more than enough storage. For Çatalhöyük, this is only the minimum estimated amount of storage, as perishable containers and roof space are omitted from these Çatalhöyük storage estimates. In fact, there are phytolith traces of both basketry and matting, which indicate using perishable containers within and outside of the bins (Russell and Bogaard, 2014: 70). It is likely that more storage space was possible (Araus, Slafer et al., 2003, Bogaard, Charles et al., 2009, Russell and Bogaard, 2014: 70). Grain could have easily been stored outside of bins, including on the roof or hanging from the roof inside of animal skins, for example (Atalay and Hastorf, 2006, Hastorf, 2017). In sum, there was plenty of permanent and moveable storage space for Çatalhöyük peoples to utilise to store both domestic cereals and wild plant products.

Now that the amount of seedcorn required to sustain Çatalhöyük's agricultural practises has been calculated and both ethnographic and Çatalhöyük archaeological data confirm seedcorn storage availability, the energy of planting itself can be quantified. Before proceeding on to determine Çatalhöyük's planting energy, however, a brief discussion on how the physical activity ratio of planting was determined must occur.

There are multiple ways in which seeds can be planted, therefore, the PAR of planting is a compilation of planting activities. The PAR values used for Çatalhöyük's planting energy were calculated from an average of multiple planting PARs which is presented below in Table 20.

Table 20: Physical Activity Ratios utilised to determine the average planting PAR. Although there is no PAR specifically for planting wheat and barleys, the average PAR for a range of crop plantings was used for this analysis. The description of the activity, the PAR, and the reference are provided in the table below. The average PAR of these planting activities is 3.7; therefore, this is the designated PAR for planting in this analysis.

Activity	**Physical Activity Ratio Value**	**Reference**
Bending planting potatoes	4.13	(Vaz, Karaolis et al., 2005)
Planting Rice	3.96	(Vaz, Karaolis et al., 2005)
Planting Rice	4.96	(Vaz, Karaolis et al., 2005)

Planting Manioc	3.18	(Vaz, Karaolis et al., 2005)
Planting Maise	4.14	(Vaz, Karaolis et al., 2005)
Planting Root Crops	3.69	(Vaz, Karaolis et al., 2005)
Planting Ground Nuts	3.13	(Vaz, Karaolis et al., 2005)
Planting Fruit Crop	3.1	(UNU, 1985, UNU, 2004)
Planting Rice Crop	3.7	(UNU, 1985, UNU, 2004)
Planting Rice Crop	3.6	(UNU, 1985, UNU, 2004)
Transplanting Seedlings	3.3	(UNU, 1985, UNU, 2004)
Transplanting Seedlings	3.6	(UNU, 1985, UNU, 2004)
Planting Tuber Crops	3.9	(UNU, 1985, UNU, 2004)
Planting Çatalhöyük (average PAR)	***3.7***	

The PARs for planting related activities range from 3.1, planting fruit crops, to as high as 4.96, planting rice. Although planting wheat is not amongst the list of PARs, rice planting is completed via broadcasting, and planting fruit crops, tubers, or transplanting seedlings often requires dibbling or row-sowing; planting maize often requires row-sowing or, broadcasting. These PARs reflect the variation in potential wheat planting activities and, therefore, utilising the average of these planting PARs is an appropriate avenue towards quantifying Çatalhöyük's panting energy.

With the amount of seedcorn required for Çatalhöyük, confirming the storage capacity for seedcorn at Çatalhöyük, and establishing a planting PAR for Çatalhöyük, to determine Çatalhöyük's planting energy, the seeding rate must now be determined. This is the focus of the subsection below.

5.5.2 Quantifying seeding (planting) rates and measuring time spent on planting at Çatalhöyük

Having calculated the amount of seedcorn required for Çatalhöyük's population estimates and confirming storage capacity for seedcorn at Çatalhöyük, the time it would have taken to plant seeds must be determined. In other words, the seeding rates in hectares per hour must be determined. This can be deduced from ethnographic and experimental archaeological literature. Then, by utilising the amount of seedcorn required, the Çatalhöyük land requirements, BMR, PAR, the amount of energy planting required at Çatalhöyük can be determined.

Accurate time estimates are crucial to determining planting energy. Archaeobotanical and experimental archaeological data are sources that can aid in determining accurate planting time estimates at Çatalhöyük. Time requirements for planting were based on Gregg 1988 household labour requirements for wheat planting and Steensberg's 1979 *Draved* experiments. Gregg 1988 utilised historical records and cropping experiments to estimate planting time and timings from ethnographic accounts of hunter-gatherers working during the planting season in southeast Asia. Axel Steensberg's *Draved: An experiment in Stone Age Agriculture; Burning, Sowing, and Harvesting* (1979), pursued reconstructing Neolithic agriculture; his work provides ample experimental archaeology data from land clearance and seed planting to harvesting. Steenberg's data included but was not limited to felling trees with stone tool axes, digging with digging sticks, planting seeds by hand, tracking seed grain planted and yields, harvesting crops with Neolithic tools, and, more importantly, recording the time each activity took (Steensberg, 1979).

Again, although we cannot extrapolate exactly how Çatalhöyük peoples planted their crops, hectare per hour estimates can be utilised to determine the minimum amount of time it took Çatalhöyük peoples to distribute seed across plots of land. The average of these seeding rates is sound and can be utilised to inform Çatalhöyük's seeding rates. This information was amalgamated and is presented in Table 21 below.

Table 21: Time estimates for planting. This table presents the time estimates for planting with descriptions of the type of planting activity, the estimated time needed to perform the activity in hectares per hour, and references from which the time estimates came. Planting rates activities range from general wheat planting, planting seeds by hand, to planting seeds with a digging stick. The average planting time utilised for this analysis, in hectares of land per hour, is 0.004.

Description	hectare of land/hour	Reference
Wheat planting	0.008	Gregg 1988: 158
Wheat planting	0.008	Gregg 1988: 158
Planting seeds by hand	0.0004	Steensberg 1979: 9
Planting seeds with digging stick	0.0001	Steensberg 1979: 9
Average	**0.004**	

The table above represents planting rates ranging from general wheat planting to planting seeds by hand and planting seeds with digging sticks, all of which are methods Çatalhöyük peoples could and would have utilised. By averaging these planting rates, a rate of 0.004 hectares of land seeded per hour was obtained. Utilising this rate, it is possible to determine the hours required to plant the seeds to keep Çatalhöyük's agricultural system sustained by dividing the amount of land required by the seeding rate. This quantification, time spent planting per year based on population and crop yield, is presented below in Table 22.

Table 22: Çatalhöyük's Planting Time Requirements. This table presents the planting hours required based on Çatalhöyük's population and crop yield, with a 75% reliance on domestic cereals (A), 50% reliance on domestic cereals (B), and 25% reliance on domestic cereals (C). As Çatalhöyük's population increases, time dedicated to planting also increases, i.e., planting time scales with population. With regards to crop yield, low yielding crops require more planting time, as more land is required to grow enough crops to sustain Çatalhöyük's population; therefore, seed is distributed across more land. High yielding crops require less planting time, as less land is required to grow crops to sustain Çatalhöyük's population. Finally, the higher the reliance on domestic cereals, the more seed and land that is required, thus, the more time dedicated to planting.

A. 75% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield	12000	75000	140000	270000	390000
Average yield	6900	43000	82000	160000	230000
High yield	5300	33000	62000	120000	180000

B. 50% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield	10000	56000	87000	180000	290000
Average yield	6300	32000	51000	100000	170000
High yield	4600	24000	38000	77000	130000

C. 25% reliance on domestic cereals

Population	100	500	1000	2000	3000
Low yield	4000	21000	56000	88000	160000
Average yield	2800	14600	32000	51000	95000
High yield	1800	9800	24000	38000	70000

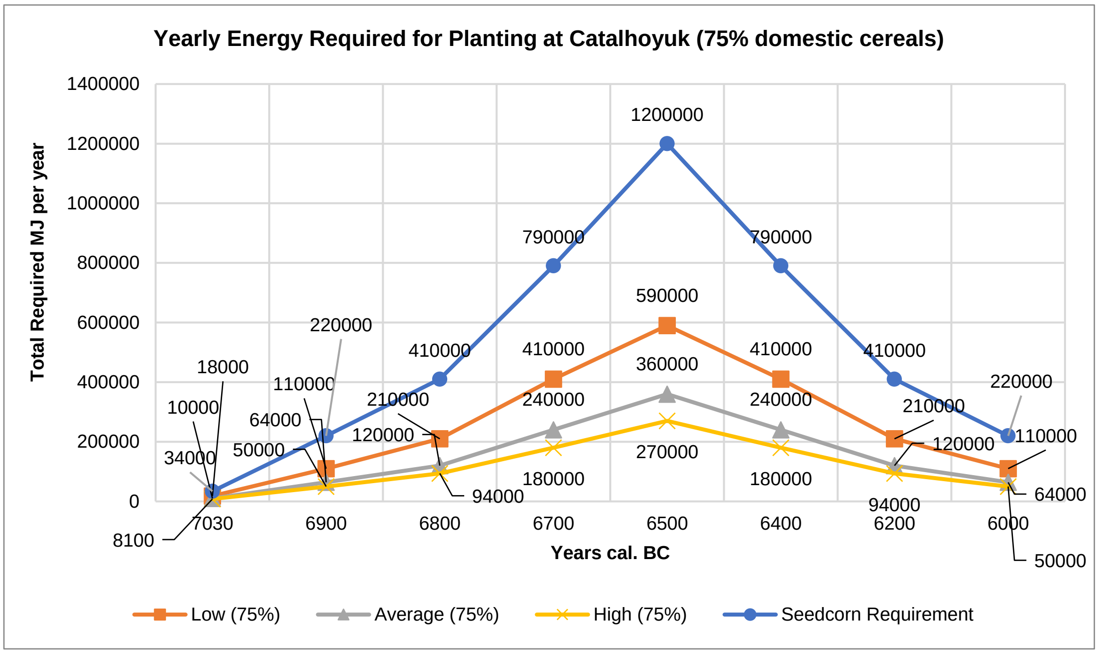
Referring to Table 22, Çatalhöyük had to dedicate 5,300 to 390,000 hours to planting with a diet of 75% domestic cereals, 4,600 to 290,000 hours to planting with a diet of 50% domestic cereals, and 1,800 to 160,000 hours with a diet of 25% domestic cereals. The higher the reliance on domestic cereals, the more energy dedicated to planting. Further, low yielding crops take more time to plant than average or high yielding crops. This is not necessarily surprising, as if crops were low yielding, more land would have been needed to keep Çatalhöyük sustained. Also expected is the increasing time dedicated to planting as the population increases; the more people Çatalhöyük has, the more crops that must be planted, and therefore, the more time that will be spent on planting. Furthermore, for Çatalhöyük’s population growth from 500, 1000, to 2000, planting hours would be the same when its population decreased. In other words, planting for 500 during Çatalhöyük’s growth is the same as its decline and planting for 1000 people is the same for Çatalhöyük’s growth as it is for when it declined. Planting energy is the same for these estimates regardless of whether it occurs during Çatalhöyük’s growth or decline, as the same amount of land is required to sustain these population numbers.

Having calculated the planting hours required at Çatalhöyük, it is now possible to determine the amount of energy planting would have required at Çatalhöyük. This is the focus of the subsection below.

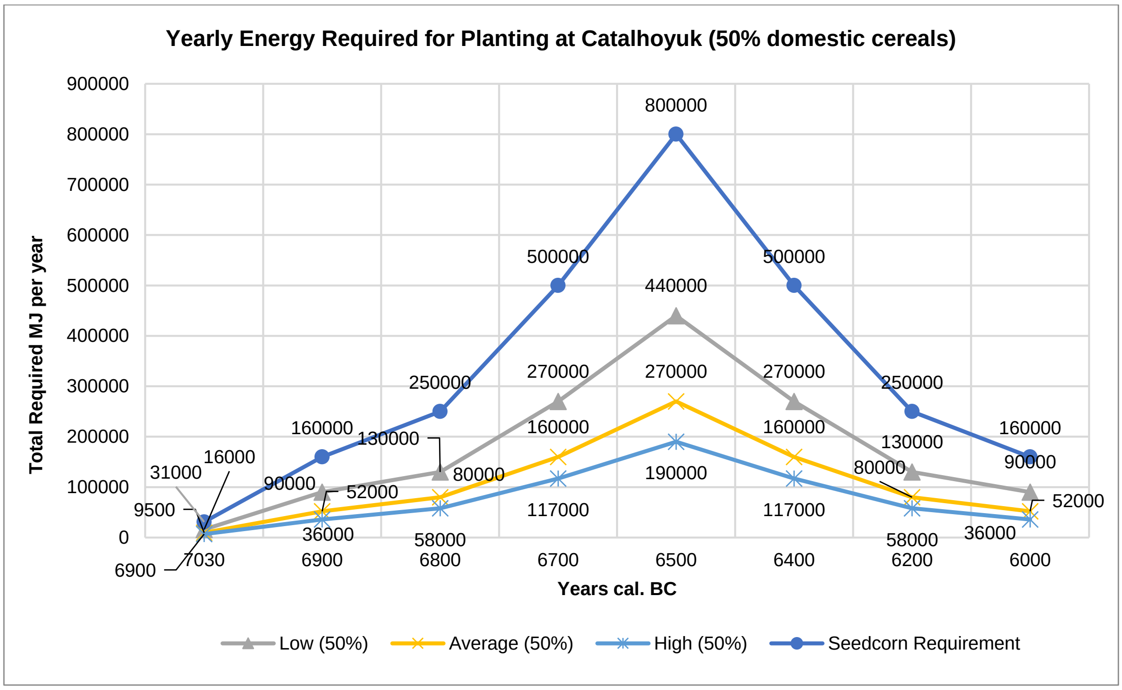
5.5.3 Çatalhöyük's Planting Energy and Seed Storage

Section 5.5.1 outlined Çatalhöyük's planting method, seed requirements, and seed storage availability by utilising ethnographic, experimental archaeological, and archaeobotanical data. Section 5.5.2 drew from this and quantified Çatalhöyük' planting rates, in hectares per hour, by utilising ethnographic and experimental archaeological literature. With this, it is now possible to quantify Çatalhöyük's planting energy and seed storage energy; this is the focus of this subsection.

To determine Çatalhöyük's planting energy, we must multiply the average BMR (Table 2) with the physical activity ratio of planting (Table 5) and the time allocated for planting (Table 21). To determine the energy embedded in seed storage, the cereal grain must be quantified from kilograms to megajoules[9]. The cumulative planting energy and seedcorn storage energy are both presented below.



A:



B:

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[9] Converting the kilograms of cereal required to store to megajoules was calculated as follows: [(kilograms of cereal required for next year's planting) X (cereal kilocalorie value per kilogram from Table 8) x (4184J)]/10000J.

C:

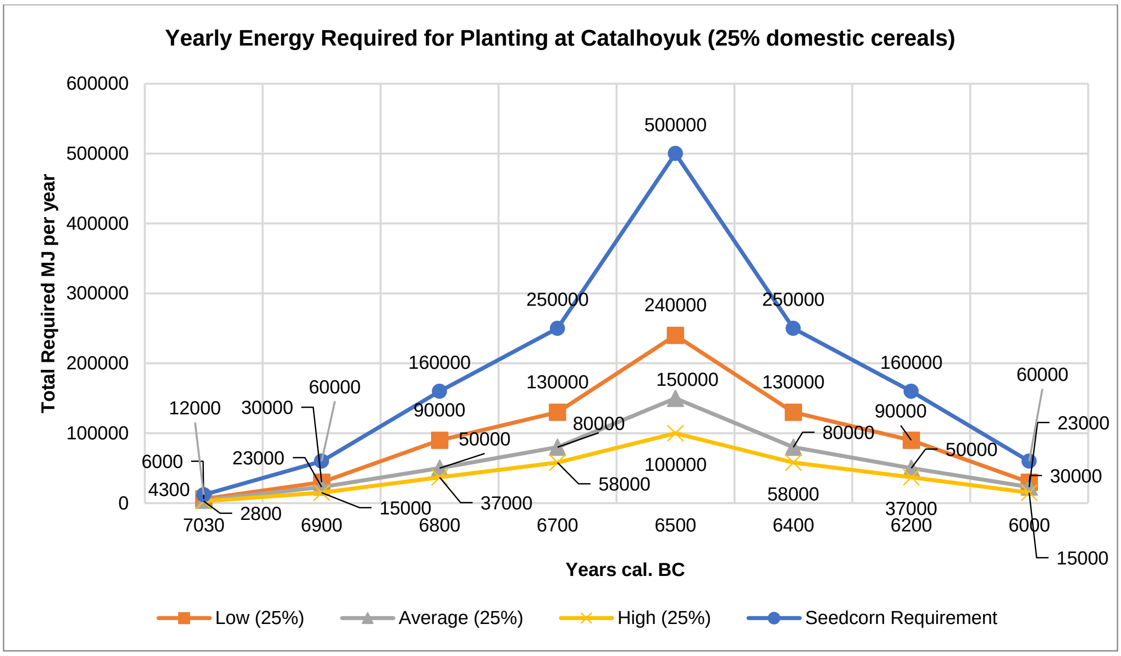


Figure 25: Planting Energy Required and Seedcorn Requirement for Çatalhöyük in Megajoules per year. This figure demonstrates the energy input for planting, which would have been required to sustain agriculture at Çatalhöyük, for low, average, and high yielding crops with a 75%, 50%, and 25% reliance on domestic cereals. Seedcorn requirement is also demonstrated in the figure above. Both planting and seedcorn requirements scale with population and reliance on domestic cereals. The higher the reliance on domestic cereals, the more seedcorn that is required and the more energy that must be dedicated to planting. As Çatalhöyük's population grows, more land is needed to keep it sustained; therefore, more land must be planted, and more seed is required to plant crops. Further, with low crop yields, planting energy is highest. Again, this is because with low yielding crops, more land is needed to plant more crops to sustain Çatalhöyük, and thus, seeds are planted upon a larger area of land. For high yielding crops, planting energy is lower. High yielding crops require less land, and therefore, less planting is required to keep Çatalhöyük sustained. As aforementioned, 20% of the grain produced from agriculture at Çatalhöyük is saved for planting the following year; this is the seedcorn requirement. As Çatalhöyük's population grows, more cereals must be planted; therefore, more seed must be stored by the Çatalhöyük peoples.

Referring to Figure 25, Çatalhöyük had to dedicate 8,100 to 590,000 megajoules of energy per year to planting with a 75% reliance on domestic cereals, 6,900 to 440,000 megajoules of energy per year to planting with a 50% reliance on domestic cereals, and 2,800 to 240,000 megajoules of energy per year to planting with a 25% reliance on domestic cereals. With regards to seedcorn required, 34,000 to 1,200,000 megajoules of energy per year had to be stored for a 75% reliance on domestic cereals, 31,000 to 800,000 megajoules of energy per year had to be stored for a 50% reliance on domestic cereals, and 12,000 to 500,000 megajoules of energy per year had to be stored for a 25% reliance on domestic cereals. As Çatalhöyük grows over time, more crops must be planted, requiring Çatalhöyük to dedicate more energy to planting, and requiring more seed storage.

Compared to land clearance and tillage energy, planting is the least energy intensive of what can be deemed the "pre-harvesting" processes. Planting has a much lower average PAR, 3.9, which is 1 to 1.5 times lower than tillage and land clearance, respectively. It also takes less time than either land clearance or tillage (Table 12, Table 15). With regards to seedcorn requirement, which is recycled back into the agricultural system itself, seed requirement only becomes larger than land clearance energy under low and average yield conditions for a population of 3000 people with a dietary reliance on domestic cereals of 75 and 50 percent. However, with a dietary reliance on domestic cereals of 25 percent, seedcorn requirement exceeds land clearance energy with a population of 3,000 no matter the yield scenario. Seedcorn requirement never reaches a point at which it is more energy intensive than tillage. Overall, planting mostly depends on how much of the diet is dependent on domestic cereals, land and yield: if yields are lower, more energy is required to plant because more land is required. On the other hand, if yields are high less energy is required to plant, as less land is required for higher yields.

Figure 25 also demonstrates that, overall, seed requirements are higher than planting energy input. Although these two processes are compared on the same scale, planting energy is an energy *intensive* process, whereas seedcorn Is more representative of recycled energy within agriculture. Referring to Figure 24, seedcorn energy does not directly sustain Çatalhöyük, but instead, is recycled back into sustaining agriculture via planting. Overall, this indicates the agricultural energy feedback system (Figure 1), especially in that agricultural processes are dependent upon and entangled with one another. Planting energy is mostly dependent upon and related to land and adequate tillage, however, planting cannot take place without seedcorn, as planting itself is also dependent upon the amount of seedcorn. If no seedcorn is available, planting cannot take place. Further, having enough seed for the next year's crop cannot occur without having a successful harvest. A harvest will not be successful if harvested too late or if the harvest goes awry, if there is not enough land, if tillage is inadequate, or even if storage is insufficient. In order to subsist from agriculture, Çatalhöyük peoples must successfully save and store seedcorn for the next year's crop. To store seedcorn for the next year's crop, other agricultural processes must also be successful. Therefore, agriculture's processes, including planting and seed storage, become increasingly dependent upon each other and other agricultural processes.

Having quantified the energy Çatalhöyük's land clearance, tillage, and planting processes, we must now quantify and model other agricultural processes, i.e., harvesting and crop processing. Therefore, the succeeding sections of this chapter focus on demonstrating how to quantify and quantifying the energy of post-harvesting agricultural processes at Çatalhöyük.

6 CHAPTER 6: HARVESTING AND CROP PROCESSING AT ÇATALHÖYÜK

6.1 “GRIEF WITH THE SICKLE”: QUANTIFYING THE ENERGY OF HARVESTING

Harvesting is known to be one of the most critical agricultural processes, as it is central to agriculture itself and lives and livelihoods depend upon it (Halstead, 2014). Harvesting, generally defined as collecting ripened plants via uprooting, general gathering, or sickle reaping, is a complicated and laborious process (Gregg, 1988, Halstead, 2014, Van Alfen, 2014). Harvesting itself is dependent upon the context of agriculture such as climate, weather, soil type, and crop type, which parts of the plants are collected, which tools are used to harvest, intended use of crops, practical or cultural factors, and labour force (Halstead, 2014: 77, 119). Further, the timing of harvesting is crucial. Crops must be harvested as soon as they are ready, as predation by animals increases as the crop ripens and crops become more susceptible to grain scattering by both natural causes and the harvesting processing itself (Filipović, 2014: 138, Gregg, 1988: 161).

For many cereals, harvesting involves grabbing a cluster of stalks with one hand and cutting stalks with a sickle in the other, which is not an easy-going task (Van Alfen, 2014: 169). Further, harvesting labour differs between cereals. For instance, harvesting short barley can be slow, tiring, and more time-consuming than gathering taller cereals, due to barley’s sharp awns; harvesting tall barley, however, is faster and less time consuming, despite its sharp awns (Halstead, 2014: 103-105). Overall, the height at which cereals are cut is also an important factor; if the point at which the cereal is cut is higher on the stem, less bending over is involved, thus, this makes cereal reaping easier (Halstead, 2014). In comparison, sprawling pulses can be harvested faster than cereals; however, they should not be harvested by sickle, as they require uprooting, and thus, more bending over (Halstead, 2014: 79, 103, 114). Harvesting methods themselves are not only central to agriculture but harvesting has been established as one of the essential factors in plant domestication (Abbo, Lev-Yadun et al., 2014, Bogaard, 2004: 32, Evans, 1993, Fuller, Allaby et al., 2010, Halstead, 1995, Halstead, 2014, Tzarfati, Saranga et al., 2013: 114). Ethnographically, harvesting is known to be laborious and a “labour bottleneck”, and it is, therefore, quite likely that it is also an energy bottleneck within agricultural energy systems (Fuller, Allaby et al., 2010, Halstead, 2014, Wright, 1994). Although it may be quite laborious, harvesting is a required agricultural process in extracting energy from agriculture. Harvesting typically occurs after planting, and the time of year depends upon the crop; it also requires an energy input to perform, as demonstrated in Figure 26 below, which shows harvesting within Çatalhöyük’s agricultural energy system.

Once a crop is harvested, for this model, the grain will either be utilised for seed or curation, i.e., food. However, before either seedcorn is stored or food is consumed, it must be processed. For seedcorn to be stored, it must be semi-processed and if it is to be used as food, it must be fully processed (further discussed in section 6.2). Only after all this processing takes place, which also requires energy investment, can the energy gathered from harvested domestic crops make it back to Çatalhöyük in the form of food, or seed for the next year’s planting. Further, a successful harvest cannot occur without viable seedcorn, and successful planting *and* successful planting cannot occur without a successful harvest. Harvesting is yet another agricultural process that is dependent upon others, and other agricultural processes are dependent upon it. Harvesting emphasises the two primary aspects of the agricultural energy feedback system: energy must be continuously invested into agricultural processes, and, to benefit from agriculture, all agricultural processes must be successful, e.g., agricultural processes are inherently dependent upon one another.

Being that it is one of the most crucial agricultural processes, the energy requirement of harvesting at Çatalhöyük must be determined. Throughout the remainder of this subsection, harvesting is quantified by utilising the energy methodology outlined in the preceding sections of this thesis. Section 6.1.1 also presents a description of how harvesting would have taken place at Çatalhöyük, and quantifies the time investment required for harvesting, which will be supported by archaeological, experimental archaeological, and ethnographic data.

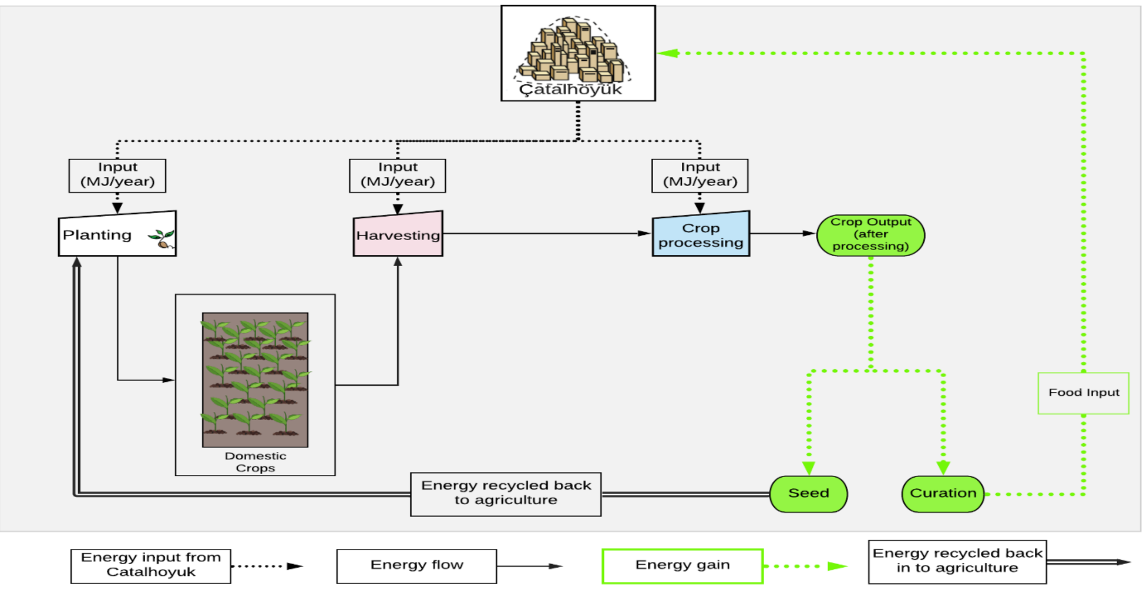


Figure 26 Harvesting within Çatalhöyük's Agricultural System: This figure demonstrates where harvesting takes place within Çatalhöyük's agricultural energy system. Harvesting itself requires energy input from the Çatalhöyük population in addition to requiring successful planting. After crops grow, Çatalhöyük peoples must input energy into harvesting the crops. Once a crop is harvested, the crop must be processed before it is used for curation or stored as seedcorn. Once seedcorn is prepared and stored, the energy of the stored seedcorn does not go directly to Çatalhöyük's population, but instead, is recycled back in to Çatalhöyük's agricultural system to sustain agriculture. Harvesting must be successful in order to have adequate seed and grain for curation (food) purposes. Further, a successful harvest cannot occur without successful planting and vice versa. These aspects of harvesting emphasise the agricultural feedback cycle, especially in that for humans to benefit from agriculture, they must continuously invest energy into its agricultural processes for agriculture to take place, and agricultural processes are dependent upon one another's success.

6.1.1 Measuring time spent on harvesting at Çatalhöyük

As outlined in 4.4, time estimates are crucial in determining the energy required to perform agricultural activities, including tillage. Archaeobotanical, ethnographic, and experimental archaeological data are sources that can aid in determining harvesting time estimates at Çatalhöyük. This chapter section presents how these data sources, in addition to Çatalhöyük's archaeological data and the energy methodology previously outlined, are used to quantify harvesting time estimates.

As aforementioned, harvesting depends on which parts of the plants are collected, which tools are used to harvest, intended use of crops, practical and cultural factors, and labour force (Halstead, 2014: 77, 119). Furthermore, harvesting time and labour are partially dependent upon the height at which cereals are cut. Therefore, determining the height at which cereals were cut at Çatalhöyük can aid in ensuring that harvesting time estimates are as representative of the Çatalhöyük data as possible. Thus, Çatalhöyük archaeobotanical evidence is one avenue that can provide evidence of cereal reaping height.

Filipović 2014 conducted an in-depth archaeobotanical analysis focusing on crop husbandry, land use, and animal diet, to explore Çatalhöyük's crop cultivation. One of these analyses included examining Çatalhöyük's arable weed flora; Filipović's analysis indicates that Çatalhöyük cereals were cut at a medium to high stem height, above the "highest culm node" (Filipović, 2014:136, 145). In other words, cereals were cut higher up on the stem, further away from the ground. This would have made reaping slightly less time consuming and would have permitted Çatalhöyük farmers to retrieve the ears of the cereals (where the grain is located) while avoiding shattering the fully ripe grain; this also allowed for minimal straw transport (Filipović, 2014:138). Cutting at this height not only made harvesting more manageable but would have made Çatalhöyük harvesting methods more successful, rather than risk shattering and therefore losing the ripe grain. Çatalhöyük archaeobotanical evidence further indicates that straw was minimally used at Çatalhöyük as it is absent from mudbricks, was not used as fuel, not consumed by animals, and not used as temper in dung cake manufacture at Çatalhöyük (Filipović, 2014: 136-138, Ryan, 2011). Straw was simply not a widely used resource at Çatalhöyük. This, combined with arable weed data and Filipović's analysis, indicates that Çatalhöyük farmers cut cereal stems at a medium to high stem height. In sum, archaeobotanical data at Çatalhöyük indicates that the cereal height would have been cut similarly to ethnographic estimates; therefore, the ethnographic data utilised in this analysis are well-representative of what could have taken place at Çatalhöyük.

Another archaeological data source which can illuminate harvesting practices is stone tool data. Çatalhöyük's stone tool evidence reveals that sickles were used to cut cereals. Sickles are found all over Çatalhöyük and in various contexts: sickle elements, sickle handles, and other sickle tools have been identified from Çatalhöyük's earliest occupation levels (Atalay and Hastorf, 2006: 294, Carter, Conolly et al., 2005, Filipović, 2014: 136). Additionally, there is even evidence that some sickles may have been hafted with wood or antler (Atalay and Hastorf, 2006: 294, Carter, Conolly et al., 2005). Çatalhöyük sickles were made from a variety of stone materials including non-local obsidian, local and non-local cherts, and they are different sizes (Carter, 2011, Carter, Conolly et al., 2005: 447-499, Carter and Milić, 2013, Tristan, Poupeau et al., 2005). Many Çatalhöyük chert sickles contain what is known as a "sickle gloss," a gloss made specifically from working silica-rich plants (Carter, 2011: 6-7). Although sickle gloss is indirect proof of sickle-harvesting, amalgamated with the arable weed data, and data suggesting minimal straw use, sickle-reaping was quite probable at Çatalhöyük. Furthermore, ethnographic evidence from Turkey also indicates that, today, many cereals are also cut with sickles or uprooted by hand (Filipović, 2014: 136). Overall, Çatalhöyük archaeobotanical stone-tool data indicate that sickles were used at Çatalhöyük and sickle-harvesting was the most likely cereal harvesting method at Çatalhöyük.

Archaeobotanical, stone tool, and ethnographic evidence supports sickle harvesting at a medium to high stem height at Çatalhöyük. Now, to determine the harvesting energy of crops, time estimates for such sickle harvesting must be determined. Harvesting time is heavily dependent upon the tool used to harvest cereals. Fortunately, harvesting is a well-studied aspect of non-mechanised agricultural processing, and there is ethnographic and experimental archaeological data on harvesting based on both crop type and the type of tool used. In addition to Halstead (2014) and Steensberg's (1979) works, for this analysis, data from Kenneth Russell's *After Eden: The Behavioral Ecology of Early Food Production in the Near East and North Africa* (1988) was used. Russell (1988) modelled wild-cereal exploitation in the Levant which was based on a wild einkorn, an Iranian village's threshing and winnowing rates, experiments with Roman querns, Roman texts regarding Roman slave labour, farmers dehusking millet in wooden mortars, and reaping experiments with replica sickles (Halstead, 2014, Russell, 1988, Wright, 1994).

By utilising such ethnographic and experimental archaeological data it is possible to estimate times which are representative of the Çatalhöyük archaeological data. The time requirements for harvesting, presented as hectare per hour, are presented in Table 23 below. These time estimates provided below account for tool use, the need for some bending, and a medium cereal reaping height; therefore, they are apt for this analysis. For comparison, three other harvesting tool comparisons (bronze and iron replica sickles) are also provided in the table.

Table 23: Time requirements for harvesting based on both crop type and tool used. The table below presents time estimates for harvesting, with descriptions of the crop harvested, implement used, harvesting in hectares per hour, and the sources from which this data came. The estimates here primarily focus on flint sickles or flake knives and dependent upon the crop type; however, bronze and iron implements are presented for comparison.

Crop	**Implement**	**Harvesting time ha/hour**	**Source**
Barley	Flint Sickle, Flake Knife	0.005	(Halstead, 2014: 105-106, 114, Russell, 1988: 116, table 20)
Emmer	Flint Sickle, Flake Knife	0.003	(Halstead, 2014: 105-108, 114, Russell, 1988: 116, table 20, Steensberg, 1979)
Einkorn	Flint Sickle, Flake Knife	0.003	(Halstead, 2014: 105-106, 114, Russell, 1988: 116, table 20, Steensberg, 1979)
Wheat (general)	Flint Sickle, Flake Knife	0.003	(Halstead, 2014: 105-106, 114, Russell, 1988: 116, table 20, Steensberg, 1979)
Crops (general)	Bronze Replica Sickle	0.004-0.006	(Halstead, 2014: 105-106, 114, Russell, 1988:116, table 20, Steensberg, 1979)
Crops (general)	Iron Replica Sickle	0.013	(Halstead, 2014: 105-106, 114, Russell, 1988: 116, table 20, Steensberg, 1979)

Overall, reaping with flint is slower than other tools, but, as Halstead 2014 explains, this is more than likely due to reach (Halstead, 2014: 114). In fact, experimental archaeological research has indicated that a replica Neolithic-type sickle can cut einkorn three times faster than modern iron reaping clamps (Halstead, 2014: 114, and reference within: Ibanez et al 1998). This explains the nearly two-fold difference in time between harvesting barley and other cereals with flint sickles; although barley is more challenging to harvest with its sharp awns, the flint sickle is still efficient for reaping this crop. For this analysis, as harvesting times vary based on crop, harvesting time is determined by utilising the rates in the table above: 0.003 hectares per hour for wheat, einkorn, and emmer, and 0.005 hectares per hour for barley.

Having designated the harvesting rate for each crop based off crop types and Neolithic tool types, it is now possible to determine how much time was required to harvesting domestic cereals at Çatalhöyük. By dividing the average amount of land needed in hectares (Figure 19, Table 10) by the harvesting time in hectares per hour, the harvesting hours can be quantified. These quantifications are presented in Table 24 below.

Table 24 Harvesting Hours Required at Çatalhöyük Per Year. This figure presents the harvesting hours required for Çatalhöyük based on dietary composition (A-75% domestic cereals, B- 50% domestic cereals, C-25% domestic cereals), population, and crop yield. As Çatalhöyük's population increases, time dedicated to harvesting also increases, i.e., harvesting time scales with population. Regarding crop yield, low yielding crops require more harvesting time, as more land is required to grow enough crops to sustain Çatalhöyük's population. Therefore, harvesting occurs across more land. Conversely, high yielding crops require less harvesting time, as less land is required to grow high-yielding crops to sustain Çatalhöyük's population. Finally, the more Çatalhöyük's diet relies upon domestic cereals, the more harvesting that must take place.

A. Harvesting hours with a diet of 75% domestic cereals

Population	100	500	1000	2000	3000

Low yield	14000	89000	170000	320000	460000
Average yield	8700	54000	100000	200000	290000
High yield	6800	43000	79000	150000	220000

B. Harvesting hours with a diet of 50% domestic cereals

Population	100	500	1000	2000	3000
Low yield	12000	65000	100000	200000	340000
Average yield	7700	40000	63000	130000	210000
High yield	5900	30000	49000	97000	160000

C. Harvesting hours with a diet of 25% domestic cereals

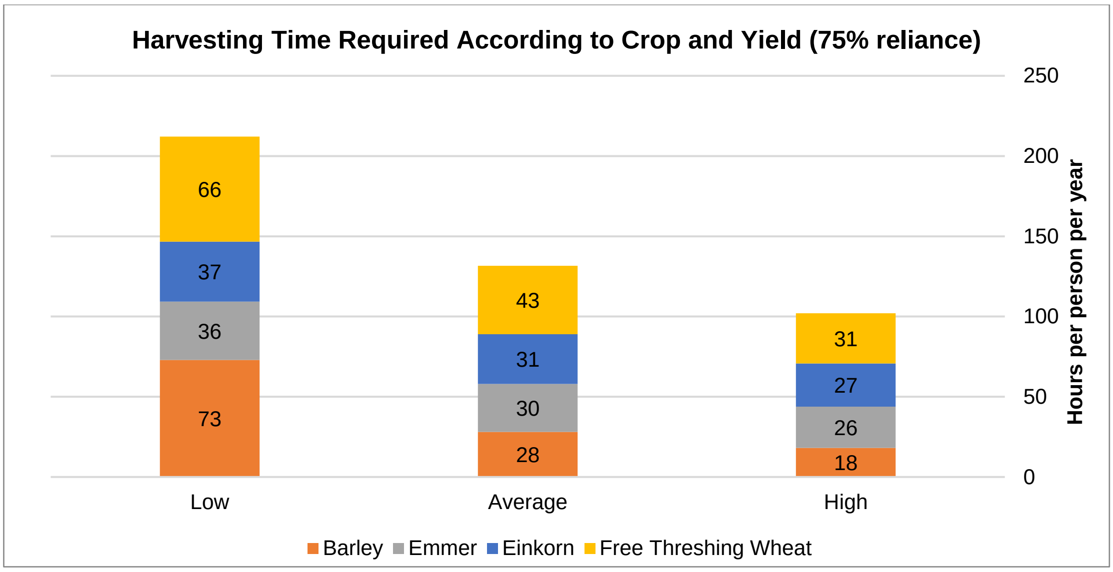
Population	100	500	1000	2000	3000
Low yield	4600	25000	65000	110000	190000
Average yield	2900	17000	40000	63000	120000
High yield	2300	12000	30000	49000	89000

Referring to Table 24 A Çatalhöyük had to dedicate a 6,800 to 460,000 hours to harvesting per year with a diet comprised of 75% cereals. With a diet comprised of 50% domestic cereals (Table 24 B), Çatalhöyük would have had to dedicate 5,900 to 340,000 hours to harvesting per year. Finally, with a diet of 25% domestic cereals, Çatalhöyük had to dedicate 2,300 to 190,000 hours to harvesting per year. The higher the dietary reliance upon domestic cereals, the more harvesting that must take place. Further, as Çatalhöyük's population grows over time, more crops must be harvested, harvesting, therefore, scales with population. Harvesting time is also dependent upon yield; with low yields, more land area must be harvested, whereas with high yields, less land is required to grow crops and, thus, less land area must be harvested.

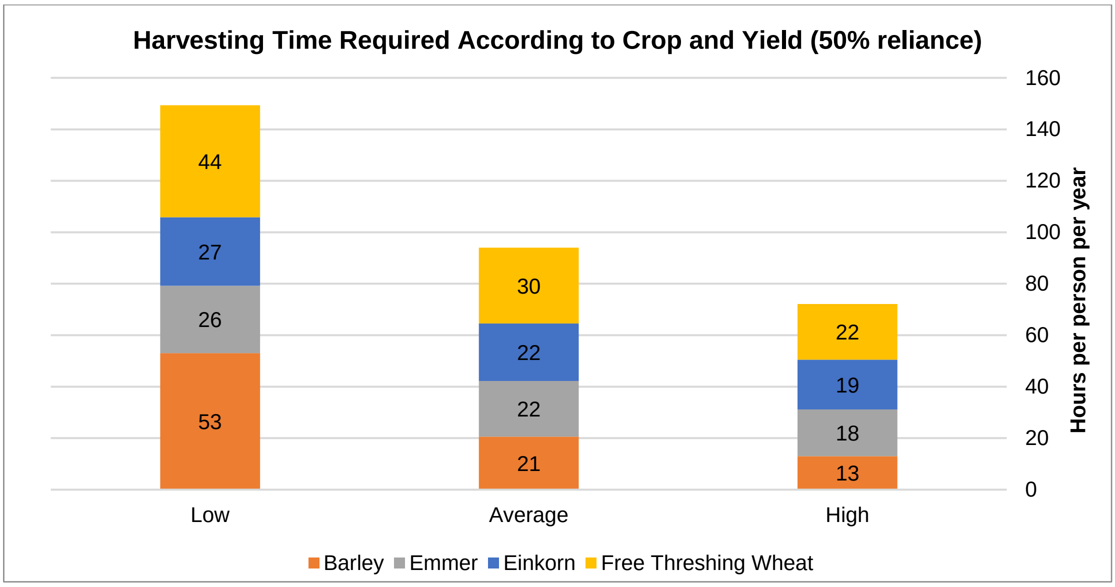
With regards to Çatalhöyük's population growth and decline, harvesting hours would be the same during its growth as for its decline. In other words, harvesting for a population of 500 during Çatalhöyük's growth is the same as its decline; harvesting crops for 1000 people is the same for Çatalhöyük's growth as when it declined to this number. Harvesting energy is the same for population estimates regardless of whether it occurs during Çatalhöyük's growth or decline, as the same amount of land is required to sustain these population numbers. Overall, harvesting cereals for Çatalhöyük, especially when Çatalhöyük's population was growing, would have been time intensive.

Similar to land clearance and tillage, harvesting is a time-consuming activity. It is dependent upon labour force, the time available throughout the year to harvest, and the crop. The figure below (Figure 27 A-C) presents the number of harvesting hours by crop type, per person per year, and based on the reliance of domestic cereals. it is unfeasible that the entire Çatalhöyük population would have been harvesting land; therefore, for this analysis, the hours per person per year below are presented for the 75% of population participating.

A:


Harvesting Time Required According to Crop and Yield (75% reliance)
Hours per person per year
250
200
150
100
50
0
Low
Average
High
73
36
37
66
28
30
31
43
18
26
27
31
Barley
Emmer
Einkorn
Free Threshing Wheat

B:


Harvesting Time Required According to Crop and Yield (50% reliance)
Hours per person per year
160
140
120
100
80
60
40
20
0
Low
Average
High
53
26
27
44
21
22
22
30
13
18
19
22
Barley
Emmer
Einkorn
Free Threshing Wheat

C:

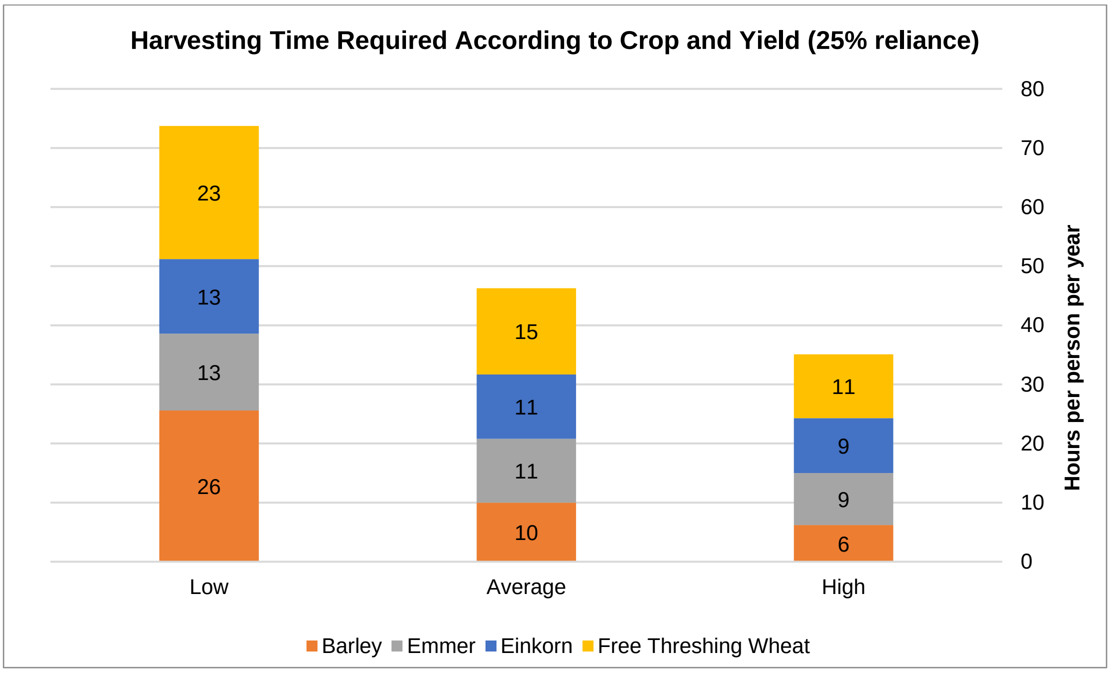

Harvesting Time Required According to Crop and Yield (25% reliance)
Hours per person per year
80
70
60
50
40
30
20
10
0
Low
Average
High
26
13
13
23
10
11
11
15
6
9
9
11
Barley
Emmer
Einkorn
Free Threshing Wheat

Figure 27: Harvesting hours per person per year at Çatalhöyük, according to crop type, reliance on domestic cereal, and yield. Figure A represents harvesting time with a diet of 75% domestic cereals, figure B represents harvesting time with a diet comprised of 50% domestic cereals, and figure C represents the harvesting time with a diet of only 25% domestic cereals. All three figures above show Çatalhöyük's average time requirement for harvesting per person per year, assuming 75% of the population participates in agricultural processing). Harvesting becomes less time consuming when the reliance on domestic cereals is lower, and, crop yields are high. With low yields harvesting becomes more time consuming for the average individual, as more land must be harvested to account for the low yields of crops. The opposite is true with regards to high yields. These figures also demonstrate the differences in harvesting time between crops. For low yields, barley and free-threshing wheat require more time to harvest regardless of the percent reliance on domestic cereals. On average, free-threshing wheat and einkorn require more time to harvest. With regards to high yields, free-threshing wheat and einkorn require the most harvesting time. This is due to both the differing yields of these crops and the differences in harvesting between crops, which has been well documented ethnographically and historically. Finally, these figures also show that the higher the reliance on domestic cereals, the more time that must be dedicated to harvesting them.

Highlighted in Figure 27 A to C above are the differences in harvesting time between crops. With low-yielding crops, the differences in harvesting time differs dramatically, with barley and free-threshing wheat requiring more harvesting time than emmer or einkorn. With high yields, the difference between crops is not as dramatic, and barley demands the least amount of time to harvest compared to einkorn, emmer, and free-threshing wheat. This is primarily due to the differences in crop yields. This in itself emphasises that low yields are more time consuming than high yields. Referencing Table 9, low crop yields were designated as 250 kilograms per hectare, 480 kilograms per hectare, 700 kilograms per hectare, and 855 kilograms per hectare for barley, free-threshing wheat, einkorn, and emmer, respectively. High crop yields were 970 kilograms per hectare, 1000 kilograms per hectare, and 1200 kilograms per hectare for einkorn, barley and wheat, and emmer, respectively. Overall, high yields are less time intensive. This is emphasised by the fact that even with harvesting rate being faster with a flint sickle for barley, this does not make a substantial difference with regards to harvesting time, especially with low yields.

With the harvesting hours required for Çatalhöyük being determined, to calculate the energy requirement of harvesting at Çatalhöyük, we must again utilise PAR. Harvesting is a laborious task, often involving grabbing stalks with one hand whilst cutting stalks with a sickle in another (Van Alfen, 2014: 169). The PAR values for harvesting reflect this laborious task and are presented in the table below.

Table 25: Physical Activity Ratios utilised to determine the average harvesting PAR. Although there is no PAR specifically for harvesting wheat and barleys, the average PAR for a range of crop harvesting was used for this analysis. The description of the activity, the PAR, and the reference are provided in the table below. The average PAR of these harvesting activities is 4.7, therefore, this is the designated PAR for harvesting in this analysis.

Activity	**Physical Activity Ratio Value**	**Reference**
Harvesting groundnut crop	4.7	(UNU, 1985, UNU, 2004)
Harvesting maize	5.1	(UNU, 1985, UNU, 2004)
Harvesting Rice	3.5, 3.8, 2.4-4.2, 3.8, 3.5-4.4	(UNU, 1985, UNU, 2004)
Harvesting Tubers	4.4, 3.0, 3.5-5.7, 2.8-3.4	(UNU, 1985, UNU, 2004)
Harvesting rice	4.2	(Vaz, Karaolis et al., 2005)
Harvesting palay (unhusked rice)	4.4	(Vaz, Karaolis et al., 2005)
Harvesting groundnuts	4.7	(Vaz, Karaolis et al., 2005)
Harvesting Maize	5.1	(Vaz, Karaolis et al., 2005)
Harvesting Manioc	4.2	(Vaz, Karaolis et al., 2005)

Harvesting root crops	3.4	(Vaz, Karaolis et al., 2005)
Harvesting (bending)	3.7	(Vaz, Karaolis et al., 2005)
Harvesting (general)	4.2	(Vaz, Karaolis et al., 2005)
Harvesting Çatalhöyük (average PAR)	***4.2***	

The PAR for harvesting related activities ranges from 3.0 to 5.7. Although none of the PARs are harvesting wheat products per se, harvesting with bending is approximately 3.7, whereas harvesting more generally is 4.2. The harvesting average for this analysis is 4.2. This average PAR reflects the variation in wheat harvesting activities, including uprooting, bending, and standing; therefore, utilising this PAR average is the most appropriate avenue for quantifying Çatalhöyük's harvesting energy.

Having quantified the harvesting rate, the harvesting hours that would have been required, and the PAR of harvesting at Çatalhöyük, it is now possible to quantify harvesting energy. Harvesting energy is presented and discussed below.

6.1.2 Harvesting energy

Harvesting is dependent upon the context of agriculture, tools used to harvest, use of crops, labour force, which part of the plants are collected, and the crop itself. From an energy systems point of view, harvesting must take place in order for Çatalhöyük to extract energy from domestic crops, but the action itself also requires an energy input from Çatalhöyük's population. Harvesting's timing is crucial; if harvesting is not completed when the grain is ready, the harvest could fail via grain shattering, or predation by animals, thereby effecting Çatalhöyük's food input as well as seedcorn for the next year's planting (Figure 26). This aspect of harvesting demonstrates that harvesting is dependent upon other agricultural processes, and vice versa. Therefore, quantifying the energy of harvesting at Çatalhöyük is important for quantifying, modelling, and understanding Çatalhöyük's agricultural system and the agricultural energy feedback system at Çatalhöyük.

Section 6.1.1 drew from ethnographic and experimental archaeological data as well as Çatalhöyük's own archaeobotanical and stone tool data to determine harvesting rate, and thus, harvesting time required for Çatalhöyük. The harvesting PAR was also determined, which was averaged from a range of harvesting activities. Harvesting is a time consuming and laborious activity; therefore, it is expected that it will require a significant energy investment. To determine the energy of harvesting at Çatalhöyük, the basal average basal metabolic rate (Table 2), the PAR of harvesting, (Table 5, Table 25), and the time allocated for harvesting (Table 24 A-C) must be multiplied. Harvesting energy is presented below in megajoules per year.

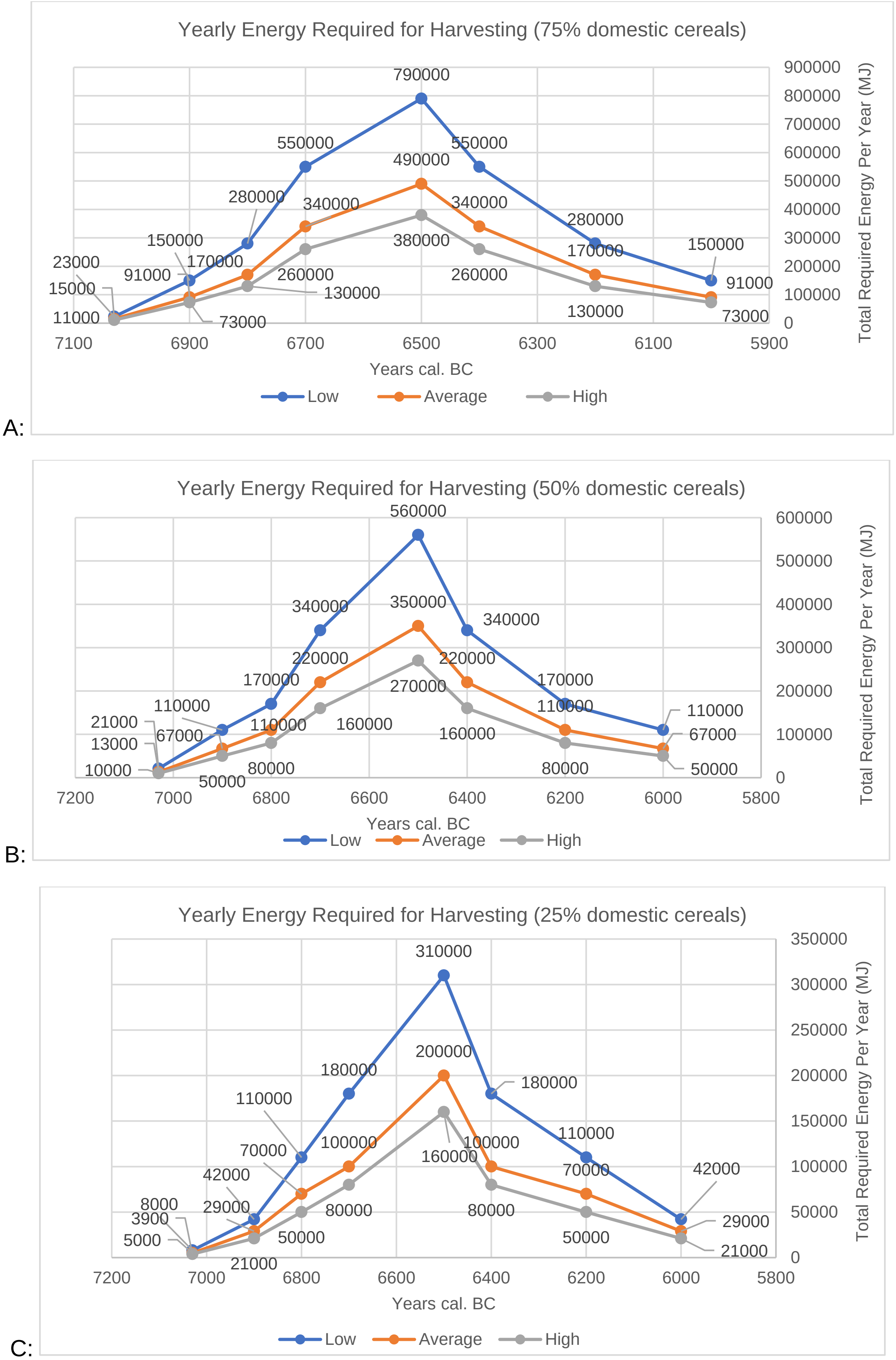


Figure 28 Harvesting Energy Required for Çatalhöyük in Megajoules per year depending on crop yield and domestic cereal reliance. This figure demonstrates the energy input for harvesting which would have been required to sustain agriculture at Çatalhöyük, for low, average, and high yields with 75% (A), 50% (B), and 25% (C) reliance on domestic cereals. Harvesting energy scales with population growth. As Çatalhöyük's population grows, more

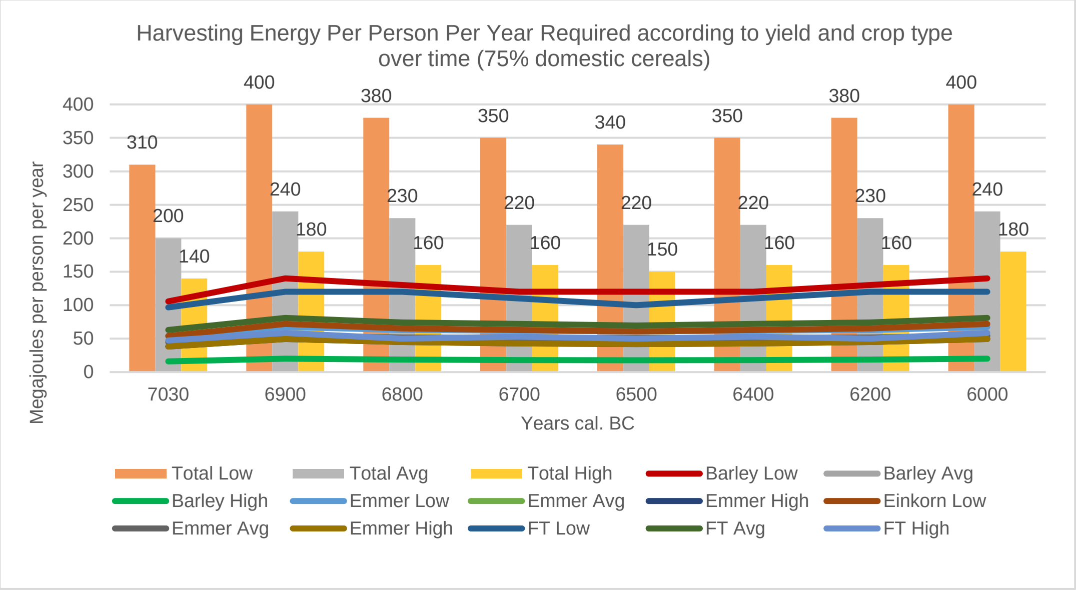
land is needed to keep it sustained, therefore, more harvesting must take across a larger amount of land. However, harvesting energy also depends upon yield. With low crop yields harvesting energy is the highest. Again, this is because if crops are low yielding, more land is needed and thus harvesting area must be extended. For high yields harvesting energy is lower because high yielding crops require less land, and therefore, less land must be harvested to keep Çatalhöyük sustained.

Referring to Figure 28 A, with a 75% reliance on domestic cereals, Çatalhöyük would have had to invest 11,000 to 790,000 megajoules of energy per year into harvesting. With a 50% reliance on domestic cereals, Çatalhöyük had to invest 10,000 to 560,000 megajoules of energy into harvesting, whereas with a 25% reliance on domestic cereals, Çatalhöyük would have had to invest 3,900 to 310,000 megajoules of energy to harvesting per year. The higher the reliance on domestic cereals, the more energy that must be dedicated to harvesting. As Çatalhöyük grows over time more grain must be harvested over more land, and therefore, Çatalhöyük will dedicate more energy to harvesting. Harvesting also depends on yield. Although it seems counterintuitive, with low yields, more energy is dedicated to harvesting; low yields require *more* land. With higher yields, less energy is dedicated to harvesting, as less land is required.

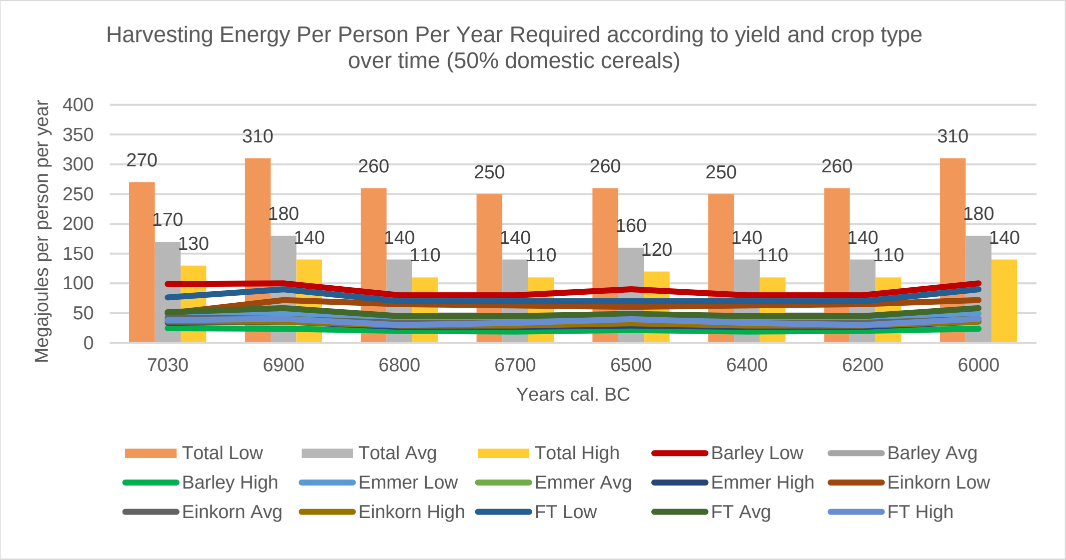
Comparing harvesting to other agricultural processes, harvesting is always less energy intensive than tillage and more energy intensive than planting, regardless of yield scenario or percent reliance on domestic cereals. With regards to land clearance, however, there is a different picture. With a 75% reliance on domestic cereals, harvesting is more energy intensive than land clearance at a population of 3000 people with low yields (6500 cal. BC) but is less energy intensive than land clearance with a population of 3000 and high or average yields. With a 50% reliance on domestic cereals, at a population of 3000 people, harvesting is always more energy intensive than land clearance, regardless of yield. Finally, with a 25% reliance on domestic cereals, harvesting is always less energy intensive than land clearance, regardless of yield. Harvesting and land clearance are both laborious, time consuming and dependent upon population and yield, however, their PARs are quite different. The PAR of land clearance (5.7) is greater than harvesting (4.2). However, harvesting (Table 24) has the potential to take up far more time than land clearance (Table 12), depending upon yield. Finally, harvesting is an activity which must take place every year, for all crops, whereas land clearance only occurs with population growth when more land needs to be cleared.

In comparison to tillage, which is also laborious, time consuming and dependent upon population and yield, tillage however, takes far more time than harvesting, as the former occurs three times and the latter only once. With regards to harvesting and planting, although harvesting and planting both take place once, harvesting requires more time than planting and has a higher PAR, therefore, it is more energy intensive.

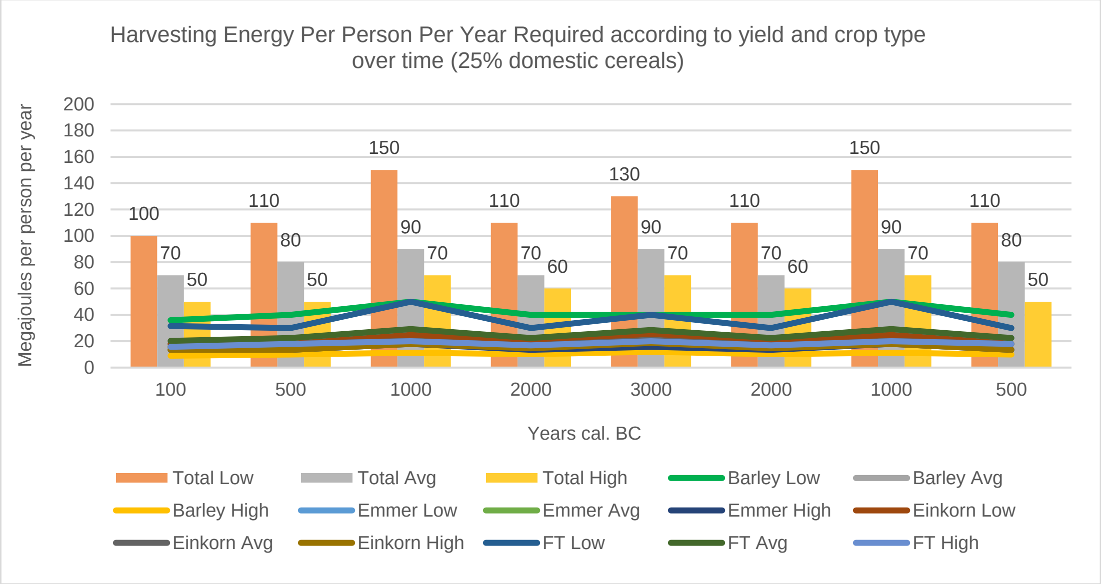
On an individual level, harvesting is quite like tillage and planting in that it is more dependent upon yield. The average energy requirements for harvesting fields needed to sustain the Çatalhöyük population on an individual level are presented in Figure 29 below. With a 75% reliance on domestic cereals (A), one person harvesting these four domestic cereals would require 140 to 400 megajoules per year. With a 50% reliance on domestic cereals (B), one person harvesting these four domestic cereals would require 110 to 310 megajoules per year. Finally, with a 25% reliance on domestic cereals (C), one person harvesting these four domestic cereals would require 50 to 150 megajoules per year. Figure 29 also highlights some differences between domestic cereals. Again, it is unfeasible that the entire Çatalhöyük population would have been harvesting, therefore, for this analysis, the harvesting energy is quantified as if 75% of the population was working.


Harvesting Energy Per Person Per Year Required according to yield and crop type over time (75% domestic cereals)
Megajoules per person per year
0
50
100
150
200
250
300
350
400
310
200
140
400
240
180
380
230
160
350
220
160
340
220
150
350
220
160
380
230
160
400
240
180
7030
6900
6800
6700
6500
6400
6200
6000
Years cal. BC
Total Low
Total Avg
Total High
Barley Low
Barley Avg
Barley High
Emmer Low
Emmer Avg
Emmer High
Einkorn Low
Emmer Avg
Emmer High
FT Low
FT Avg
FT High

A


Harvesting Energy Per Person Per Year Required according to yield and crop type over time (50% domestic cereals)
Megajoules per person per year
0
50
100
150
200
250
300
350
400
270
170
130
310
180
140
260
140
110
250
140
110
260
160
120
250
140
110
260
140
110
310
180
140
7030
6900
6800
6700
6500
6400
6200
6000
Years cal. BC
Total Low
Total Avg
Total High
Barley Low
Barley Avg
Barley High
Emmer Low
Emmer Avg
Emmer High
Einkorn Low
Einkorn Avg
Einkorn High
FT Low
FT Avg
FT High

B


Harvesting Energy Per Person Per Year Required according to yield and crop type over time (25% domestic cereals)
Megajoules per person per year
0
20
40
60
80
100
120
140
160
180
200
100
70
50
110
80
50
150
90
70
110
70
60
130
90
70
110
70
60
150
90
70
110
80
50
100
500
1000
2000
3000
2000
1000
500
Years cal. BC
Total Low
Total Avg
Total High
Barley Low
Barley Avg
Barley High
Emmer Low
Emmer Avg
Emmer High
Einkorn Low
Einkorn Avg
Einkorn High
FT Low
FT Avg
FT High

C

Figure 29 Harvesting energy at Çatalhöyük, per person per year. The figure above shows the average energy requirement for harvesting per person per year, in megajoules at Çatalhöyük, showing the total harvesting energy per year and according to crop type. Like tillage and planting, harvesting is an agricultural process which does not necessarily become less energy intensive, on an individual level, when more people are available. Harvesting does, however, become less energy intensive when less land must be harvested, i.e., with high yields. With low yields, harvesting becomes more energy intensive, as more land must be harvested to account for low yields. This diagram also demonstrates the difference in harvesting energy between crops at Çatalhöyük, which also vary according to their yield. Of note is with low yields, barley and free threshing wheat are the most energy intensive crops. On average, emmer, barley, and einkorn have relatively the same harvesting energy intensity, however free threshing wheat is still the most energy intensive crop comparatively speaking. For higher yields, again, free threshing wheat and einkorn are the most energy intensive while barley is the least energy intensive.

Overall, regardless of dietary composition, the figure above demonstrates that harvesting becomes less energy intensive when less land must be harvested, i.e., with high yields. With low yields, harvesting becomes more energy intensive, as more land must be harvested to account for the low yields. There is also a difference in harvesting energy between crops at Çatalhöyük and according to yield. With low yields, barley and free threshing wheat are the most energy intensive crops to harvest. On average emmer, einkorn, and barley are roughly the same, however, free threshing wheat is still the most energy intensive crop to harvest. With higher yields, barley is the least energy intensive to harvest, whereas, again, free threshing wheat is the most energy intensive crop to harvest. To fully understand these energy differences, we must briefly discuss the differences between the crops.

The harvesting energy of these crops is not just due to the amount of land required. As a crop, barley has the lowest average yield, requires the most land to grow, and, despite its sharp awns, is quick to harvest with a Neolithic sickle. Nutritionally, it has the highest kilocalorie value per kilogram than the other domestic cereals (Table 8). Barley is not as time intensive to harvest despite its lower yield, and therefore high-land requirement (Table 9). Emmer has a relatively high yield, requires the least amount of land, and takes longer to harvest with a Neolithic sickle than barley (Table 9, Table 23, respectively). Emmer also has smaller kilocalorie value per kilogram than barley (Table 8). Einkorn has an average to high yield compared to other crops, requires the least amount of land to grow, and takes longer to harvest with a Neolithic sickle than barley (Table 9, Table 23 respectively). Einkorn also has the second-highest kilocalorie value per kilogram (Table 8). However, einkorn is a more time-intensive crop than both emmer and barley with regards to harvesting. Finally, free-threshing wheat is the most energy-intensive domestic cereal to harvest at Çatalhöyük. The yield of free-threshing wheat is average, it requires a fair amount of land, and it has a slow harvesting time (Table 9, Table 23). Overall, free-threshing wheat is the most energy-intensive domestic cereal to harvest and has the lowest kilocalorie value per kilogram than the other domestic cereals (Table 8).

With regards to the differences between a dietary composition of 25%-75% cereals, it must be noted that scale is important. For a domestic cereal reliance of 50% to 75%, the differences between both crops and especially crop yields is larger, whereas with a domestic cereal reliance of 25%, the difference between crops and crop yields is smaller. Thus, with a smaller reliance on domestic cereals, the crop differences for individuals are not very large, *except* when it comes to crop yield. This emphasises that the act of harvesting depends upon land: if yields decline, more energy is required to harvest because more land is required for lower yields. If yields are high, less energy is required to harvest, as less land is required.

6.2 CROP PROCESSING: THRESHING, WINNOWING, DEHUSKING, AND SIEVING

Threshing, winnowing, dehusking, and sieving, are all crop processing stages which are pivotal to extracting energy from domestic cereals. Depending on the cereal, these processes must take place to extract and utilise the energy embedded in cereal grains. Therefore, this subsection focuses on these four crop processing stages at Çatalhöyük. Prior to quantifying the energy of these processes, however, a discussion on the differences between free-threshing (naked) cereals and hulled (glumed) cereals in relation to these crop processes must take place.

Threshing is the physical act of breaking or separating cereal grain from the stalks and husks of the plant; in other words, threshing releases the chaff which encloses the grain, from the rachis (stem or stalk) (Hillman, 1983, Van Alfen, 2014: 169). Threshing loosens what holds the edible part of the crop from the main part of the plant, making it one of the most fundamental crop processing stages (Russell and Bogaard, 2014: 68). Thus, threshing is an extremely important step in retrieving and utilising the energy from domestic cereals. Threshing itself is dependent upon timing of the harvest, especially the weather. The weather after harvest influences location, timing, and the method of threshing as harvested crops must be sufficiently dry before they are threshed (Halstead, 2014). If crops are not permitted to dry, grains can potentially sprout, which would be detrimental to the food system at hand (Halstead, 2014).

Threshing is accomplished by beating the harvested crop with a flailing device like a stick, cereal sheaves can be beaten on a board, or, the crop is laid on hard ground and trampled on by humans or animals (Halstead, 2014, Van Alfen, 2014). In drier areas, however, threshing with sticks is quite effective as it allows the crop to dry more thoroughly (Halstead, 2014: 146, Hillman, 1984). All of these options are hard work, as Halstead's ethnographic accounts explain: "for glume wheats and perhaps hulled barley, *manual* dehusking was sufficiently laborious that this and initial threshing (with or without animals) together were probably more time-consuming than reaping with an iron sickle or *plow-based* (but not *manual*) cultivation" (Halstead, 2014: 171, original emphasis). Threshing is a laborious activity, especially for glume wheats and hulled barley, no matter the way in which it is completed.

Threshing labour is heavily dependent upon the type of cereal being threshed, especially whether the wheat is hulled or free-threshing (naked). Free-threshing wheats, like bread wheat, are wheats where the grain is "naked" and *loose* in the plant's chaff; to remove the grain, free-threshing wheats must be threshed to break the ear and free the naked grains from the loose chaff, as demonstrated in Figure 30 below (Bogaard, 2016, Halstead, 2014: 360). Glume wheats or hulled wheats and hulled barleys (i.e. einkorn, emmer, hulled barleys) on the other hand, are those which have their grains tightly enclosed in the chaff and have an extra layer of covering known as a husk or glume (spikelet), which sits within the plant's chaff (Halstead, 2014: 360, Hillman, 1983). Instead of breaking the ears of the wheat into grains, for glume or hulled species, threshing breaks the ears of the species into spikelets (glumes) which enclose the grain (Halstead, 2014: 136).

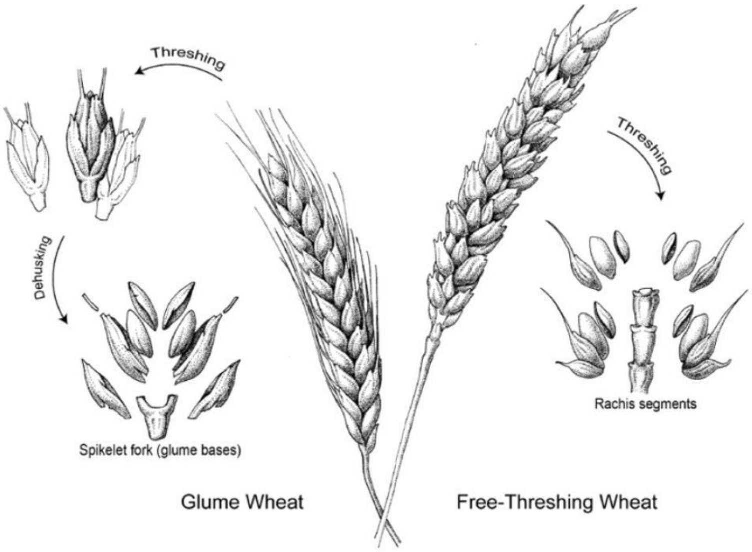


Figure 30 Wheat structure schematic altered from Bogaard 2016: Schematic representation of wheat structure and demonstration of what happens to wheat when threshed. For free-threshing wheats, threshing separates the seed from the chaff easily and dehusking does not need to take place. With glume or hulled wheats, however, they must be threshed as well as dehusked to free the grain. Although the act of threshing must take place on all domestic cereals, with glume or hulled cereals, threshing typically occurs twice.

Glume or hulled species, thus, require more threshing labour than free-threshing wheats. In fact, for hulled species, an extra round of threshing and winnowing is required in addition to a dehusking (pounding or grinding) the cereal, as the tough glumes of hulled wheats and barleys require more force to release the grains from the hull (Halstead, 2014, Tzarfati, Saranga et al., 2013, Van Alfen, 2014). Hulled barleys, emmer wheat, and einkorn wheat are all threshed twice for this reason (Halstead, 2014, Hillman, 1983). The spikelets also require pounding, which is not necessary for free-threshing cereals (Hillman, 1983). Figure 31 and Figure 32 demonstrate these crop processing stages within Çatalhöyük's agricultural energy system and visualise the differences in processing hulled and naked cereals at Çatalhöyük.

Referring to Figure 31, free-threshing cereals typically require only one round of threshing, winnowing, and coarse and fine sieving, as the grain is not enclosed in a tight chaff or glume (Halstead, 2014). Hulled cereals (Figure 32) require two rounds of threshing, winnowing, pounding, and sieving. These figures also indicate the differences in the ways free-threshing and hulled cereals must be processed for storage. As mentioned, the grain of hulled species is enclosed in a spikelet or glume within the chaff which protects the grain; this makes it less susceptible to storage losses (Halstead, 2014: 178). It is common that after hulled species are threshed, they are stored in the spikelet form to provide extra protection against storage losses (Halstead, 2014). For free-threshing grains, this is not necessarily an option. Free-threshing wheat grain, with its loose chaff, is not stored within its chaff and is usually stored soon after it is processed into grain. Further, because free-threshing grains do not have an extra layer of protection, their grains more susceptible to rotting, damage, sprouting, and even predation from rodents; it thus has a shorter storage life than hulled grain and is known to be “a less dependable staple for self-sufficient farmers” (Halstead, 2014: 178). Hulled species take more effort to process, however, the potential of storing hulled species in the spikelet form, thus better protecting them, has the advantage of “spreading the labour” of other crop processing steps like manual dehusking, since dehusking does not have to occur at the same time as threshing (Halstead, 2014: 178). The storability benefits of hulled wheats and barleys and their potential in spreading labour could also make them an advantageous crop for buffering risk (Halstead, 2014).

Soon after threshing, winnowing takes place. Winnowing is the act of tossing the threshed crop in air and allowing heavy grain to fall to the ground, whilst light straw and chaff are carried downwind (Halstead, 2014: 129). Winnowing uses wind power to help further separate the heavier grain from the chaff (Atalay and Hastorf, 2006, Van Alfen, 2014: 169). Summarised, winnowing helps to remove the lighter parts of the of the plant: straw, awns, light seeds, and light chaff (Filipović, 2014: 66). Winnowing is of course very dependent on wind and weather patterns and must take place when both are favourable (Halstead, 2014). Although winnowing appears to be an easy task since it uses wind energy to complete, it actually requires a joint labour force (Halstead, 2014, Hillman, 1983). One person tosses the threshed crop into the air; as this happens, the crop reduces "to a pile of grain with heavy pieces of straw (especially culm nodes) and partially threshed (and unthreshed) ears or pods, while the lighter chaff and straw accumulate downwind" (Halstead, 2014: 129). While this occurs, another person must rid the other bits of remaining straw and ensure there is proper chaff and straw separation (Halstead, 2014). Winnowing is a restrictive agricultural process, as only one to two people can effectively winnow at a time, however, even today winnowing is still most effective way to separate grain from lighter straw and chaff (Halstead, 2014: 151-152).

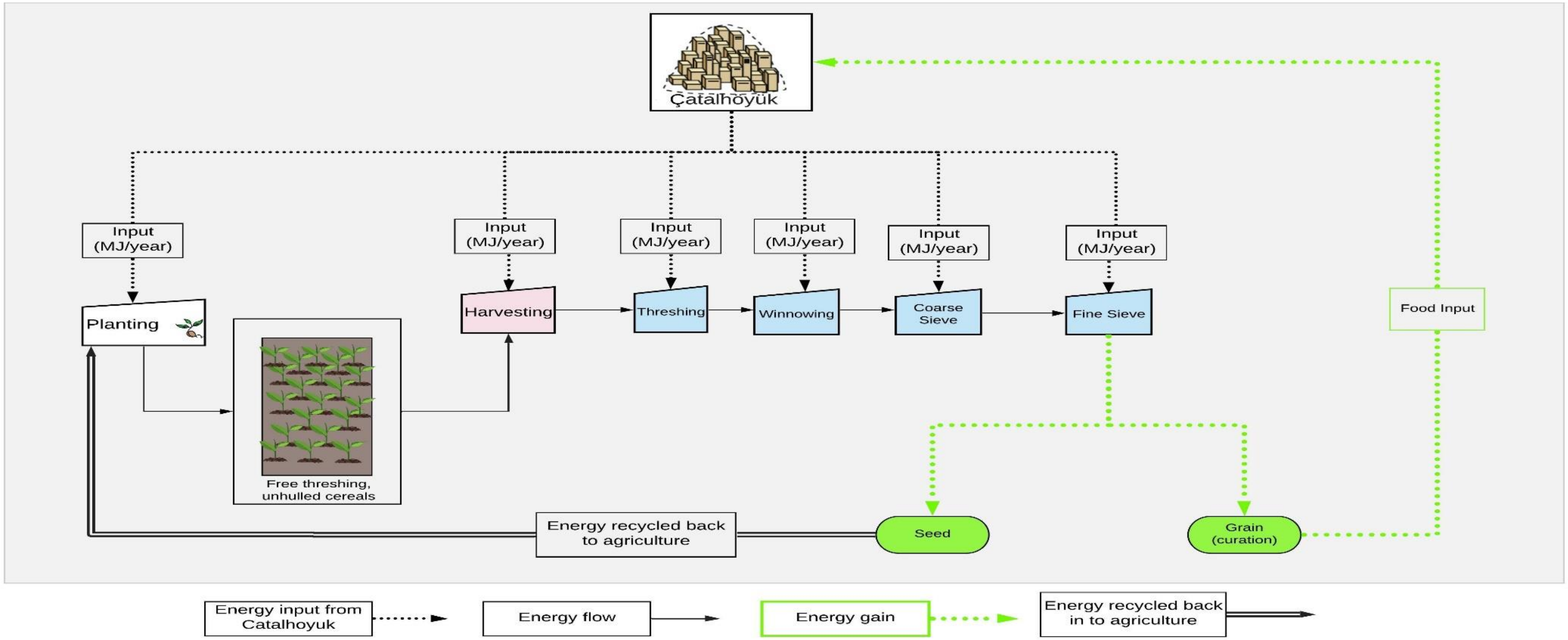


Figure 31: Crop processing stages for free-threshing cereals within Çatalhöyük's Agricultural System. This figure demonstrates the crop processing stages for free-threshing cereals, including threshing, winnowing, and coarse and fine sieving. Once crops are harvested, Çatalhöyük peoples must input energy into threshing, winnowing, and sieving the crops. When these processes are complete, it results in the cereal grain which is either is recycled back into Çatalhöyük's agricultural system to sustain agriculture, or, to Çatalhöyük's population in the form of curation or food energy. Threshing, winnowing, and sieving ***must*** *take place to retrieve the grain for both free-threshing (naked) and hulled (glume) cereals. Free-threshing cereals require less energy input from Çatalhöyük, due to having less crop processing steps. Further, all crop processing stages require energy input from the Çatalhöyük population in addition to requiring a successful harvest. A successful harvest cannot occur without adequate seed storage to provide seed for the next year's crop. This in itself also emphasises the role crop processing plays in the agricultural energy feedback system, especially that in order for humans to benefit from agriculture, they must continuously invest energy into its processes for agriculture to take place, and agricultural processes are inherently dependent upon one another's success.*

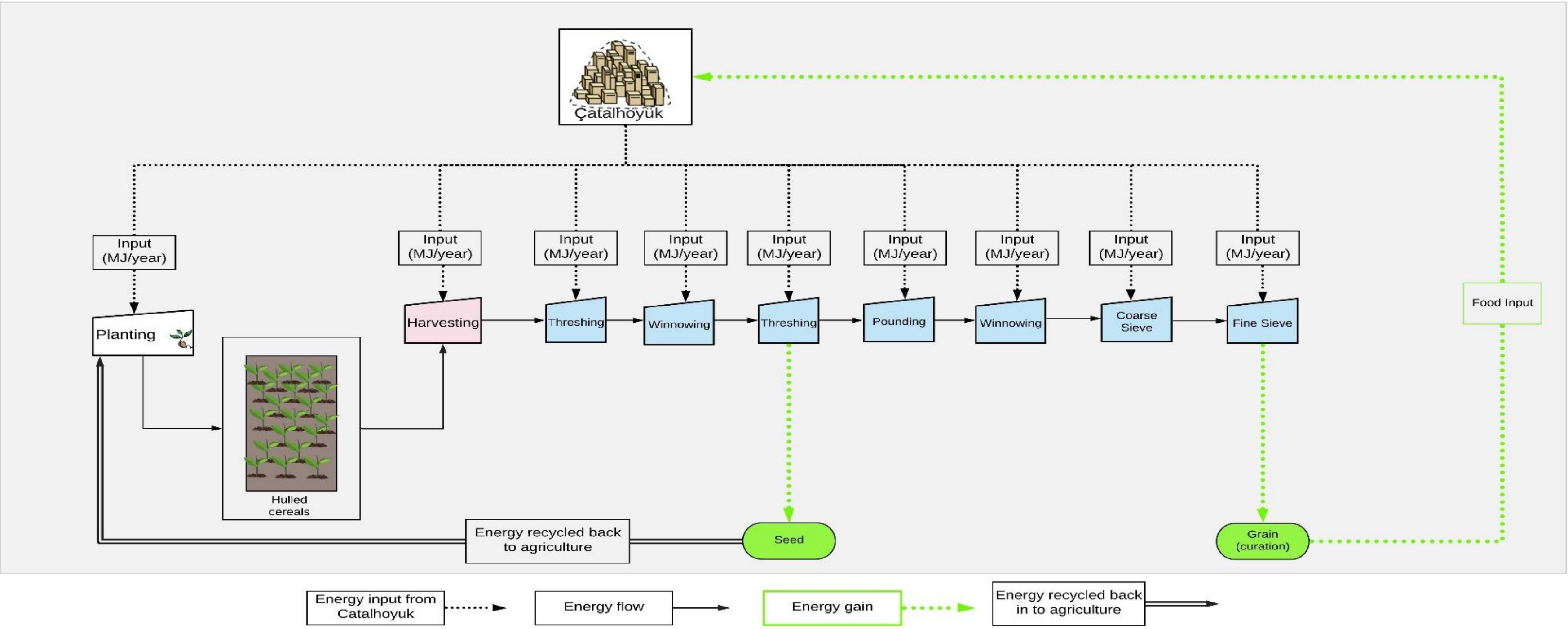


Figure 32: Crop processing stages for *<u>hulled cereals</u>* *within Çatalhöyük's Agricultural System. This figure demonstrates the crop processing stages for hulled cereals, including threshing, winnowing, pounding (dehusking), and coarse and fine sieving. Once crops are harvested, Çatalhöyük peoples must input energy into these processes. Unlike free-threshing cereals, which typically require one round of threshing, winnowing, fine and coarse sieving, hulled cereals require extra processing steps. Typically, they are threshed, winnowed, threshed again, pounded to dehusk the grain, winnowed to be rid of extra husk and chaff, and subsequently coarse and fine sieved. When these processes are complete, it results in the cereal grain. However, if the hulled cereal is to be stored, the extra steps of pounding, winnowing, and coarse and fine sieving are not required; the cereal can simply be stored after two rounds of threshing and one round of winnowing, and replanted the next year. Either way, the cereal is either is recycled back into Çatalhöyük's agricultural system to sustain agriculture, or flows to Çatalhöyük's population in the form of food energy. Hulled cereals thus require more energy input from Çatalhöyük, due to having to having more crop processing steps. All of these crop processing stages, however, require energy input from the Çatalhöyük population. Further, a successful harvest cannot occur without adequate seed storage to provide seed for the next year's crop. This in itself emphasises the role crop processing plays in the agricultural energy feedback system,, especially that in order for humans to benefit from agriculture, they must continuously invest energy into its processes for agriculture to take place, and, that agricultural processes are inherently dependent upon one another's success. .*

For hulled cereals, in this model, two rounds of threshing and one round of winnowing, dehusking (i.e., pounding) takes place. The glumes or husks around the grain of hulled cereals are indigestible, therefore to be utilised for consumption pounding must occur to remove the husk around the grain (Wright, 1994: 242). In essence, pounding physically frees the grain from tough glumes for hulled species; mortars and pestles are the most efficient tools for this process (Nesbitt, Hillman et al., 1995). When a grinding slab or quern, a stationary stone used along with an upper, mobile stone, is used, this action can be referred to as grinding, but, both pounding and grinding can both be used to process hulled cereals (Nesbitt, Hillman et al., 1995: 47, Wright, 1994: 240). With regards to mortars and pestles, mortars are typically made of stone, but the pestle should be made of wood; this is the best combination for cereal dehusking (Meurers-Balke and Lüning, 1999, Wright, 1994: 243). Stone pestles can be used; however, they often crush the grain and make it difficult to separate the glume from the grain; this is also a problem with hand stones and grinding slabs (Wright, 1994: 243). It is for this reason that even if hulled cereals are to be ground into flour they are typically pounded first, to prevent contaminating flour with indigestible cereal husk (Ertuĝ-Yaras 1997: 425, Wright, 1994). Pounding husked grain, on the other hand, using a stone mortar and a wooden pestle along with a bit of water forces the cereal husks to "rub off" one another, which properly separates the grain from the glume without cracking or over processing (Wright, 1994: 243).

Dehusking can be a laborious task, especially if there is a large amount of cereal to be processed. However, unlike harvesting or threshing, dehusking is not typically a seasonal or a large scale task, i.e. they can be completed as daily chores on an "as-needed" basis (Meurers-Balke and Lüning, 1999: 250). Once hulled cereals are dehusked, they must be further cleaned via sieving to separate the husked and dehusked grains as well as grain and chaff from one another (Meurers-Balke and Lüning, 1999: 250). The combination of pounding with sieving helps to fully remove the glume of hulled cereals, leaving a fully processed grain. Although free-threshing wheats do not require dehusking, it has been ethnographically attested that consumption wise, they are often ground to a flour (Brady, 2020, Ertuĝ-Yaras 1997, Halstead, 2014, Hillman, 1983, Hillman, 1984, Meurers-Balke and Lüning, 1999, Nesbitt, Hillman et al., 1995, Wright, 1994).

During winnowing (for free-threshing wheats) and dehusking (for hulled cereals), sieving takes place. It is often the case that the first round of sieving is completed at the same time as winnowing. Depending on how thoroughly winnowing was completed, there are usually two rounds of sieving: coarse and fine sieving (Halstead, 2014, Hillman, 1983). Coarse sieving helps to remove contaminants larger than the grain itself, such as any unthreshed ears, large weed pods, straw nodes, seeds larger than the grain, extra rachis fragments, awn fragments and even pebbles or bits of extra chaff (Filipović, 2014, Hillman, 1983: 4). Barleys and hulled cereals are typically coarse sieved twice, often combined with a round of winnowing and typically with pounding (Hillman, 1983, Hillman, 1984). Coarse sieving can only take place after at least one round of winnowing and threshing, otherwise, "the light chaff and straw would immediately clog the sieves" (Hillman, 1983: 9). However, coarse sieving can occur directly after winnowing, or *during* winnowing to help speed up the process, especially if threshing was completed in damp conditions, or if winds were not strong enough (Halstead, 2014: 151-152). If winnowing is thorough enough, a round of coarse sieving may not even be necessary (Halstead, 2014). Once coarse sieving is complete, a round of fine sieving takes place to remove weed seeds (which are smaller than the grain), any remaining fine chaff, and any other remaining rachis and awn fragments (Hillman, 1983: 4, Nesbitt, Hillman et al., 1995: 244). Sieving marks the "final" crop processing stage for this analysis; once cereal grain is processed, there are many ways in which cereals can be utilised for curation, i.e., food.

Cereals are generally further processed in at least three ways: lightly processed by utilising whole grains for gruels or stews, moderately processed into meals or groats, and heavily processed into flour (Atalay and Hastorf, 2006, Brady, 2020: 99, Ertuĝ-Yaras 1997, Hastorf, 2017). Grinding grain into a flour not only increases the volume of the edible product, although the weight remains the same, but grinding cereals into flour also allows for an increase in nutrient uptake in the gut (Wright, 1994: 243). Cereal grains can also be consumed via roasting, or parching, depending upon the context. Such foodways depend on individual and familial preferences, the local environment, taboos, traditions, nutritional needs, and can even differ by age group or gender (Atalay and Hastorf, 2006, Ertuĝ-Yaras 1997, Halstead, 2014, Hastorf, 2017). Foodways are pivotal in understanding subsistence and they are considered to many as being fundamental in social structure: "societies are made manifest in their food traditions, recipes, and the daily cycles that meals create formed in the sharing of meals and dishes" (Hastorf, 2017: 3). Foodways and modes of subsistence require certain forms of energy use, energy flows, and, are of course directly tied to social institutions. Socially, it known foodways are a mechanism for identifying and reinforcing social structures (Hastorf, 2017, Pearson, Haddow et al., 2015: 212). Biologically, food is the primary way in which humans consume energy extracted from the environment to sustain themselves. In essence, foodways bring together the biological and social worlds of a society (Hastorf, 2017).

Quite often, however, the actions of foodways themselves are missing from the archaeological record and it is simply unfeasible to obtain an accurate, holistic picture of foodways in the past (Hastorf, 2017, Pearson, Haddow et al., 2015). For this analysis, energetically analysing foodways, the variety of dishes that could be created from domestic cereal products, and how they were further processed (e.g., ground for flour and subsequent breadmaking, paste making, boiled in stews) is not included. Although an energetic analysis of the further curational techniques can be completed by combining more food energetics data with the energetic framework at hand, it is beyond the scope and focus of this PhD analysis. Therefore, this agricultural energy model does not include an energetic analysis of further food processing after the cereal grain is processed into grain.

Referring to Figure 32, hulled cereals must be threshed, winnowed, threshed again, then they are pounded and subsequently winnowed and sieved. With regards to free-threshing cereals Figure 31, they are threshed, winnowed, and then sieved. For barleys, it is a combination of the two models (discussed further throughout this section). These figures also demonstrate that threshing, winnowing, pounding, and sieving, are agricultural processes which require an energy investment, are dependent upon one another, and other agricultural processes are dependent upon them. Grain cannot be utilised unless it is processed or unless there is a successful harvest. A successful harvest cannot occur without viable seedcorn and successful planting; successful planting cannot occur without a successful harvest. Cereals cannot be adequately stored unless they are processed; if storage fails, the crop fails. Further, with regards to processing for grain, cereals cannot be sieved unless they are winnowed, or, winnowed unless they are threshed. They also cannot be threshed unless they are adequately dried and successfully harvested. Hulled cereals cannot even be utilised until they are dehusked. This emphasises the primary aspects of the agricultural energy feedback system: energy must be continuously invested into agricultural process, to benefit from agriculture all agricultural processes must be successful, and agricultural processes are inherently dependent upon one another.

The remaining subsections of this chapter will focus on quantifying the energy of threshing, winnowing and sieving by utilising the energy methodology outlined in preceding sections of this chapter, the Çatalhöyük land estimates, and, archaeological, ethnographic, and experimental archaeological data. Threshing, winnowing, dehusking, and sieving were occurring at Çatalhöyük, therefore, section 6.2.1 focuses on presenting and describing these processes and the archaeological evidence substantiating their occurrence at Çatalhöyük. This section also presents the time estimates for how threshing, winnowing, and sieving were determined, which will also be supported by experimental archaeological and ethnographic data. 6.2.2 presents the energy of threshing, winnowing, and sieving, which concludes this chapter subsection.

6.2.1 Measuring time spent on threshing, winnowing, and sieving at Çatalhöyük

Ethnographic, and experimental archaeological data are sources which can aid in determining threshing, winnowing, and sieving time requirements at Çatalhöyük. This chapter section presents how these data sources, amalgamated with Çatalhöyük's archaeological data and the energy methodology previously outlined, are used to quantify threshing, winnowing, dehusking, and sieving time estimates.

Archaeobotanical evidence is the primary form of evidence which specifies the cereal processing steps that took place at Çatalhöyük. Combined with experimental archaeology and ethnographic research, the Çatalhöyük team has been able to specify the cereal processing steps that would have taken place at Çatalhöyük. Ethnographic evidence and experimental archaeology have revealed that threshing, winnowing, coarse sieving, and fine sieving each produce a predictable assemblage of plant parts and weed seeds which can be identified in the archaeological record (Filipović, 2014: 67, Hillman, 1983, Hillman, 1984). Since these patterns are well known, consequently, Çatalhöyük's archaeobotanical data discloses what crop processing stages occurred at Çatalhöyük. Prior to delving into time estimates of these crop processes, we must determine how they might have occurred at Çatalhöyük.

Overall, Çatalhöyük's archaeobotanical evidence indicates threshing and some winnowing occurred offsite, whereas winnowing, dehusking, and sieving occurred on site. Filipović (2014) conducted an in-depth taphonomic analysis investigating the products and by-products present in the Çatalhöyük archaeobotanical assemblage which provides evidence of crop processing stages at Çatalhöyük (Filipović, 2014). There are two ways in which crop-processing stages can be determined from archaeobotanical samples: crop-based methods and weed-based methods (Filipović, 2014: 67). The former relies upon proportions of different crop parts and weed seeds whilst the latter is based upon the physical characteristics of weed seeds with regards to crop processing stages (Filipović, 2014: 67). Filipović 2014 utilised both methods to determine what crop processing stages occurred at Çatalhöyük (Filipović, 2014: 66-85). Filipović's analysis of hulled cereals indicated that these archaeobotanical samples represented "unmixed processing stages" which likely originated from "winnowing and/or fine sieiving of pounded hulled wheats" or "crop in the form of semi-cleaned grain accompanied by weed seeds" (Filipović, 2014: 85). In other words, crop processing stages at Çatalhöyük not only occurred, but they occurred separately. Hulled wheats were winnowed and fine sieved after being dehulled, or they were stored in a semi-clean state (i.e., threshed prior to storage). Filipović utilised the same method of analysis, more specifically the proportion of grain to rachis fragments, to also determine the crop processing stages for free-threshing wheats and naked barley (Filipović, 2014). Filipović's analyses indicated that winnowing, coarse sieving, and fine sieiving were completed on both free-threshing wheat and naked barley. Further, both these crops' grain to rachis ratios indicated *different* early and late stage by-product materials, which indicates they were both grown and processed separately (Filipović, 2014: 76). This may in fact relate to barley's sharp awns. Barley, whether it is hulled or not, requires at least two rounds of threshing due to needing to remove its sharp awns; if these are not removed, they can cause irritation when consumed, even when ground into a flour (Halstead, 2014: 129, Hillman, 1983). This is a potential explanation for why naked barley and free-threshing wheat were treated differently at Çatalhöyük.

Çatalhöyük's archaeobotanical analyses also indicates that other forms of crop processing took place on site, as chaff is often found within Çatalhöyük's middens, house floor rakeouts, and even in tertiary building fills (Russell and Bogaard, 2014: 68). Chaff being present in middens, sweep outs of house floors, and in building fills is the direct result of winnowing, dehusking, and sieving, as it is a by-product of these processes (Hillman, 1983). Therefore, this is direct evidence that winnowing, dehusking, and sieving occurred at Çatalhöyük, on site. There are also high chaff densities which have been identified on the side of and next to buildings, meaning that Çatalhöyük peoples engaged in crop processing on roofs and even outside of buildings (Atalay and Hastorf, 2006: 297). Further, ethnographic research indicates that winnowing and sieving require baskets and of course, sieves; it is plausible that reed baskets and skin sieves were utilised to complete this task at Çatalhöyük (Atalay and Hastorf, 2006: 297, Hastorf, 2017: 101, Rosen, 2005). Baskets have been identified at Çatalhöyük and there is direct evidence of wheat chaff within baskets at Çatalhöyük, indicating they were used for winnowing and perhaps even for storage of grain (Filipović, 2014: 66, Hastorf, 2017). Thus, some winnowing and most sieving absolutely occurred on site and Çatalhöyük peoples had the toolsets required to complete these tasks.

With regards to dehusking hulled cereals, there is also material and archaeobotanical evidence that dehusking occurred at Çatalhöyük, on site. There are in-situ grinding stones, stone querns, and pestles and mortars present throughout Çatalhöyük (Atalay and Hastorf, 2006, Ertuĝ-Yaras 1997, Wright, 2014). The simple presence of mortars, pestles, querns, grinding slabs and handstones themselves, however, does not provide direct evidence of domestic cereal processing, as these objects can also be used for processing wild cereals, wild nuts, tubers, oil-rich seeds, pigments, and even meat processing (Atalay and Hastorf, 2006, Bogaard, Charles et al., 2009, Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000, Hastorf, 2017). However, amalgamated with the archaeobotanical evidence above, the dehusking of hulled cereals utilising mortars, pestles, querns, grinding slabs, and handstones more than likely did take place. Further, there is no way to consume hulled cereals without dehusking them; dehusking simply had to take place.

Querns and handstones were common throughout Çatalhöyük. Wright et al. 2014 analysed 2429 ground stone artefacts from 20 buildings and 9 yards at Çatalhöyük East, indicating that 50% or more of Çatalhöyük houses had quern fragments and small hand tools, especially handstones (i.e. portable food processing tools) (Wright, 2014: 18-20). This illustrates that the toolkits for pounding and grinding cereals were widely available to Çatalhöyük's general population and implies dehusking was commonplace. Further, the storage room of building 77, for example, contained pestles, anvils, abraders, polishers, a well-worn stone hoe, a broken digging stick weight, a small portable quern, a handstone, and botanical remains, all of which has been interpreted as agricultural toolkit and food processing tools (Wright, 2014: 14). There is also direct evidence that grain was pounded for consumption within Çatalhöyük households, specifically within building 65 in the form of burned, in-situ hulled wheat by-products (Russell and Bogaard, 2014: 68). This has been interpreted as the result of fine sieving and cleaning of pounded spikelets (Russell and Bogaard, 2014: 68). In sum, the artefactual and archaeobotanical evidence indicates dehusking absolutely took place at Çatalhöyük.

The archaeobotanical and artefactual evidence described thus far demonstrates that winnowing, dehusking, and sieving occurred at Çatalhöyük. However, these processes cannot occur unless a crop is threshed; threshing is a required step in cereal processing, no matter the cereal. Overall, the on-site archaeobotanical evidence indicates that late stages in crop cleaning, mainly winnowing, sieving, and dehusking, occurred within the Çatalhöyük settlement itself; the initial threshing and winnowing took place elsewhere (Atalay and Hastorf, 2006, Fairbairn, Near et al., 2005, Filipović, 2014: 145). The archaeobotanical analyses within the KOPAL area of Çatalhöyük, just at the edge of the settlement, provides evidence that initial threshing and winnowing took place here (Atalay and Hastorf, 2006: 297, Fairbairn, Near et al., 2005, Rosen, 2005). There are "high incidences of chaff and processing fragments" including "silicified awns, spines, hairs, and glume breaks," all of which are by-products of combined actions of threshing and winnowing; this archaeobotanical evidence is densely distributed throughout this part of the site (Atalay and Hastorf, 2006: 297, 303, Hastorf, 2017: 101). As threshing separates the grain from the rachis (stalk) of the cereal and winnowing helps separate the chaff from the grain, to have chaff as a waste product, threshing and winnowing must have occurred. Therefore, this indicates that threshing was a crop process in which Çatalhöyük peoples partook near the settlement at the KOPAL area. Additionally, ethnographic evidence implies this may be a threshing site, as the local residents of Küçükköy, near Çatalhöyük, have noted that the KOPAL site is "the same orientation to the site as threshing fields" they utilise; it is the orientation which takes advantage of strong winds in the area (Atalay and Hastorf, 2006: 297, 303). Having the threshing site on the edge of the settlement, at a place where winds can aid with the first round of winnowing, as opposed to being indoors is also a matter of practicality, as threshing is a dusty job. Hillman describes, "all the dusty jobs such as threshing, winnowing, and pounding" can and should be completed outside, if the environment is a dry one (Hillman, 1983: 8). Ethnographic work by Halstead indicates that threshing can take place inside if weather is bad or in wetter climates, however it is extremely unpleasant: "even on an open-air floor, dust from threshing could make breathing difficult, while fine chaff fragments penetrated clothing, hair, and skin" (Halstead, 2014: 142). Therefore, due to the dry environment and archaeobotanical evidence, it is quite feasible that this was the central threshing site for Çatalhöyük.

The by-products of threshing and subsequent winnowing and sieving indicate these processes occurred at Çatalhöyük. Other than these by-products and basketry, however, the way in which threshing, winnowing, and sieving occurred at Çatalhöyük cannot be completely verified, as the tools utilised to carry out these activities would not necessarily survive in the archaeological record (e.g., leather, wooden threshing sticks, leather sieves, etcetera). However, as aforementioned, ethnographic research can provide a model to the way in which crop processing took place at Çatalhöyük. Ethnographically, threshing via trampling by animals or animals dragging sledges is quite a common occurrence; however, this requires dedicated threshing floor space, sledges, and other large-scale equipment; there is no archaeological evidence which supports that this could have been an applicable threshing method at Çatalhöyük (Halstead, 2014, Hillman, 1983). Ethnographic research does indicate, however, that for locations in drier areas, especially those with a summer drought like Turkey, crops dry more thoroughly which makes threshing with sticks particularly effective (Halstead, 2014: 146, Hillman, 1984). It is quite likely that flailing and beating with a stick was a suitable method of threshing at Çatalhöyük.

With regards to winnowing and sieving, as aforementioned, there is evidence that basketry at Çatalhöyük was utilised for winnowing. Additionally, ethnographic research conducted by Hillman shows that winnowing and sieving can take place with a combination of baskets and sieves fitted with both pierced and unpierced leather "sheets," even a "mesh made of strips of uncured, scoured leather" can be utilised for sieving and is well-documented throughout Turkey (Hillman, 1984: 123-125). Occasionally, mesh for sieves can also be made from scraped leather, woven reeds, or they can even be made from double strands of animal gut

(Hillman, 1984: 131). Although these would not necessarily survive the archaeological record, these examples very easily could have occurred at Çatalhöyük.

Having archaeobotanical and artefactual evidence from Çatalhöyük indicating threshing, winnowing, dehusking, and sieving occurred, and ethnographic evidence which provides an account of how this may have occurred, it possible to determine how these crop processing stages occurred at Çatalhöyük. For this analysis, as indicated in Figure 31 and Figure 32, hulled cereals are threshed and winnowed twice, pounded, coarse sieved twice, and fine sieved once whilst free-threshing wheat is threshed, winnowed, and coarse and fined sieved once. Naked barley, on the other hand, is threshed, winnowed, and coarse sieved twice, and fine sieved once. The grain which is processed will either be utilised for seed or curation, i.e., food. Once these stages take place, all of which require an energy investment from Çatalhöyük peoples, the energy gathered from domestic crops either sustains Çatalhöyük or Çatalhöyük's agricultural system. By specifying these parameters for how threshing, winnowing, and sieving would have taken place at Çatalhöyük, it is possible to determine the time it would have taken to complete these activities. Fortunately, the timing and rate at which these processes take to complete has been attested for ethnographically as well as determined via experimental archaeology. By utilising these data sources, it is possible to provide time estimates which are representative of the Çatalhöyük archaeological data. The time requirements for threshing, winnowing, dehusking, and sieving are provided below.

Table 26: Time requirements for threshing, winnowing, dehusking, and sieving based on both crop type action. The table below presents time estimates for threshing, winnowing, and sieving, with descriptions of crop processing action, harvesting in hectares per hour, and the source from which this data came. Overall, dehusking takes the most time to complete, followed by threshing, winnowing and sieving.

Crop	Action	Time estimate	Description	Source
Cereals (general)	Manual threshing	1.6 to 33 kg/hr/pers.	800 kilograms of cereal, average 100-300 kilograms per man day, between 3-8 days	(Halstead, 2014: 182)
Wheat	Manual threshing	15 kg/hr/pers.	Manual threshing by flailing, leave straw intact; 120 kilograms per man day	(Halstead, 2014: 166)
Barley	Manual threshing	15-19 kg/hr/pers.	Manual threshing by flailing, leave straw intact; 120 to 150 kilograms per man day	(Halstead, 2014: 166)
Cereals (general)	Manual threshing	19-23 kg/hr/pers.	Flailing ears and straw indoors/outdoors; 18 kilograms per man day	(Halstead, 2014: 168)
Cereals (general)	Manual Threshing	11-13 kg/hr/pers.	5 to 6 flailers produce 450-525 kilograms (90 kilograms/person)	(Halstead, 2014: 168)
Cereals (general)	Manual Threshing	38 kg/hr/pers.	2 men flail 600 kilograms in one day	(Halstead, 2014: 168)

Cereals (general)	Trampling	16-19 kg/hr/pers.	3 men trampling 750-900 kilograms of grain in 2 days	(Halstead, 2014: 168)
Cereals (general)	Threshing and primary crop cleaning	0.11-0.17 hectares/hr/pers.	2-3 workdays per hectare of land	(Gregg, 1988: 161-163)
Threshing for Çatalhöyük		***16 kilograms per hour***		
Cereals (general)	Winnowing	50 -63 kg/hr/pers.	Winnowing with a favourable breeze, one person sweeping and coarse sieving; 200-250 kilograms of grain in one afternoon	(Halstead, 2014: 169)
Cereals (general)	Winnowing	75-100 kg/hr/pers.	300 kilograms winnowed in 3 to 4 hours	(Halstead, 2014: 169)
Cereals (general)	Winnowing with winnowing sieves	63 kg/hr/pers.	1000 kilograms winnowed by 2 women in 1 day	(Halstead, 2014: 168)
Wheat	Winnowing	40 kg/hr/pers.	40 kilograms of wheat per man-hour	(Halstead, 2014: 167, Russell, 1988: 124-125)
Barley	Winnowing	50 kg/hr/pers.	50 kilograms per man-hour	(Halstead, 2014: 167, Russell, 1988: 124-125)
Winnowing for Çatalhöyük		***63 kilograms per hour***		
Emmer	Grinding	1.9 kilograms/hour	Stone slab and cylindrical handstone, grinding very hard emmer (Zimmerhackl) wheat to coarse meal	(Samuel, 2010)
Emmer	Grinding	2.1 kilograms/hour	Stone slab and cylindrical handstone, grinding soft emmer (Garfagnana) wheat to coarse meal	(Samuel, 2010)
Emmer	Pounding and grinding	0.6 kilograms/hour	Dehusking experiments with various tools	(Meurers-Balke and Lüning, 1999)
Dehusking wild einkorn	Pounding and grinding	0.3 kilograms/hour		(Russell, 1988, Wright, 1994)

Dehusking einkorn	Pounding and grinding	0.03		(Valamoti, Chondrou et al., 2013)
Einkorn dehusked to meal	Pounding and grinding	0.02		(Valamoti, Chondrou et al., 2013)
Einkorn	Grinding	0.6	Einkorn ground to flour, result was a mix of cereals and stone particles; ground utilising replica grinding stones	(Dietrich, Meister et al., 2019: 25)
General hulled cereals	Pounding and grinding	0.6 kilograms/hour	A single handstone used bidirectionally can produce an average of 4800 grams within 8 working hours. Experiments utilising replica grinding stones at Göbekli Tepe	(Dietrich, Meister et al., 2019: 25)
General hulled cereals (Emmer, Einkorn, Spelt)	Pounding and grinding	3.4 kilograms/hour	Using a saddle quern, however, saddle quern is less efficient. Using a saddle quern only yields 53 to 74% of grain	(Meurers-Balke and Lüning, 1999)
General hulled cereals (Emmer, Einkorn, Spelt)	Pounding and grinding	2.0 kilograms/hour	Using a wooden mortar is very efficient, yields 94% to 100% of the grain	(Meurers-Balke and Lüning, 1999)
General hulled cereals	Pounding and grinding	0.5 to 7 kilograms per hour	Groat grinding experiments with handstones and grinding slabs	(Wright, 1994: 246)
Dehusking Einkorn for Çatalhöyük	***1.8 kilograms per hour***			
Dehusking Emmer for Çatalhöyük	***2.4 kilograms per hour***			
Cereals (general)	Sieving	150 to 200 kg/hr/pers.	300 kilograms coarse sieved in 1.5 to 2 hours	(Halstead, 2014: 169)
Sieving for Çatalhöyük		***175 kilograms per hour***		

Referring to the table above, threshing rates range from 1.6 to 33 kilograms of cereal per hour per person, depending on the method of threshing (manual, trampling) as well as the type of cereal. All of the threshing estimates above are provided by Halstead's (2014) detailed Mediterranean accounts and are comprised of a variety of threshing activities, all of which include some sort of *manual* threshing, without the aid of machines, which makes them apt for this analysis. Some of the threshing activities including flailing, flailing with straw intact, flailing indoors and outdoors, trampling (by people), as well as manual threshing with primary crop cleaning (Dietrich, Meister et al., 2019, Halstead, 2014, Meurers-Balke and Lüning, 1999, Valamoti, Chondrou et al., 2013, Wright, 1994). Halstead's (2014) threshing accounts also include the difference between barley and wheat. Although we cannot verify the exact method by which Çatalhöyük peoples threshed crops, these activities reflect the potential variation in threshing activities that would have taken place, therefore, they are appropriate threshing rates for this analysis. The average threshing rate of these estimates, which is utilised for this analysis, is 16 kilograms per hour. This value was utilised for all cereal types.

Winnowing rates range from 40 to 100 kilograms per hour per person, depending on the cereal. All the winnowing rates above are provided by Halstead's (2014) detailed accounts of winnowing activities in the Mediterranean and Russell's (1988) threshing accounts within an Iranian village. Although we cannot verify the exact method by which Çatalhöyük peoples winnowed crops, winnowing is a straightforward activity; these activities reflect the variation in winnowing practices and therefore serve as an appropriate time estimate for winnowing. The average winnowing rate of these estimates is 63 kilograms per hour. Winnowing takes much less time to complete compared to threshing; approximately four times less, on average. For this analysis, the average of 63 kilograms per hour per person was utilised for all cereals.

Dehusking (pounding or grinding) rates range from 0.03 to 7 kilograms per hour per person, depending upon the method of dehusking and the cereal. Fortunately, dehusking is a well-researched crop processing activity, both within ethnographic research and experimental archaeology. The issue surrounding dehusking cereals, however, is that quite often pounding rates are neglected in ethnographic and even experimental archaeological literature. Grinding rates with slabs, querns, and rotaries are well established, however, grinding with pestles and mortars, and handstones is much more difficult to acquire (Samuel, 2010). Further, with regards to ethnographic research, smaller, hand-held mortars and pestle are no longer widely used for cereal processing; therefore, there is simply not a significant amount of ethnographic research on the rates of these processes. However, there is ample experimental archaeological literature utilising replica tools. Therefore, the dehusking rates from Table 26 above come from multiple ethnographic and experimental archaeological sources, which are further described below.

Samuel 2010 conducted experiments on cereal grinding in ancient Egypt specifically focused on using a saddle quern to process three varieties of emmer wheat (very hard and soft types), a durum wheat (hard wheat), and a free-threshing bread wheat (soft wheat). Samuel used a flat granite quern and a cylindrical handstone for grinding, with the miller kneeling behind the quern to complete the process (Samuel, 2010: 458). Samuel ground all five wheats into coarse and fine meals, compared them, and even compared the results with a rotary quern. The hardness of the wheat and time taken to coarse and fine meal the wheats were also recorded. The dehusking rates from stone slabs and a cylindrical handstone are provided in Table 26.

Jutta Meurers-Balke and Jens Lüning in *Some Aspects and Experiments Concerning the processing of Glume Wheats,* present results from sowing, cultivating, harvesting, storing, and processing experiments, based on ethnographic observations. Meurers-Balke and Lüning used einkorn wheat, emmer wheat, spelt, and harvested from experimental fields, reported comparisons and findings, and compared to charred archaeobotanical data(Meurers-Balke and Lüning, 1999). Their experiments focused on reconstructing Neolithic agricultural activities, specifically sowing, cultivating, harvesting, storing and processing einkorn, emmer, and spelt, all of which were harvested from their experimental fields (Meurers-Balke and Lüning, 1999). Meurers-Balke and Lüning compared dehusking emmer, einkorn, and spelt in the following ways (1) dehusking untreated on saddle querns, wooden mortars, and in a solid mortar (a hollowed out tree-trunk), (2) experimented with dehusking after 4 hours of heating, (4) dehusked after treatment at various temperatures (compared parching methods), (5) experimented on winnowing (6) experimented with dehusking and grinding to flour in one operation, (7) ground husked grains on a quern, and (9) compared winnowing, sieving, and casting up (Meurers-Balke and Lüning, 1999). Meurers-Balke and Lüning utilised replica Neolithic tools to complete their experiments. For this analysis, their pounding and grinding estimates utilising a saddle quern and wooden mortar are utilised and provided in Table 26 above.

Dietrich et al. 2019 in *Cereal Processing at Early Neolithic Göbekli Tepe, southeastern Turkey,* analysed cereal processing at Early Neolithic Göbekli Tepe, southeastern Anatolia. Dietrich et al. 2019 integrated formal, experimental, macroscopical, and microscopical use-wear analyses and concluded that the people of Göbekli Tepe produced standardised and efficient grinding tools. Dietrich et al. 2019 used 3D replicas of grinding tool equipment to experimentally grind materials and establish a reference collection to identified observed traces and compared to phytolith samples from Göbekli Tepe (Dietrich, Meister et al., 2019 :3). Analysing more than 7000 artefacts, they utilised archaeobotanical evidence, experimental archaeology, and macroscopical and microscopical use-wear analyses to reveal that Göbekli Tepe's people produced standardised and efficient grinding tools for cereal processing (Dietrich, Meister et al., 2019). Their experiments utilised replica tools from Göbekli Tepe and focused on dehusking and grinding cereals; the rates at which they pounded or ground cereals were provided and compared, and, the Göbekli Tepe assemblage was also compared to Çatalhöyük's (Dietrich, Meister et al., 2019). Çatalhöyük's assemblage includes querns, slabs, roughouts and handstones, whereas grinding slabs, grinding bowls, handstones, pestles, and mortars are present at Göbekli Tepe, therefore, the rates provided from this analyses are particularly apt for this thesis (Dietrich, Meister et al., 2019, Wright, 2014). The rates for this analysis utilised from their experiments include einkorn being ground to flour with replica grinding stones and grinding general cereals using a single handstone bidirectionally, again, with replica stone tools.

Katherine Wright in her article *Ground-Stone Tools and Hunter-Gatherer Subsistence in Southwest Asia: Implications for the Transition to Farming* (1994), examines subsistence in late Pleistocene southwest Asia in relation to ethnographic and experimental data on cereal processing data. Wright 1994 examined ground stone tools and hunter-gatherer subsistence trends in southwest Asia through the lens of ethnographic and experimental data on plant processing methods which are required for consumption. Wright emphasises that pounding and grinding are labour-intensive processing methods, and, that these processes, which would have also been required to make wild cereals edible, have been wildly underestimated (Wright, 1994). This is something which archaeologists have neglected with regards to the uptake of agriculture. Further, Wright also critiques and reviews ethnographic and experimental archaeology research which has focused on cereal processing and provides dehusking rates (Wright, 1994: 244-246). The dehusking rates from Wright's analysis utilised here include general hulled cereal pounding and grinding, more specifically groat grinding experiments with handstones and grinding slabs.

Although it was not utilised for time estimates, the data and information within Füsun Ertuĝ-Yaras' ethnobotanical studies in Central Anatolia (1997, 2000) was pivotal to this analysis. Ertuĝ-Yaras presents detailed ethnographic accounts of plant use at a contemporary village in the Askaray province of Central Anatolia (Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000). This study was completed in order to help inform archaeologists, archaeobotanists, botanists, pharmacologists, and economists regarding the variety and intensity of use and processing of wild and domestic plants (Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000).

Finally, in *Plant food processing and ground stone equipment in prehistoric Greece: An experimental investigation using seeds of einkorn and grass-pea,* Valamoti et al. 2013 present findings from experimental projects focused on cereal and pulse processing with replica grinding stones and assess the efficiency of small-sized grinding stones for food processing, preparation, and consumption. Their experiments focused on einkorn and grass-pea (pulse) processing with replica Neolithic grinding stones (Valamoti, Chondrou et al., 2013). They utilised small to medium sized grinding stones to process both einkorn and grass-pea and conducted a multitude of experiments including comparing unprocessed and pre-processed cereals (simmered, soaked, and dried), recorded the number of movements, how long the dehusking took, and, the amount of end product (Valamoti, Chondrou et al., 2013).

The dehusking rates in Table 26 represent a range of pounding and grinding activities which could have been used to dehusk hulled cereals at Çatalhöyük. The average of these dehusking rates is 1.8 kilograms per hour for einkorn and 2.4 kilograms per hour for emmer. The tools utilised in the experimental archaeological experiments are all Neolithic replica tools, which would have been similar to those at Çatalhöyük. Therefore, the data produced from these works is invaluable to this analysis.

Unfortunately, unlike threshing, winnowing and dehusking, sieving rates are more difficult to come by. Occasionally, sieving is completed via shaking machines, therefore sieving rates with machines are inapplicable for this analysis. Sieving mesh measurements, on the other hand, are ubiquitous although they, too, are currently inapplicable. Ethnographic research indicates that sieving itself is not considered to be a very arduous activity, and, it is completed in a piecemeal way, especially fine sieving (Halstead, 2014). In all, far less data is available for sieving rates. Although coarse sieving typically occurs while or just after winnowing, fine sieving is often completed on an "as needed" basis; therefore, ethnographic accounts do not always contain sieving rates. However, Halstead's 2014 work does provide a coarse-sieving rate of around 150 to 200 kilograms per hour, averaging to be 175 kilograms per hour. This average was utilised for this model.

With designating the threshing, winnowing, pounding, and sieving rates, which were calculated utilising ethnographic and experimental archaeological data, and how these would have taken place at Çatalhöyük, it is now possible to determine how much time as required for these processes. These quantifications, time spent threshing, winnowing, dehusking, and sieving per year, are presented below in Table 27.

Table 27 Threshing, Winnowing, Dehusking and Sieving Hours Required at Çatalhöyük Per Year. This table presents the threshing, winnowing, pounding, and sieving hours required for Çatalhöyük based on population and crop type. As Çatalhöyük's population increases and more domestic cereals are required, time dedicating to processing cereals (threshing, winnowing, dehusking, and sieving) also increases, i.e. threshing, winnowing, dehusking, and sieving scale with population. Further, dehusking hulled cereals requires the most amount of time, followed by threshing, winnowing, then sieving.

A. 75% reliance on domestic cereals

Population	100	500	1000	2000	3000
Dehusking Hours	4800	30000	57000	110000	160000

Threshing hours	2500	16000	30000	57000	85000
Winnowing Hours	680	4500	8200	16000	23000
Sieving (Coarse and Fine) Hours	330	2100	3860	7000	11000

B. 50% reliance on domestic cereals

Population	100	500	1000	2000	3000
Dehusking Hours	4300	22000	35000	70000	110000
Threshing hours	2300	11000	18000	36000	59000
Winnowing Hours	810	4200	6800	14000	22000
Sieving (Coarse and Fine) Hours	300	1500	2400	5000	8000

C. 25% reliance on domestic cereals

Population	100	500	1000	2000	3000
Dehusking Hours	1600	9000	22000	40000	70000
Threshing hours	900	5000	11000	18000	33000
Winnowing Hours	240	1300	3100	5000	9000
Sieving (Coarse and Fine) Hours	110	600	1460	2000	5000

Referring to Table 27 A, with a 75% reliance on domestic cereals, Çatalhöyük had to dedicate 330 to 11,000 hours to sieving, 680 to 23,000 hours to winnowing, 2,500 to 85,000 hours to threshing, and 4,800 to 160,000 hours to dehusking. With a 50% reliance on domestic cereals (Table 27 B), Çatalhöyük had to dedicate 300 to 8,000 hours to sieving, 810 to 22,000 hours to winnowing, 2,300 to 59,000 hours to threshing, and 4,300 to 110,000 hours to dehusking. With a 25% reliance on domestic cereals (Table 27 C), Çatalhöyük had to dedicate 110 to 5,000 hours to sieving, 240 to 9,000 hours to winnowing, 900 to 33,000 hours to threshing, and 1,600 to 70,000 hours to dehusking. The higher the reliance on domestic cereals, the more time that must be dedicated to processing cereals. Further, as Çatalhöyük's population grows over time, more cereals are required, thus, more cereals must be processed. Threshing, winnowing, pounding, and sieving are not necessarily dependent upon crop yield but instead are based on how much crop is processed. This model assumes that harvests are successful, no matter their yield. Similar to planting and tillage, the amount of hours required for dehusking, threshing, winnowing, and sieving for various population estimates during Çatalhöyük's growth would be the same for its decline. In other words, these crop processing hours for a population of 500 people during Çatalhöyük's growth is the same as its decline and crop processing hours for a population of 1000 people is the same for Çatalhöyük's growth as it is for when it declined. Thus, dehusking, threshing, winnowing, and sieving energy is the same for these estimates regardless of whether it occurs during Çatalhöyük's growth or decline, as the same amount of cereals would be required to sustain these population estimates. Overall, crop processing for Çatalhöyük, especially when Çatalhöyük's population as growing, would have been time intensive.

With determining the amount of time each of these processing steps would have required, threshing, winnowing, pounding, and sieving vary significantly by the amount of time each takes. However, their PARs also vary. Table 28 below indicates the difference in PARs between these activities.

Table 28 Physical Activity ratios utilised to determine the average threshing, winnowing, and sieving PARs for this analysis. Although these PARs are not all specific to wheat, the average PAR for a range of similar crop processing steps was utilised for this analysis. The description of the activity, the

PAR, and the reference are provided in the table below. The average PAR for threshing is 5.1, the average PAR for winnowing is 2.7, and the average PAR for sieving is 4.3.

Activity	**Physical Activity Ratio Value**	**Reference**
Threshing Rice	4.6-6.0	(UNU, 1985, UNU, 2004)
Threshing by beating (various crops)	4.6	(Vaz, Karaolis et al., 2005)
Threshing (various crops)	5.6	(Vaz, Karaolis et al., 2005)
Threshing Çatalhöyük (average PAR)	***5.1***	
Winnowing (general)	3.6	(Vaz, Karaolis et al., 2005)
Winnowing Rice	2.3-3.6	(UNU, 1985, UNU, 2004, Vaz, Karaolis et al., 2005)
Winnowing (general) while sitting	2.5	(Vaz, Karaolis et al., 2005)
Winnowing	1.85	(Vaz, Karaolis et al., 2005)
Winnowing Çatalhöyük (average PAR)	***2.7***	
Pounding grain	4.97	(Vaz, Karaolis et al., 2005)
Grinding grain on millstone	4.64	(Vaz, Karaolis et al., 2005)
Pounding grain	5.8	(Vaz, Karaolis et al., 2005)
Pounding grain (single woman)	6.3	(Vaz, Karaolis et al., 2005)
Pounding rice	5.4	(Vaz, Karaolis et al., 2005)
Pounding grain	5.6, 5.0-6.3	(UNU, 1985, UNU, 2004)
Pounding Çatalhöyük (average PAR)	***5.4***	
Sift sand using sieve	4.2	(Vaz, Karaolis et al., 2005)
Sieving Manioc	4.3	(Vaz, Karaolis et al., 2005)
Sieving Çatalhöyük (average PAR)	***4.3***	

The PAR for threshing related activities ranges from 4.6 to 6.0. Although none of the threshing PARs are threshing wheat products in themselves, they all represent manual threshing, and the physical actions of threshing rice are similar to threshing wheats. Therefore, for this model, the threshing average of these PARs is 5.1, utilised for this analysis.

Winnowing PARs range from 1.85 to 3.6. The winnowing PARs for this analysis, like that of threshing, are also all completed manually, therefore they are apt for this analysis. Further, they also include winnowing whilst sitting, an activity which has been ethnographically attested for. Overall, the winnowing PARs are well-representative of the variety of winnowing activities which would have taken place at Çatalhöyük. The average winnowing PAR is 2.7, which is utilised for this model.

Referring to the PARs above, not only does dehusking take the most time to complete, but it also has the highest PAR of these particular cereal processes. Dehusking activities include pounding grain, pounding rice and pounding grain on a millstone; the PAR ranges from 4.6 to 6.3. The average PAR of these activities is 5.4, which is utilised for this model. All the dehusking PARs included in the table above were completed manually, making them appropriate for this analysis.

Finally, with regards to sieving, there is far less data and therefore, less of a range of sieving and sifting activities, which is problematic. However, sieving manioc is like sieving grain, and, sifting sand using a sieve is also, physically, a similar action. Therefore, the average PAR of these two processes is 4.3, which is utilised for this analysis.

Having quantified the threshing, winnowing, and sieving rates, the amount of time that would have been required for these activities, and, their PARs, it is now possible to quantify the threshing, winnowing and sieving energy required for Çatalhöyük. These are presented and discussed below.

6.2.2 Threshing, winnowing, sieving, and dehusking energy at Çatalhöyük

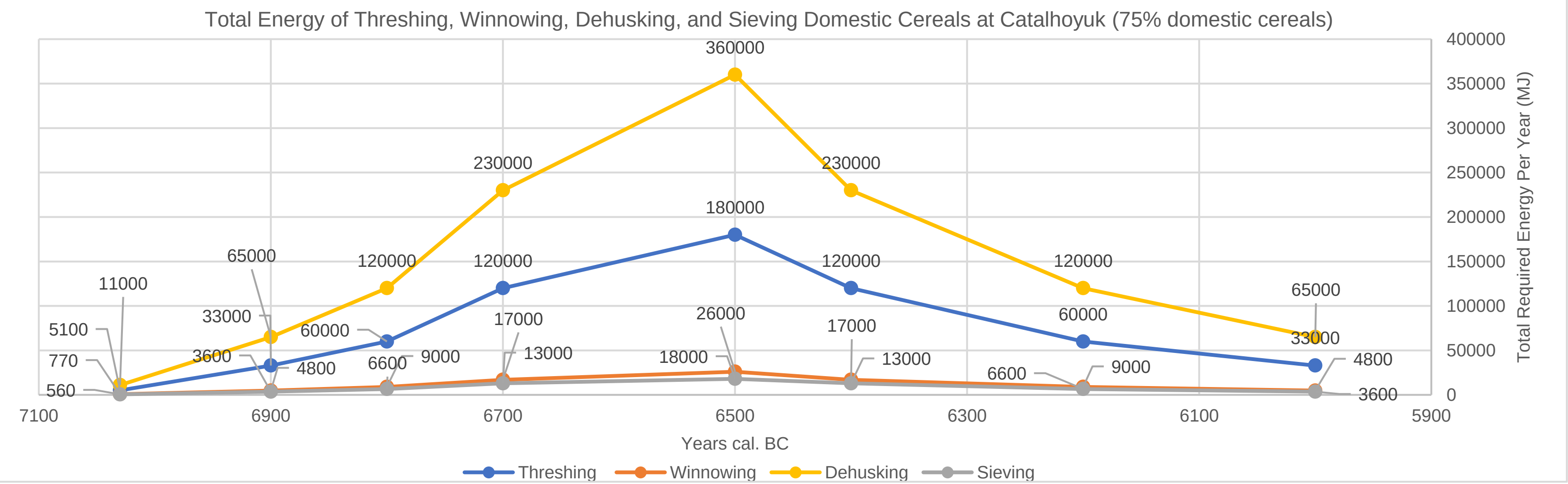
From an energy systems point of view, threshing, winnowing, dehusking, and sieving must take place for Çatalhöyük to retrieve the energy from domestic crops, but these actions in themselves also require an energy input. No matter the domestic cereal, all three of these processes must take place to extract and utilise the energy embedded in the cereal grain. Threshing helps to break or separate the grain from the main stalks of the plant, making it one of the most fundamental crop processing stages (Russell and Bogaard, 2014: 68). Threshing is a laborious task, no matter the cereal. Winnowing utilises wind energy yet it is also a pivotal task, as it helps separate the straw and chaff from the grain. Dehusking must take place on hulled cereals (here, emmer and einkorn) to process and utilise these crops; it helps to completely remove the grain from the cereal’s husk. Sieving helps to remove contaminants and any remaining chaff, rachis segments, or awns, thereby helping to retrieve clean grain.

Referring to Figure 31 and Figure 32, threshing, winnowing, dehusking, and sieving are not only dependent upon the cereal, but the processes themselves are dependent upon one another. Threshing, winnowing, pounding, and sieving cannot take place unless a crop is successfully harvested. A successful harvest cannot occur unless seedcorn is properly saved and stored, and seedcorn cannot be saved or stored unless it is properly threshed, winnowed, dehusked, and sieved (depending on the cereal). Further, these four agricultural processes require an energy input to occur. These aspects of threshing, winnowing, pounding, and sieving demonstrate three aspects of the agricultural feedback system: energy must be continuously invested into agricultural process, to benefit from agriculture all agricultural processes must be successful, and agricultural processes are inherently dependent upon one another.

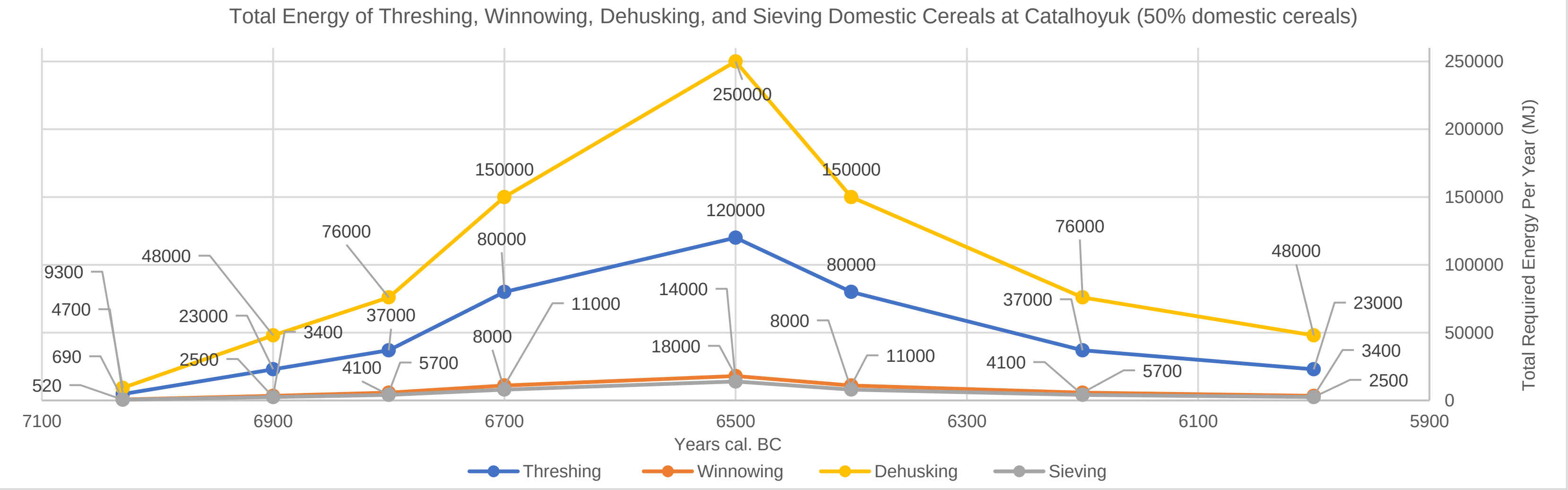
The introduction of this subsection presented the definitions of threshing, winnowing, dehusking and sieving, their place in Çatalhöyük’s agricultural feedback system, and discussed the differences in crop processing of free-threshing wheat versus hulled cereals. Section 6.2.1 presented threshing, winnowing, dehusking, and sieving at Çatalhöyük, including the archaeobotanical evidence supporting the occurrence of these processing activities, and ethnographic, artefactual, and experimental archaeological evidence supporting how these activities took place. Threshing, winnowing, dehusking, and sieving PARS were also determined, which were averaged from a range of threshing, winnowing, dehusking, and sieving activities. Dehusking hulled cereals is the most time consuming and physically laborious activity of these four, therefore, it is expected that it will require a significant energy investment. Winnowing and sieving require the least amount of time, but these processes still require an energy investment from Çatalhöyük to take place. To determine the energy of these processes at Çatalhöyük, the average basal metabolic rate (Table 2), the PAR of threshing, winnowing, pounding, and sieving (Table 28), and the time allocated for these activities must be multiplied together. The crop processing energy quantified is presented in megajoules per year, below.

Referring to Figure 33 A, with a 75% reliance on domestic cereals, Çatalhöyük would have had to invest 560 to 18,000 megajoules of energy per year to sieving, 770 to 26,000 megajoules of energy per year for winnowing, 5,100 to 180,000 megajoules per year for threshing, and 11,000 to 360,000 megajoules per year into dehusking. With a 50% reliance on domestic cereals (Figure 33 B), Çatalhöyük would have had to invest 520 to 14,000 megajoules of energy per year to sieving, 690 to 18,000 megajoules of energy per year for winnowing, 4,700 to 120,000 megajoules per year for threshing, and 9,300 to 250,000 megajoules per year into dehusking. With a 25% reliance on domestic cereals (Figure 33 C), Çatalhöyük would have had to invest 520 to 14,000 megajoules of energy per year to sieving, 690 to 18,000 megajoules of energy per year for winnowing, 4,700 to 120,000 megajoules per year for threshing, and 9,300 to 250,000 megajoules per year into dehusking. The higher the reliance on domestic cereals, the more energy that Çatalhöyük must dedicate to crop processing per year. Further, as Çatalhöyük grows, more grain must be processed, therefore, Çatalhöyük will dedicate more energy to these processes.

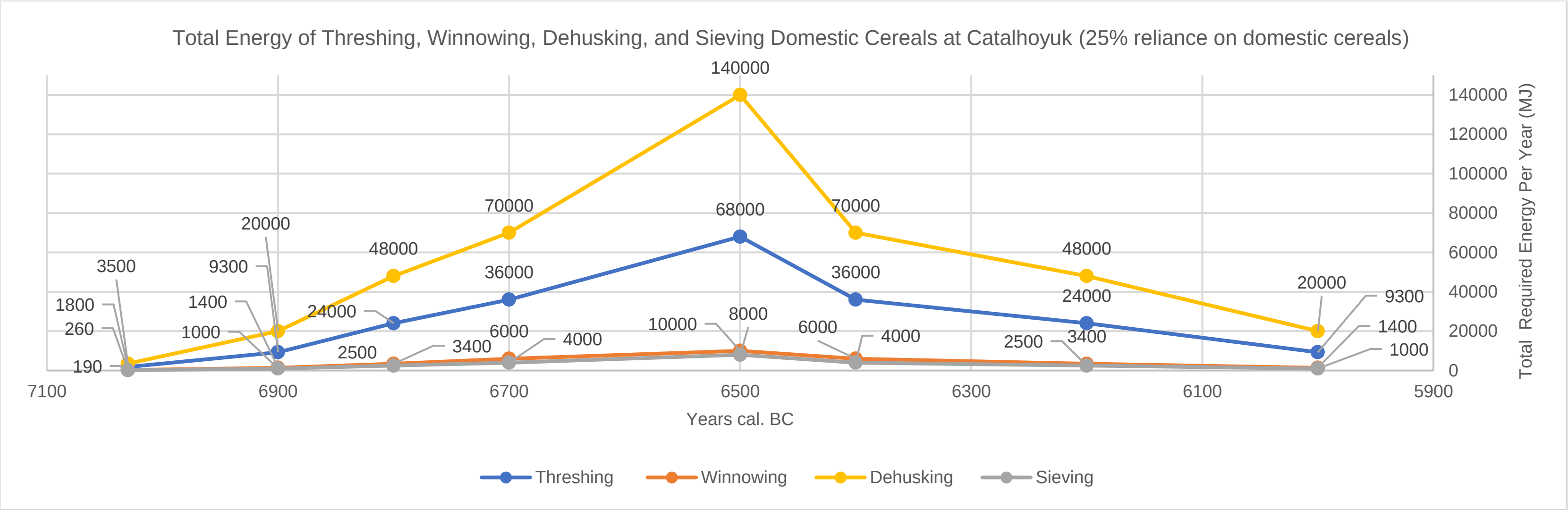
Comparatively speaking, threshing is more energy intensive than winnowing or sieving, combined, however, of these four processes, dehusking emmer and einkorn requires the most energy input from Çatalhöyük peoples, regardless of the reliance on domestic cereals. Dehusking requires more time dedicated to it and has a higher PAR than threshing, winnowing, or sieving, therefore, its high energy values are sensible. Threshing requires more time dedicated to it than winnowing or sieving and has a higher PAR than either, therefore, its high energy values are also feasible. With regards to the winnowing and sieving, there is not a significant energy difference between these two processes. Although their PARs and time requirements are different, they are quite similar in terms of energy required to perform. This is related to winnowing requiring more time than sieving yet also having a lower PAR; sieving, on the other hand takes less time, but, has a higher PAR than winnowing.


Total Energy of Threshing, Winnowing, Dehusking, and Sieving Domestic Cereals at Catalhoyuk (75% domestic cereals)
360000
230000
230000
180000
65000
120000
120000
120000
120000
11000
65000
33000
60000
100000
26000
17000
17000
60000
5100
33000
770
3600
4800
6600
9000
13000
18000
13000
6600
9000
4800
560
3600
400000
350000
300000
250000
200000
150000
100000
50000
0
Total Required Energy Per Year (MJ)
7100
6900
6700
6500
6300
6100
5900
Years cal. BC
Threshing
Winnowing
Dehusking
Sieving

A


Total Energy of Threshing, Winnowing, Dehusking, and Sieving Domestic Cereals at Catalhoyuk (50% domestic cereals)
250000
150000
150000
120000
76000
80000
80000
76000
48000
48000
9300
4700
23000
37000
14000
37000
23000
3400
11000
8000
8000
690
2500
4100
5700
18000
11000
4100
5700
3400
520
2500
250000
200000
150000
100000
50000
0
Total Required Energy Per Year (MJ)
7100
6900
6700
6500
6300
6100
5900
Years cal. BC
Threshing
Winnowing
Dehusking
Sieving

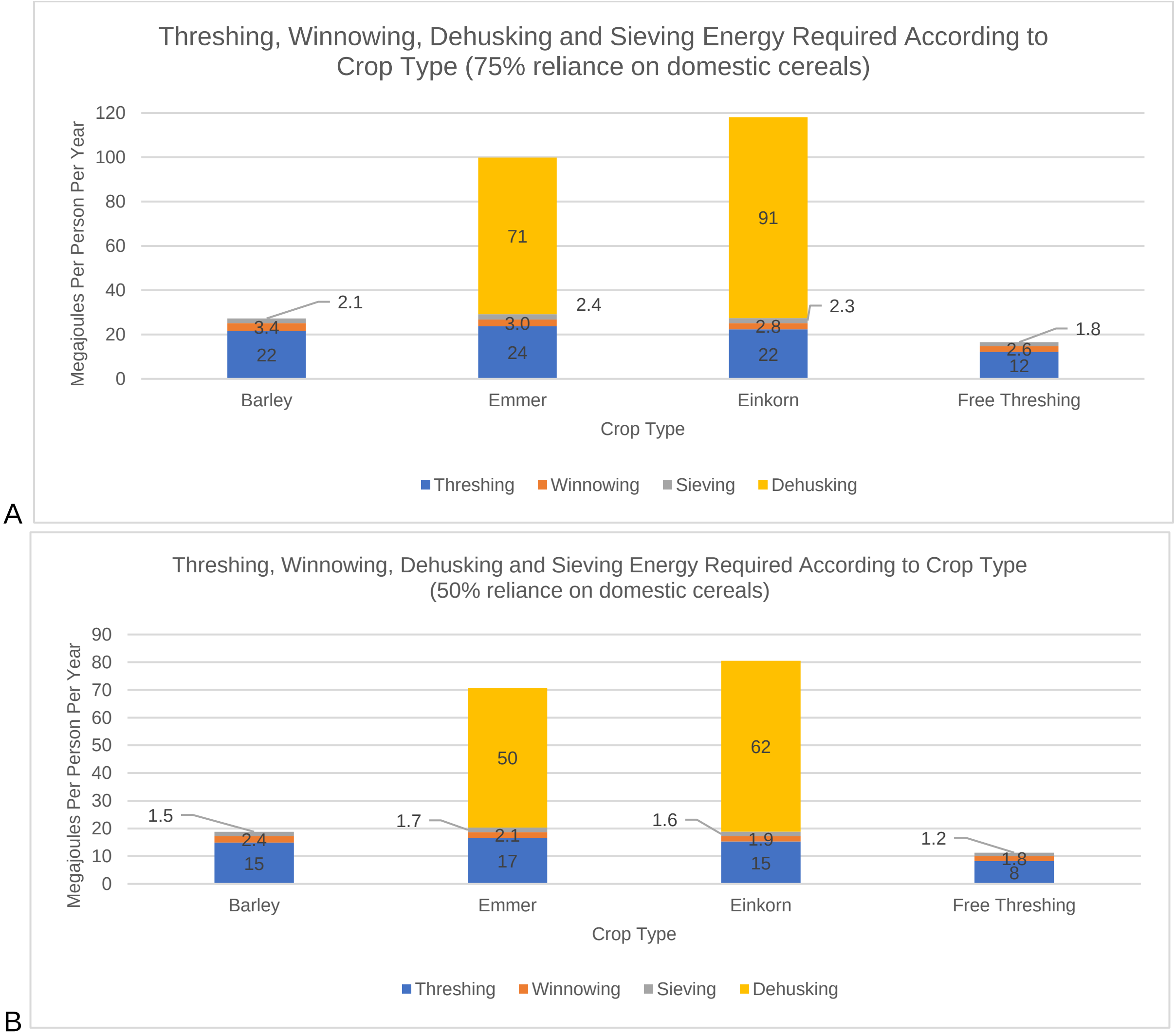
B

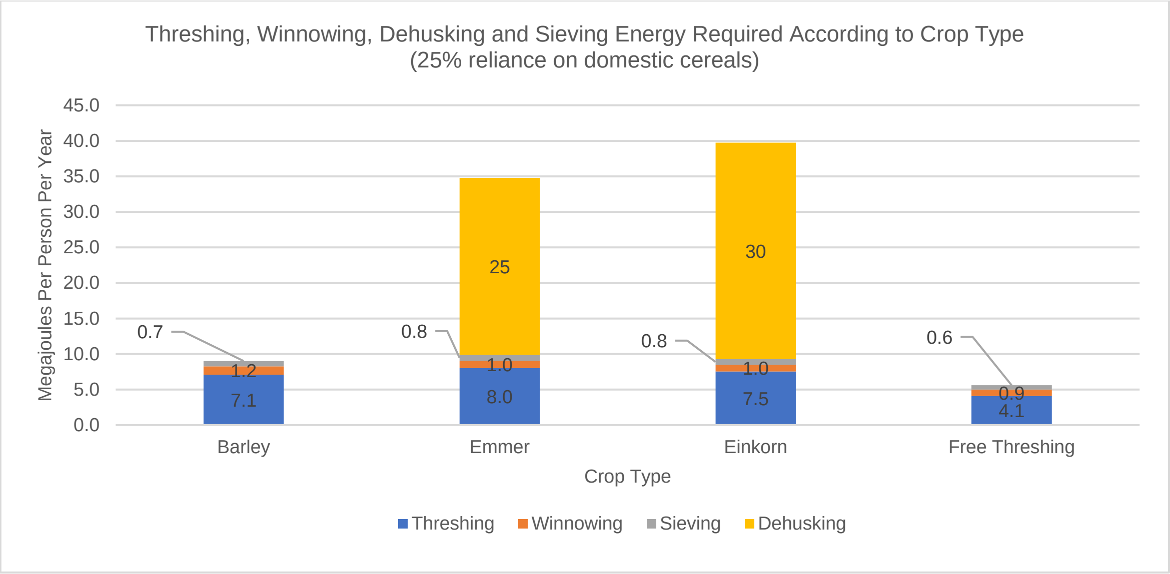


C

Figure 33 Threshing, Winnowing, Dehusking and Sieving Energy Required for Çatalhöyük in Megajoules Per Year, for a 75% reliance (A), 50% reliance (B) and 25% reliance (C) on domestic cereals. These figures demonstrates the energy input for threshing, winnowing, dehusking, and sieving which would have been required for domestic cereals to sustain agriculture at Çatalhöyük. The higher the reliance on domestic cereals, the more energy that must be dedicated to crop processing. Further, as Çatalhöyük grows over time, the energy dedicated to carrying out these processes also increases. More cereals are required to keep Çatalhöyük sustained, therefore, more threshing, winnowing, dehusking, and sieving must take place. Comparatively, dehusking emmer and einkorn requires more energy input from Çatalhöyük than threshing, winnowing, or sieving. Finally, there is not a substantial energy difference between sieving and winnowing; these two processes are quite similar in terms of energy intensity.

The energy intensity of these processes not only differs by activity, but also by crop type. Figure 34 demonstrates the difference in average energy, per person per year, for threshing, winnowing, pounding, and sieving for each domestic cereal at Çatalhöyük, depending upon the reliance on domestic cereal. Again, it is unlikely that the entire Çatalhöyük population would have been processing cereals, thus, the average crop processing energy here for the average individual was quantified as if 75% of the population was participating.





C

Figure 34: Threshing, Winnowing, Dehusking and Sieving Energy Required in Megajoules Per Person Per Year, at Çatalhöyük. This figure shows Çatalhöyük's energy requirements for threshing, winnowing, and sieving per person per year, based on crop type and percent reliance on domestic cereal. The higher the reliance on domestic cereals, the more energy that must be dedicated to processing cereals. Even on an individual level, dehusking requires a significant amount of energy, compared to threshing, winnowing and sieving. Einkorn and Emmer are required to dehusk, and thus, require the most energy input to process. Further, emmer and einkorn require the most energy to thresh, whereas free-threshing wheat requires the least amount of threshing energy. Focusing on winnowing and sieving, the difference between energy required for winnowing and sieving various crops is negligible.

Highlighted in Figure 34 are the differences in threshing, winnowing, dehusking and sieving energy between crops, on an individual (average per person per year) basis. Dehusking or pounding hulled cereals requires a significant energy input, even on an individual level. As aforementioned, glume or hulled species require not only an extra round of threshing and winnowing, but also require dehusking (pounding or grinding) the cereal, as the tough glumes of hulled wheats require more force to release the grains from the hull (Halstead, 2014, Tzarfati, Saranga et al., 2013, Van Alfen, 2014). Therefore, it was expected that einkorn and emmer are more energy intensive to process than either free-threshing wheat or barley.

With regards to other crop processes, einkorn and emmer require the most energy to thresh, whereas free-threshing wheat requires the least amount of threshing energy. Focusing on winnowing, barley and emmer require the most winnowing energy, whereas einkorn and free-threshing wheat require the least. Finally, emmer requires the most amount of sieving energy, followed by barley and einkorn, then free-threshing wheat. Dehusking, even on an individual level, is the most energy intensive of these four cereal processes, especially the dehusking of einkorn. Overall, free-threshing wheat is the least energy intensive crop, with regards to all crop processes.

For this model, the average yield for domestic crops that were present at Çatalhöyük is, from highest to lowest: emmer, einkorn, free-threshing wheat, and barley. The calorific value of these crops, from highest to lowest (Table 8, chapter 5) is, barley, einkorn, emmer, and free-threshing wheat. Based off their yields and nutritional values, and assuming all four domestic cereals provided equally to 75%, 50%, and 25% of the diet, this makes the greatest amount of cereals being required as free-threshing wheat, emmer, einkorn, and finally, barley. It is particularly interesting to note that although free-threshing wheat is the "least" nutritious and accounts for the most weight in terms of grain, it is still the least energy intensive crop to process. With regards to threshing, winnowing, and sieving; barley and einkorn are the opposite. Einkorn, nutritionally, has an average to high yield compared to other crops, requires the least amount of land to grow, the second-highest kilocalorie value per kilogram, however, it is the most energy intensive crop to process.

Having calculated the land clearance, tillage, planting, harvesting, and crop processing energy for the four primary domestic cereals utilised for Çatalhöyük, it is now possible to amalgamate, compare, and interpret this data.

7 CHAPTER 7: ÇATALHÖYÜK'S AGRICULTURAL ENERGY SYSTEM: INTERPRETATION AND DISCUSSION

7.1 INTRODUCTION

Quantifications made throughout chapters 4-6 have made it possible to investigate agricultural flows in a quantified way, allowing for conclusions about what encourages population growth, facilitates an increasing reliance upon agriculture, why agriculture requires additional land, and helps to explain limits to growth within an agricultural system. In quantifying the energy of agricultural processes at Çatalhöyük, we are getting towards a better understanding of the relationship between energy, growth, settlement, and agriculture posited by those discussed throughout chapter 2. By viewing this subsistence lifeway, agriculture, as energy system this thesis thus far has demonstrated the energy requirement of agriculture for a Neolithic society, and quantifies and proves the existence of a positive energy feedback between agriculture, surplus energy, and societal development discussed by many throughout chapter 1 (Shennan 2007, 2013, 2018; Rindos 1980) and chapter 2 (White 1943; Chaisson 2003, 2005, 2011, 2013, 2014a, 2014b, 2015; Smil 2000, 2008, 2013, 2017; Odum and Pinkerton 1955, Odum and Odum 1977, Odum 1977, 2007; Fischer-Kowalski and Haberl 2007, 1997, Fischer-Kowalski et al. 2014, Fischer-Kowalski and Weisz 1999, Lenton and Watson 2011, Lenton et al. 2021; Rappaport 1971; Barrett 2011).

To fully understand Çatalhöyük's agricultural energy system and how the agricultural energy feedback system occurred at Çatalhöyük, and thus, understand the broader implications of agriculture in the Neolithic, the succeeding sections of this chapter will focus on combining, analysing, and interpreting the energy baseline quantified in chapters 5 and 6. This chapter demonstrates how these quantifications and data allow us to better understand the agricultural energy feedback system and the intricacies of the Neolithic Revolution and the spread of agriculture. The amalgamated data provides a quantifiable reason and a potential mechanism as to why the Neolithic Revolution came with unprecedented population growth, surplus production, new land requirements, changes in nutrition, workload, mobility, social interaction, and, new ensembles of activities, behaviours, and technologies (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995).

Section 7.2 focuses on analysing Çatalhöyük's agricultural energy system including energy inputs, costs, and its efficiency. Overall, this chapter subsection demonstrates that agriculture's energetic cost and efficiency *improve* when more people participate in agriculture. This improved cost and efficiency effectively aids in population growth and enforces a reliance upon agriculture. However, this improved cost and efficiency are only beneficial if agriculture has enough people participating, enough land, and sufficiently high yields. Furthermore, this efficiency and cost change throughout Çatalhöyük's occupation depending on these factors and is not limitless. Çatalhöyük's threshold for population growth, which is influenced by domestic cereal reliance and yield (land), and maintaining energetic efficiency was 2000-3000 people. Once this threshold was reached, Çatalhöyük's agricultural system must be made to be more efficient to keep relying upon agriculture and sustaining itself. Some of the unintended consequences of sustaining agriculture and improving efficiency resulted in the changes that we see during Çatalhöyük's Middle Period, such as permanent changes to the environment and changes in diet and nutrition, material culture, technology, animal relationships, and even ritual practise. Thus, Çatalhöyük, and arguably, agricultural societies in the Asian Neolithic more generally, become increasingly reliant upon agriculture due to a combination of receiving and maintaining an energy surplus, investing more energy into agricultural processes, and the improved energetic cost and efficiency that comes with a growing population. The efficiency of their agricultural system limits their growth.

To better understand how these inputs, efficiency, and costs fit within Çatalhöyük's agricultural energy system, section 7.3 correlates the quantified model at hand with archaeological data and demonstrates the agricultural energy feedback system was occurring at Çatalhöyük. Moreover, this section demonstrates how this feedback system worked, its implications for Çatalhöyük, and its contributions about the broader Neolithic, especially in relation to energy and growth. Section 7.4 considers how these agricultural energy models fit in with Çatalhöyük's archaeological data. Finally, section 7.5 focuses upon research avenues revealed by the energy model developed in this thesis.

7.2 ANALYSING ÇATALHÖYÜK'S AGRICULTURAL ENERGY SYSTEM: ENERGY INPUTS, COSTS, AND EFFICIENCY

Chapter 2 emphasised that most theorists neglect modelling the energy of agricultural processes separately, the differences in yield scenarios are often not accounted for, and overall, comparisons between crops in terms of agricultural input are often neglected; thus, the complex mechanisms behind population growth, agricultural energy surplus, and agricultural energy input are missing. Therefore, quantifying and comparing the energy of processes at Çatalhöyük provides an opportunity to better understand the role agriculture's processes play within not only Çatalhöyük's agricultural system, but Neolithic agricultural energy systems more generally. Chapters 5 and 6 quantified the minimum energy requirements or Çatalhöyük's agricultural system, including the amount cereal energy required for Çatalhöyük's population throughout its occupation, the amount of land required for low, average, and high crop yield scenarios to sustain this population, the amount of seed storage required, and the agricultural energy investment required of agricultural processes, including land clearance, tillage, planting, harvesting, and crop processing, depending upon cereal, crop yield, population, and percent dietary reliance on domestic cereals. Overall, the yearly investment required for most agricultural processes scales linearly with population. Land clearance, however, is dependent upon the rate of population growth.

(1) At Çatalhöyük, irrespective of domestic cereal reliance, low yield crops require more energy input, are more costly, and are less efficient than high yielding crops.
(2) Tillage, harvesting, land clearance, and crop processing are energy-intensive agricultural processes, and thus, are crucial to the success of Çatalhöyük's agricultural system.
(3) The higher the reliance on domestic cereals, the more energy input required to sustain agriculture but the larger the energy received from agriculture. With a lower reliance on domestic cereals, less energy input is required to sustain agriculture; however, less energy is obtained from agriculture.
(4) For Çatalhöyük, during its Early Period, agriculture's efficiency initially increases and its cost decreases with population growth. This efficiency and cost change throughout its occupation depending on population growth and decline and the amount of land required to sustain agriculture (land required, yield, and how much of the diet is reliant upon domestic cereals).:

a. Needing more land during rapid population growth or population decline can be made efficient and less costly by utilising a smaller reliance on high yielding cereals, or a larger reliance on average yielding cereals. A lower reliance on high yielding cereals requires the least amount of extra land to sustain agriculture whereas a larger reliance on average yielding cereals produces more agricultural energy; both of which improve cost and efficiency. Furthermore, a population decline can aid in making Çatalhöyük's agricultural system less costly and more efficient, regardless of yield or domestic cereal reliance.
b. If crops are low yielding, needing more land at times of rapid population growth or decline cannot be substantially counteracted (i.e. made more efficient and less costly) regardless of domestic cereal reliance because they are too costly and too inefficient to maintain.
c. Catalhoyuk's threshold for population growth dependent on domestic cereal reliance and yield (land) is 2000-3000 people. Once this threshold was reached, Çatalhöyük's agricultural system must be made to be more efficient to keep relying upon agriculture.

The implications of these findings are significant, as the developments at Neolithic Çatalhöyük are not isolated incidents. Çatalhöyük itself is representative of the impact of the spread of agriculture throughout southwestern Asia and Europe (Barrett, 2011, Barrett, 2016, Barrett, 2019, Shennan, 2018). Thus, understanding the relationship between agriculture, energy, and population growth at Çatalhöyük, helps to distinguish the relationship between energy, population growth, and the spread of agriculture during the Neolithic.

Within this chapter subsection, first, I will compare the overall energy input of Çatalhöyük's agricultural system within low, average, and high yield scenarios. Then, I will compare the input of agricultural processes, also depending on the yield scenario. Understanding the energy differences between various yield scenarios and between agricultural processes for that matter, is crucial for several reasons. First, as emphasised in section 5.2, yields allow for understanding land requirements and how much energy can be received from crops; in other words, we can understand how much energy people receive from agriculture and better understand land use and resource catchment zones (Evans, 1993, Gregg, 1988). Second, within agricultural systems, crop yield is essentially one of the determinants of energy output; higher yields provide more energy, lower yields provide less energy (Evans, 1993, Filipović, 2014, Gregg, 1988, Halstead, 2014). Further, yields vary for a number of reasons including climate, land productivity, whether or not there is adequate tillage, soil nutrients, manuring, and the presence of weeds, for example (Bogaard, 2005, Bogaard, Filipović et al., 2017, Bogaard, Fraser et al., 2013, Charles, Doherty et al., 2014, Filipović, 2014, Halstead, 2014). Yields are not always consistent; there are bad years and good years and this could vary for a variety of reasons. Thus, modelling different yield scenarios allows for a general picture of what, for example, high yields resulting from manuring may do to an energy system. As aforementioned in chapter 5, it is impossible to know the exact proportion of cereals in the Çatalhöyük diet; however, by modelling a range of dietary reliance on domestic cereals, i.e. modelling Çatalhöyük's agricultural system based on a 25%, 50%, and 75% reliance on cereals, allows for a more robust model of potential agricultural scenarios at Çatalhöyük. By investigating different yield scenarios *and the* proportion of reliance on dietary cereals, as is done in this thesis, we can account for variations and better understand different scenarios in the past.

Third, crop yields are inherently tied to understanding the Neolithic and the spread of agriculture. Valclav Smil, for example, describes the evolution of agriculture as humanity's effort “to raise land productivity (to increase digestible energy yield) in order to accommodate larger populations” (Smil, 2017: 49). David Rindos explains that our history with agriculture is essentially “a history of instability in production and of agriculturally induced crises” and argues that yield instabilities are the root of migration and thus dispersal of agriculture during the Neolithic (Rindos, 1980: 752-753). Fischer-Kowalski and Haberl argue that agriculture’s increase in productivity allowed for populations to profit from them, grow, and aided in the colonising aspect of agriculture (Fischer-Kowalski and Haberl, 1997: 68). Lenton and Watson argue that agriculture itself requires work but is most successful with high productivity levels (Lenton and Watson, 2011: 371). Lenton et al. take this further to argue that agricultural societies typically invest or create technologies which specifically improve agricultural productivity, which only enhances the self-perpetuating aspects of agriculture (described in 2.3.5) even further (Lenton, Kohler et al., 2021). With regards to energy efficiency, Redman and colleagues argue that efficiency creates a positive feedback within societies; further, an increase in system efficiency allows for societies to gain surplus’ beyond their direct needs, setting the foundation for the emergence of complex societies (Redman, 2005, Redman and Kinzig, 2003). One of the primary assumptions of Optimal Foraging Theory and its Models are that individuals always optimise their efficiency; this is a way of testing this within an agricultural energy system (Kennett and Winterhalder, 2006: 13-14, Winterhalder and Smith, 2000: 51-54). Others mentioned throughout chapter 2 (Chaisson, 2014a, 2014b, Odum, 2007, 1977, Odum and Pinkerton, 1955, White, 1943) argue that agriculture’s surplus energy output was the cause of societal development and diversity within social systems. Crop yields, population, and agricultural energy flows are inextricably linked; investigating differences in crop yields allows for a way to explore and quantify these links.

Finally, as emphasised in chapter 2, energy input is a crucial aspect of agricultural energy systems; however, energy input does vary depending on the amount of land, which itself is often tied to crop yield. Modelling how agricultural input changes with crop yield can provide us a better understanding of how different yields relate to population growth, how crop yields relate to energy flows of other agricultural energy processes or even changes them. By understanding Çatalhöyük’s agricultural energy, using various yield scenarios, we obtain a better understanding of the potential relationship between agricultural productivity and population growth.

7.2.1 Analysing Çatalhöyük’s Agricultural Energy Inputs

Although the exact yields of Çatalhöyük crops are unknown, approximate calculations were made from experimental and ethnographic yields, as explained in chapter 5. Therefore, it is possible to compare the total energy input required from Çatalhöyük for low, average, and high yielding crops, and based on domestic cereal reliance. This data is presented in Figure 35 below, which compares the total energy input from Çatalhöyük peoples for low, average, and high yield scenarios through time, based on a 25%, 50%, and 75% reliance on domestic cereals.

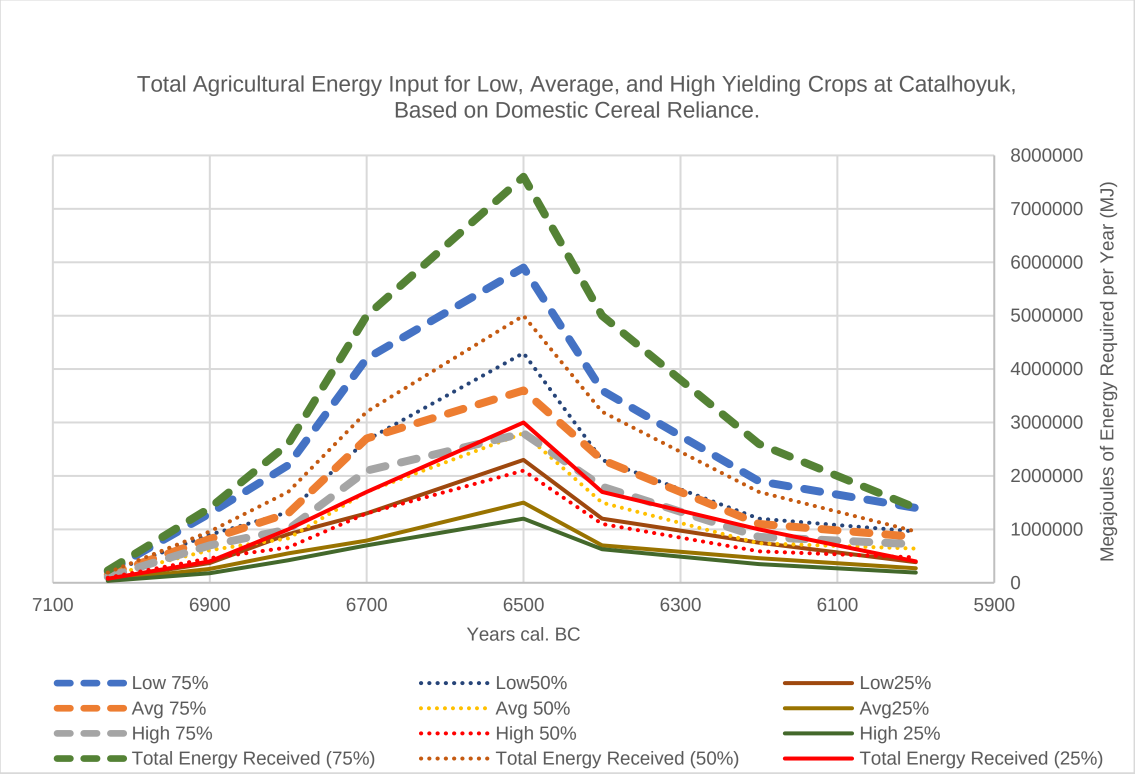


Figure 35 Total Agricultural Energy Input and Output from Çatalhöyük According to Yield and Reliance on Domestic Cereals. This figure shows the total agricultural energy input from Çatalhöyük per year in megajoules, based on low, average, and high crop yields, and various dependencies on domestic cereals. The greater the reliance on domestic cereals, the more energy input required; the lower the reliance on domestic cereals, the less energy input required. However, the greater the reliance on domestic cereals, the more energy, overall, that can be obtained. Further, low yielding crops require the most energy input, whereas high yielding crops require the least energy input; high yielding crops also allow for more energy gain compared to low yielding crops. It should be noted that total agricultural energy received in this case includes total seed required for storage.

Figure 35 above presents the total amount of energy Çatalhöyük peoples had to invest into agriculture, depending on the crop yield and, the total amount of energy received, based on the reliance on domestic cereals. No matter the yield or the percent reliance on domestic cereals, as Çatalhöyük grows over time towards its peak, more energy is required; therefore, more energy must be dedicated to sustaining agriculture and its processes. Çatalhöyük's agricultural energy input scales with population; however, it is also based upon yield and percent reliance of domestic cereals in the diet. Immediately noticeable is that low yielding crops require significantly more energy input than high yielding crops, regardless of how much of the diet is reliant on domestic cereals. With low yields, more energy must be dedicated to agriculture and its processes because low yields require more land to compensate for lower productivity. Conversely, with higher yields, less energy is invested into agriculture as less land is required due to higher productivity.

Figure 35 also indicates the total energy obtained from agriculture at Çatalhöyük, in other words, the total energy output (food energy and seed energy). Agriculture provides energy, regardless of percent reliance on domestic cereals, yet it requires a significant energy input, which depends upon both population, percent reliance on domestic cereals, and yield scenario. Further, the higher the reliance on domestic cereals, the more total energy that can be received from domestic cereals, especially with higher yields. However, a higher reliance on domestic cereals also requires significant energy input to agriculture. With a lower reliance on domestic cereals, there is less energy input required; however, the energy received is not as large as with a higher reliance on domestic cereals.

Between 7100 cal. BC to 6800 cal. BC, for this model, when Çatalhöyük's population would have 100 to 1000 people, the total energy input is close to the energy output; there does not seem to be a significant energy gain. From roughly 6700 cal. BC to 6500 cal. BC (Middle Period, Figure 10) Çatalhöyük's peak and, for this model, a population of 2000 to 3000 people, there is a substantial energy gain. After Çatalhöyük's peak and its population drops, there is subsequently a decrease in energy gain as less energy is required to sustain a smaller population. This is true regardless of how much of Çatalhöyük's diet relies on domestic cereals and is especially true for low-yielding crops.

For a 25% to 75% reliance on cereals, low yielding crops require 70,000 megajoules to 5.9 million megajoules of energy input to sustain agriculture, whilst 80,000 megajoules to 7.6 million megajoules of energy are produced from agriculture, respectively. The energy gain is only 10,000 megajoules to 1.7 million megajoules, depending on how much of the diet is reliant on cereals and the population itself. This difference is much more significant for high yielding crops, meaning more energy is gained with higher-yielding crops. For high yielding crops, only 36,000 megajoules to 3.0 million joules are required to sustain agriculture, for a 25% to 75% reliance on domestic cereals and a population of 100 to 3000 people, respectively. However, the energy gain is 44,000 megajoules to 4.6 million megajoules. High yields, overall, allow Çatalhöyük to obtain a significant energy surplus.

Consistently throughout Çatalhöyük's population growth and even for its decline, high yielding crops would require the least amount of energy input yet allow *more* energy to be obtained than low yielding crops. This energy gain or surplus from agriculture is much larger with a higher dependence on domestic cereals, even with a smaller population. This suggests that a higher reliance on domestic cereals may be more beneficial than a lower reliance on domestic cereals, especially with higher yields.

Throughout chapter 2, it was noted that the energy input of agriculture within past energy systems was missing, incomplete, or neglected. Many statements surrounding agricultural energy input of the past were vague, stating for example that agriculture had higher energy inputs, but this was not energetically modelled (Smil, 2017). However, all theorists discussed throughout chapter 2 also, in one way or another, mentioned the importance of the human energy input requirements of agriculture but were also missing that this depends on the population at hand, domestic cereals, and the energy received from agriculture. White, for example, argued that agricultural societies produce an energy surplus because domestication allowed humans to force plants and animals to work for them (White, 1943 :341-342). Figure 35 indicates that this is not the case. Figure 35, which is based on archaeological data, methods, and analyses, indicates that agriculture, even in the Neolithic, required an energy input from human populations;. Humans indeed had to work for an energy surplus just as argued by Lenton and colleagues (Lenton and Watson, 2011, Lenton, Kohler et al., 2021).

Although Figure 35 demonstrates the total energy input, as emphasised throughout chapter 2, many theorists (Binford, 1980, 2001, Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999, Odum, 1973, Odum, 2007, Odum and Odum, 1977, Odum and Pinkerton, 1955, Smil, 1994, 2000, 2008, 2013, 2017, White, 1943) have neglected to delve into the energy of agricultural processes; we are missing the complex mechanisms behind agriculture's energy input, and there is a lack of modelling agriculture's processes separately and energetically, thus preventing us from better understanding energy mechanisms within agricultural systems. Others, however, have emphasised the need for understanding and comparing the labour differences of agricultural processes (Fuller, Allaby et al., 2010, Halstead, 2014, Wright, 1994). Fuller et al. 2010 highlighted the importance of understanding the labour of threshing and winnowing and understanding the labour input of agricultural processes more generally. Wright 1994 stresses that pounding and grinding are labour-intensive processing methods and, that these processes, which would have been required to make *wild* cereals edible, have been outrageously underestimated. Therefore, quantifying the energy of agricultural processes at Neolithic Çatalhöyük provides quantifiable evidence of the labour differences between agricultural processes, as argued by Fuller et al. 2010 and Wright 1994. Further, quantifying the energy of agricultural processes separately allows us to understand how energy flows throughout past energy systems and begins to unravel the complexities between population, energy, and even technology. We need to better understand agricultural processes in the grand scheme of agricultural energy systems and how much of an energy sink some of these processes may or may not be. Therefore, quantifying the energy of agricultural processes at Çatalhöyük (chapters 5 and 6) provides an avenue towards understanding the role agricultural processes played not only within Çatalhöyük's agricultural energy system but for the Neolithic more generally. To this end, Figure 36 indicates Çatalhöyük's agricultural energy input based on percent reliance on domestic cereals, crop process and yield over time, allowing us to compare the energy of Çatalhöyük's agricultural processes.

The most energy-intensive agricultural process is tillage, no matter the yield. As outlined in 5.4, tillage is a laborious and time-consuming activity, therefore, it was expected to be one of the more energy-intensive agricultural processes. In terms of energy intensity, for a 50% to 75% reliance on cereals, following tillage is harvesting and land clearance for low yielding crops and crop processing (threshing, winnowing, dehusking, and sieving). For a 25% reliance on cereals, following tillage is low yield land clearance, low yield harvesting, and crop processing. Regardless of reliance on cereal, the less energy-intensive activities are high yield planting, land clearance, and harvesting. Overall, regarding agricultural processes and differences between Çatalhöyük's reliance on cereals, it is mostly a matter of scale; the higher the reliance, the more energy input and vice versa.

As Çatalhöyük's population grew over time, more and more energy was required to sustain Çatalhöyük's agricultural system. Once Çatalhöyük's population reached 2000 to 3000 people (for this model, Middle Period, 6700 cal. BC to 6500 cal. BC), no matter the crop yield, a significant amount of energy is required by the Çatalhöyük peoples to sustain Çatalhöyük; the energy input requirements of agriculture peak irrespective of domestic cereal reliance. Although agriculture may provide Çatalhöyük with significant amounts of energy, it also requires a significant input. Once Çatalhöyük's population declines, the energy requirement of agriculture decreases as a smaller population requires less energy, and thus, less energy input.

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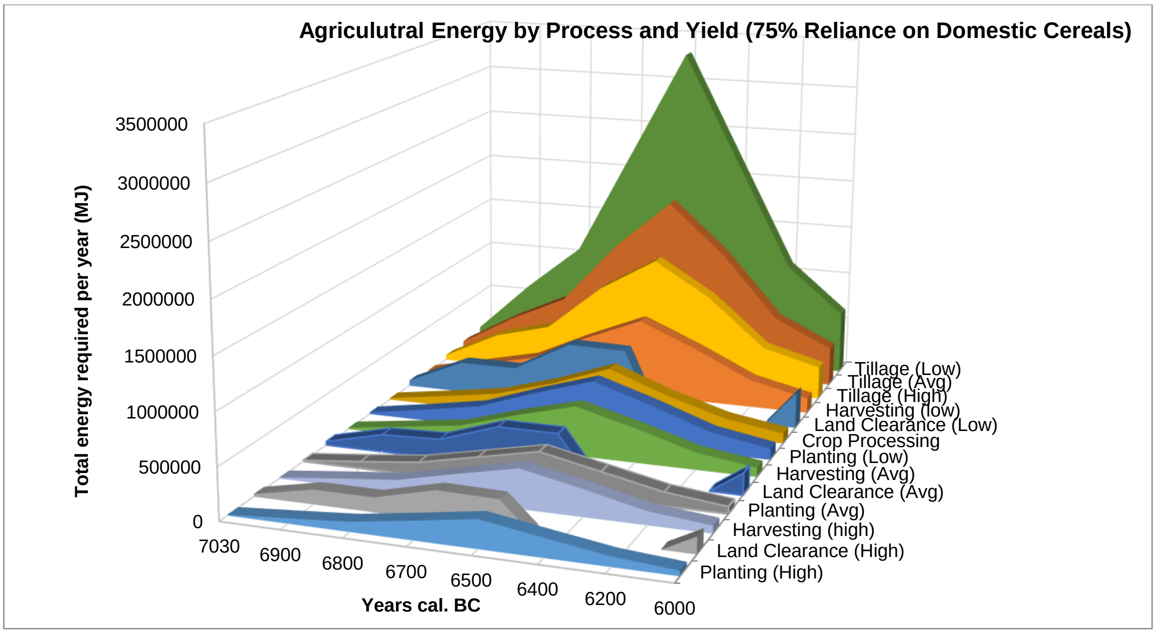
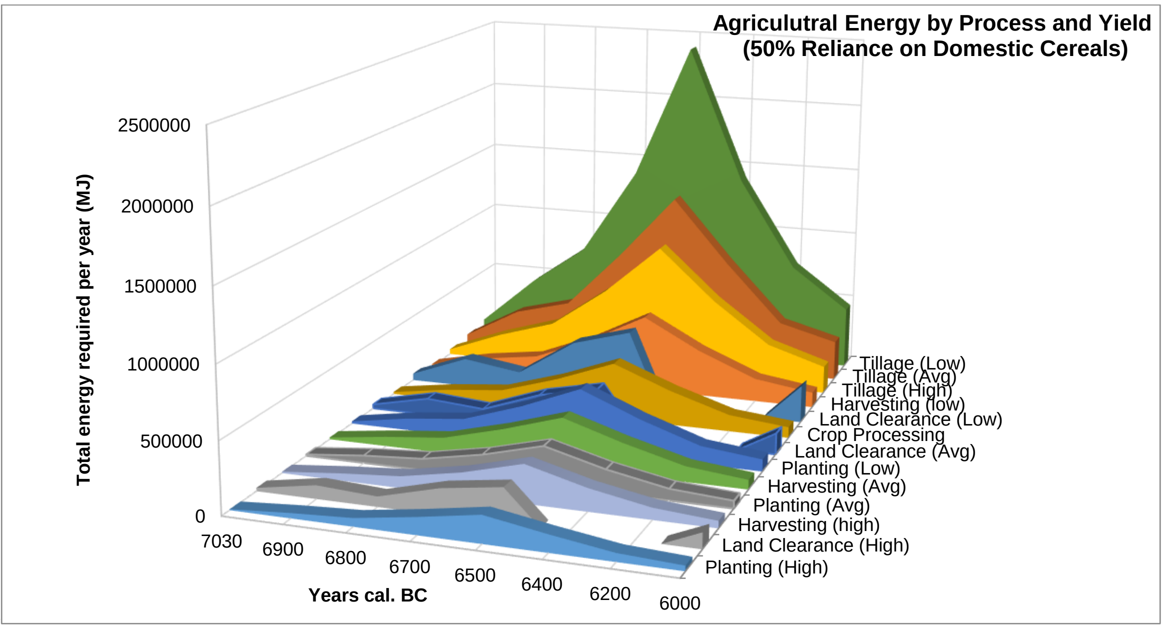

Agriculutral Energy by Process and Yield (75% Reliance on Domestic Cereals)
Total energy required per year (MJ)
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
7030
6900
6800
6700
6500
6400
6200
6000
Years cal. BC
Tillage (Low)
Tillage (Avg)
Tillage (High)
Harvesting (low)
Land Clearance (Low)
Crop Processing
Planting (Low)
Harvesting (Avg)
Land Clearance (Avg)
Planting (Avg)
Harvesting (high)
Land Clearance (High)
Planting (High)

A


Agriculutral Energy by Process and Yield (50% Reliance on Domestic Cereals)
Total energy required per year (MJ)
2500000
2000000
1500000
1000000
500000
0
7030
6900
6800
6700
6500
6400
6200
6000
Years cal. BC
Tillage (Low)
Tillage (Avg)
Tillage (High)
Harvesting (low)
Land Clearance (Low)
Crop Processing
Land Clearance (Avg)
Planting (Low)
Harvesting (Avg)
Planting (Avg)
Harvesting (high)
Land Clearance (High)
Planting (High)

B

C

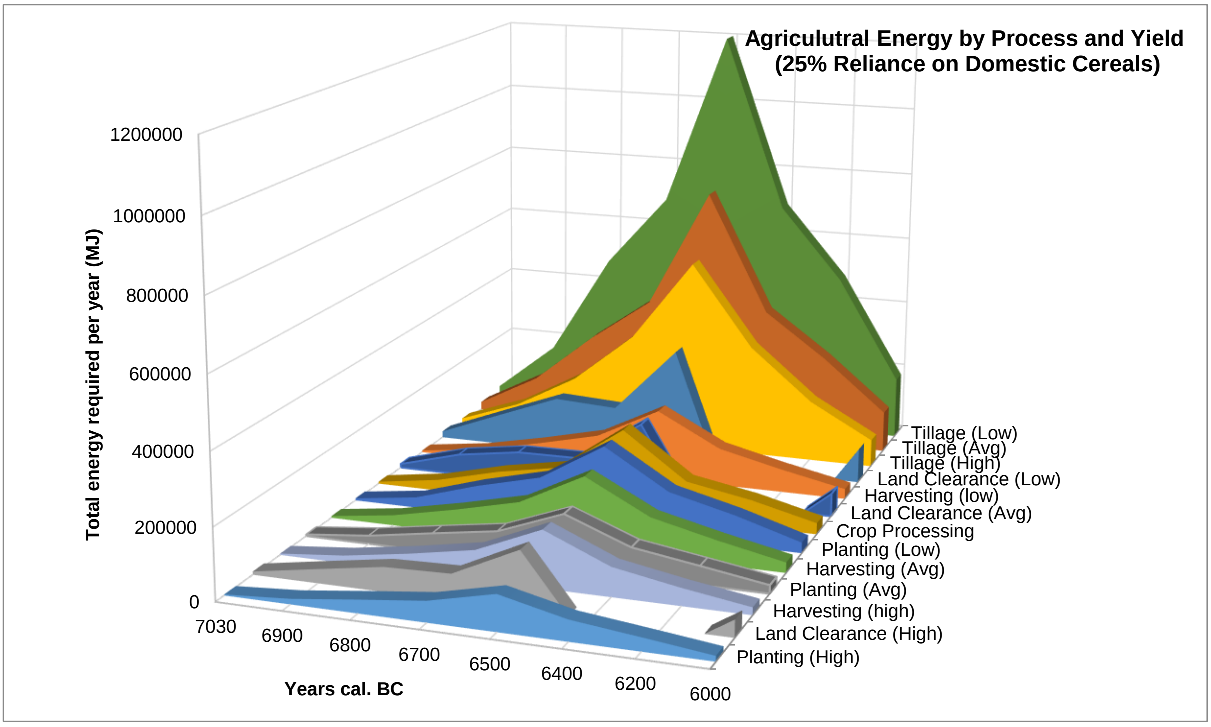


Figure 36: Energy Input for Çatalhöyük's Agricultural Processes Over Time According to Yield. These diagrams demonstrate the total energy required for each agricultural process at Çatalhöyük in megajoules per year depending on crop yield. Figure A represents the energy requirements with a 75% reliance on domestic cereals, Figure B indicates the energy requirements for a 50% reliance on domestic cereals, and Figure C shows the energy requirements for a 25% reliance on domestic cereals. The higher the reliance on domestic cereals, the more energy required to sustain agriculture and its processes. Similar to Figure 35, agricultural processes for low yielding crops consistently require more energy input than those for high yielding crops. No matter the yield, tillage requires the most energy input from Çatalhöyük. As Çatalhöyük grows over time, more and more energy must be dedicated to Çatalhöyük's agricultural processes, whereas, when its population decrease, less energy must be dedicated to Çatalhöyük's agricultural processes.

Focusing more on land clearance energy in Figure 36, as mentioned throughout 5.3, to prevent double accounting for land that had already been cleared, Çatalhöyük's land clearance energy, for 500 people for example, does not include the land that would have already been cleared for 100 people, the land clearance calculations for 1000 people do not include those for 500 people, and so on. Further, this is the same for Çatalhöyük's population decline. It is assumed for this model that after Çatalhöyük's peak of 3000 people, the land for the decline to 2000 then 1000 people does not need to be cleared. Thus, no land clearance was required for a population of 2000 and 1000 people, hence, the shape of the graph post-peak. However, land clearance for a population of 500 people *would* occur, as the amount of land required is greater than what would have been left over from previous land clearances. Finally, it is worth noting that irrespective of how much of the Çatalhöyük diet relies on domestic cereals, tillage, harvesting, crop processing, and land clearance are significant energy burdens for the Çatalhöyük population, especially during Çatalhöyük's peak.

In quantifying both the overall energy input of agriculture (Figure 35), and the energy input of agricultural processes (Figure 36), we have completed one of the first steps in understanding both the overall cost and efficiency of Çatalhöyük's agricultural system and the cost and efficiency of agriculture's processes. Understanding the overall cost and efficiency of Çatalhöyük's agricultural system, especially in relation to population growth, can aid in understanding the mechanisms behind agriculture, growth and energy (Smil, 1994, Smil, 2000, Smil, 2008, Smil, 2017).

7.2.2 Analysing Çatalhöyük's Agricultural Energy Costs

The cost of any process is the total input of the process minus total losses, divided by the total output. The cost of any system represents how much of the energy produced from the system would go back into sustaining the system[10]. The smaller the cost, the more efficient, beneficial, and less energetically expensive. For Çatalhöyük's agricultural system, the agricultural energy cost was determined from the following:

$$\frac{total\ agricultural\ energy\ input + total\ losses}{total\ agriculutral\ energy\ output}$$

(Casado and de Molina, 2009, Evans, 1993, James and Schofield, 1990, Kennett and Winterhalder, 2006, Smil, 2017).

Therefore, in Çatalhöyük's case, the agricultural energy costs represent how much of the energy produced from its agricultural system must go back into sustaining agriculture the next year. With regards to overall cost, Figure 37 represents the total energy cost of Çatalhöyük's agricultural activities based on low, average, and high-yield scenarios and percent reliance on domestic cereals. Figure 38 represents the energy cost of Çatalhöyük's agricultural activities for a 75% reliance on domestic cereals with low, average, and high yields. Figure 39 indicates the energy cost of Çatalhöyük's agricultural activities for a 50% reliance on domestic cereals with low, average, and high yields. Figure 40 represents the energy cost of Çatalhöyük's agricultural activities for a 25% reliance on domestic cereals with low, average, and high yields.

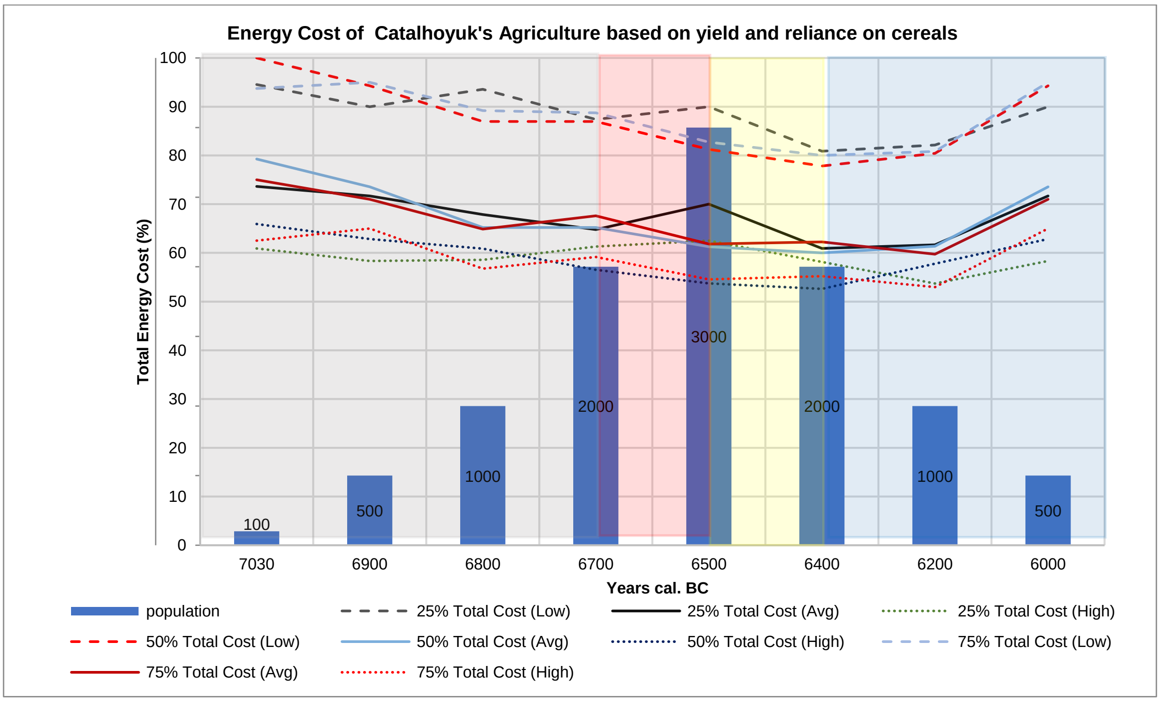


Figure 37 Energy cost of Çatalhöyük's agricultural system as a percentage of the total available energy. The figure above shows the cost of Çatalhöyük's agricultural system, based on yield and percent reliance on domestic cereals.

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[10] Costs for this analysis are quantified similarly to those within Optimal Foraging Theory models Kennett, D. J. and B. Winterhalder (2006). *Behavioural Ecology and the Transition to Agriculture*. Los Angeles: University of California Press..

It also indicates Çatalhöyük's population growth throughout its occupation. The grey area highlights Çatalhöyük's Early Period, the red area emphasises Çatalhöyük's Middle Period (peak), the yellow area indicates Çatalhöyük's Late Period, and the blue area signifies its Final period as per Figure 10. Regardless of how much of the diet is reliant on domestic cereals, low yield scenarios are the costliest, whereas high yield scenarios are the least costly. Again, the total agricultural energy cost includes seed requirements as a form of output.

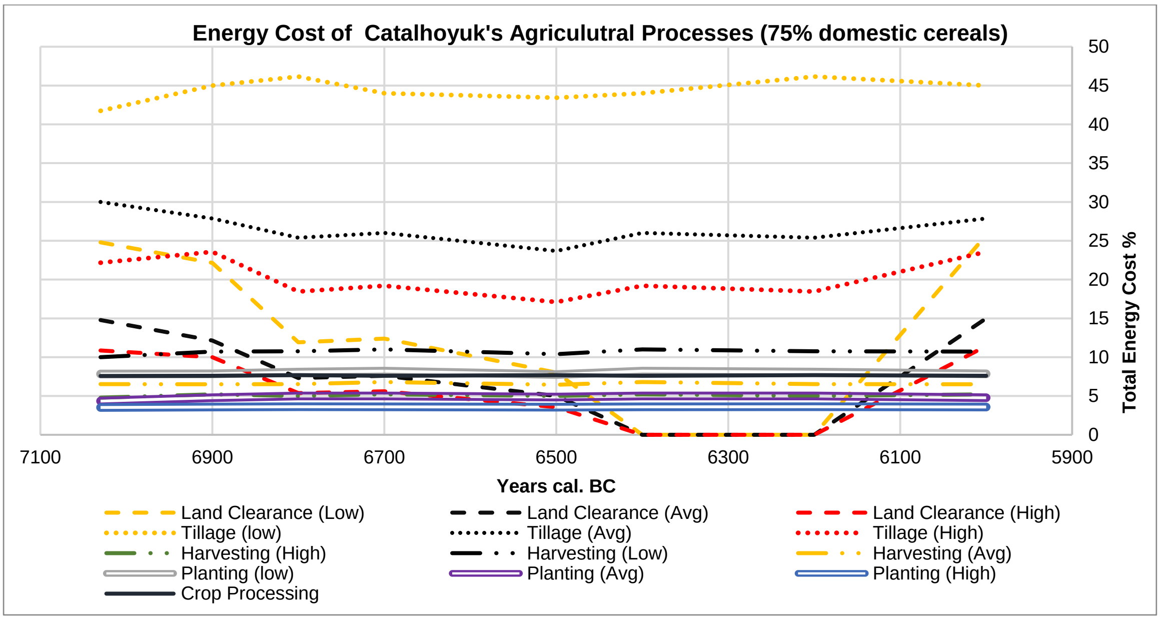

Figure 38 Energy cost of Çatalhöyük's agricultural processes over time, as a percentage of the total available energy. The figures above show the cost of Çatalhöyük's agricultural system, showing the cost of all agricultural processes, based on yield and 75% percent reliance on domestic cereals. With a 75% reliance on domestic cereals, agricultural cost scales with land clearance and tillage.

Focusing first on a 75% reliance on domestic cereals and low yields, Figure 37 indicates that during the Early Period (marked in grey), with a population of 100 to 500 people the total cost of agriculture increases slightly (by 1%). Relating this to Figure 38, which provides more specific costs of agricultural processes, during this time we see that land clearance cost decreases slightly, whilst tillage and harvesting costs increase slightly. At this point, the combined effects of land clearance, tillage, and harvesting lead to total cost increasing marginally. Moreover, it seems that needing more land, and thus inputting more energy into agriculture at a higher growth rate increases the cost of agriculture. Focusing on a population of 500 to 1000 during the Early Period, Figure 37 indicates a decrease in total agricultural cost. Referring to Figure 38, land clearance cost decreases significantly whilst the cost of tillage increases. Here, land clearance costs are a stronger determinant of total energetic costs. Finally, with a population growth of 1000 to 2000 people, at the end of Çatalhöyük's Early Period Figure 37 shows that total cost plateaus. Relating this to more specific agricultural processes, Figure 38 indicates that with a population of 1000 to 2000 people during Çatalhöyük's Early Period, the cost of land clearance does not necessarily change significantly, but tillage cost decreases whilst harvesting, planting, and crop processing costs increase; the effects of these processes help to essentially plateau total agricultural cost.

With regards to Çatalhöyük's Middle Period (peak, red Figure 37) when Çatalhöyük's population increases from 2000 people to 3000 people, total cost decreases. At this point Figure 38 indicates that land clearance costs decrease and tillage cost decreases slightly, along with harvesting and planting; the compounding effects of these processes lead to a decrease in the total cost of agriculture.

At the end of Çatalhöyük's Middle period to the Late Period (yellow, Figure 37), when Çatalhöyük's population declines from 3000 to 2000 people, total cost continues to decrease.

During this period and with this population reduction, Figure 38 indicates that land clearance costs decrease significantly, harvesting costs decrease, and tillage costs increase slightly. The combined effects of these processes lead to an overall decrease in total agricultural cost.

During Çatalhöyük's Final Period, with a population decrease to 1000 people, Figure 37 shows us that total cost increases slightly. In Figure 38 there is no land clearance cost (see 5.3.2), but tillage cost increases slightly. Here, tillage seems is the primary determinant of agricultural cost. Finally, with a population of 500 during the last portions of the Final Period (blue), Figure 37 indicates that total agricultural cost increases significantly. At this point, referring to Figure 38, land clearance costs increase significantly whilst tillage decreases slightly, thus leading to an increase in total agricultural cost. Here, land clearance cost is the primary determinant of total agricultural cost.

Concentrating on a 75% reliance on domestic cereals with average yields, during Çatalhöyük's Early Period with population growing from 100 to 500 people, Figure 37 shows us that total cost decreases. Relating this to other agricultural processes, Figure 38 indicates that at this point, land clearance cost and tillage cost both decrease, thus, their combined effects lead to a decrease in total cost. Here, unlike with the low yield scenario needing more land at a time of higher growth rate does not lead to increasing the cost of agriculture. This, I believe, is due to the yield. With a higher yield, the amount of energy received from agriculture is larger than that of low yields, and less energy input is required. Thus, the cost of agriculture for average yields (which are more productive than low yield scenarios) would decrease agricultural costs.

When the population rises from 500 to 1000 people, Figure 37 indicates that total cost decreases again. Relating this to Figure 38, both land clearance and tillage costs decrease during this time. However, at end of the Early Period, when population increases from 1000 to 2000 people (Figure 37), we see total agricultural cost increase. During this time, Figure 38 indicates that land clearance and tillage costs increase; thus, total costs increase.

During Çatalhöyük's peak Middle Period (Figure 37, red) where the population rises from 2000 to 3000 people, total agricultural cost decreases substantially. Figure 38 indicates that land clearance cost decreases along with tillage; thus, total agricultural cost decreases.

Focusing on Çatalhöyük's Late Period, where the population decreases from 3000 to 2000 people (Figure 37, blue), we should expect total agricultural cost to significantly decrease, as referring to Figure 36, land clearance energy is negligible. However, cost remains the same. Relating this to more specific agricultural processes, Figure 38 indicates that land clearance cost significantly decreases at this point; however, tillage costs and harvesting energy costs both increase. Further, we must keep in mind that with a decrease in population there is also a decrease in the total amount of energy produced by agriculture and a decrease in losses[11]. In fact, with a population decrease to 2000 people, 2.6 million megajoules is lost in energy output and losses only amount to 2.1 million megajoules, regardless of yield scenario[12]. Losing such a substantial energy output, having a decrease in losses, having no land clearance costs (decreased input), and a slight decrease in tillage and harvesting (both input increases) would effectively make no change in cost from a population of 3000 people; hence, the stagnation of total agricultural cost here is sensible.

During Çatalhöyük's Final Period, where the population decreases from 2000 to 1000, we would, again, expect total cost to decrease, as there is no land clearance energy at this point. Referring to Figure 37, total agricultural energy costs indeed decrease. Focusing on Figure

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[11] Losses were calculated in section 5.2, included for in land requirements. Further, agricultural output in this case *includes* seed required, as the Çatalhöyük population would have to account for this, as described in 5.2

[12] As compared to 7.6 million megajoules and 3.2 million megajoules for a population of 3000 people

38, land clearance cost is negligible and both tillage and harvesting costs decrease only slightly. Tillage seems to be the primary determinant of total cost, and harvesting is the secondary determinant of agricultural cost. Finally, with a population decrease to 500 people, total agricultural energy cost increases substantially. Referring to Figure 38, both land clearance and tillage costs increase; therefore, it is sensible that the cost of agriculture at this point would indeed, increase.

Regarding the total cost of a 75% reliance on domestic cereals with high yields, during Çatalhöyük's Early period, with population growing from 100 to 500 people, the total cost of agriculture increases (Figure 37). During this time, Figure 38 indicates that land clearance costs, tillage costs, and harvesting costs increase; thus, combining these processes leads to an overall increase in cost. In this case, needing more land, and therefore needing more energy into agricultural processes at a higher growth rate, seems to be a limiting factor for efficiency within Çatalhöyük's agricultural system even with higher yields. When Çatalhöyük's population grows from 500 to 1000 people, Figure 37 shows us that total cost decreases. Referring to Figure 38, land clearance and tillage costs decrease when this occurs. Clearly, at this point, tillage and land clearance are both determinants of the cost of Çatalhöyük's agricultural system. At the end of the Early Period, when Çatalhöyük's population increases from 1000 to 2000 people, Figure 37 indicates that total agricultural cost increases. Figure 38 illustrates that at this point, land clearance and tillage costs both increase, hence the increase in total cost.

With regards to Çatalhöyük's Middle Period, where the population increases from 2000 to 3000 people, Figure 37 reveals that total agricultural cost decreases. Figure 38 shows that land clearance costs, tillage costs, and even harvesting costs also decrease at this point; thus, it makes sense that there is a decrease in total agricultural cost.

During Çatalhöyük's Late period, with a population decrease from 3000 to 2000 people, one would expect a significant decrease in total cost, as Figure 36 indicates land clearance energy significantly decreases. However, we see in Figure 37 that there is, instead, no change in agricultural cost with a decrease in population from 3000 to 2000 people. Relating this to other agricultural processes, Figure 38 shows us that land clearance costs decrease; however, tillage costs and harvesting costs increase; thus, at this point, the combination of these processes (land clearance, tillage, and harvesting) are the most significant determinants of agricultural cost. This is quite similar to the modelling scenario with a 75% reliance on domestic cereals with average yields. This, I believe, suggests that at times with a higher rate of population decline, needing less land and dedicating less energy to agriculture's process does not necessarily improve costs with higher yields because of the substantial decrease in agricultural output that comes with a population decline.

With Çatalhöyük's Final period and a population decrease of 2000 to 1000 people, again, one would expect the total cost to decrease, as there is no land clearance cost as per Figure 38 . We indeed see in Figure 37 a decrease in total agricultural cost. At this point, Figure 38 shows a decrease in tillage cost and harvesting cost, hence there also being a decrease in total agricultural costs. Here, tillage and harvesting are the primary determinants of agricultural costs. Finally, with a population decrease from 1000 to 500 people in Figure 37, there is a significant increase in total agricultural cost. Again, referring to Figure 38, land clearance cost increases along with tillage and there is a slight increase in harvesting costs. Thus, land clearance cost is the determinant, but the combined effects of tillage and harvesting aid in increasing total agricultural costs.

Thus far, with a 75% reliance on domestic cereals, a few patterns have arisen. First, a 75% reliance on domestic cereals can be costly, depending on yield. For a 75% reliance on domestic cereals, the total agricultural costs of low yields range from 83% to 94%, average yields range from 62% to 75%, and high yields range from 56% to 63% (Figure 37). In other words, for a 75% reliance on domestic cereals, 56% to 94% of the energy received *from* agriculture must be *invested back into* sustaining Çatalhöyük's agricultural system. It is no surprise that high yields are less costly than lower yields and provide more energy for Çatalhöyük with a 75% reliance on domestic cereals. This is sensible, as, high yields require less energy input than low yields.

Further, combining the above analysis of low, average, and high yields, although tillage is the most energy-intensive process (Figure 36) when land clearance must occur, more energy is required to sustain agriculture. However, we have also seen that when land clearance is not a significant factor, tillage is the primary determinant of agricultural cost and harvesting is the secondary cost determinant. This is sensible, as, referring to Figure 36 tillage is one of the most energy-intensive processes, followed by harvesting. Harvesting, like tillage, is related the amount of land required, yield, and population. As established in 6.1.2, the larger the population, the more grain that must be harvested over more land; therefore, Çatalhöyük will dedicate more energy to harvesting. Therefore, harvesting affecting cost in some instances, is practical. Finally, with Çatalhöyük's Middle Period, there is a decrease in agricultural cost, regardless of yield scenario, and, during the end of the Final Period, there is an increase in cost. Thus far, this indicates that needing more land to sustain a population during a time of higher growth rate seems to increase agricultural costs for Çatalhöyük's agricultural system, except for if yields are high enough (i.e., high energy output). Conversely, at times with a higher rate of population decline, needing less land and dedicating less energy to agriculture's process does not necessarily improve costs with higher yields because of the substantial decrease in the amount of energy received from agriculture. However, relying on a 75% reliance on domestic cereals does not provide us with a comprehensive agricultural model of Çatalhöyük; thus, we must further analyse cost concerning a 50% and 25% reliance on domestic cereals.

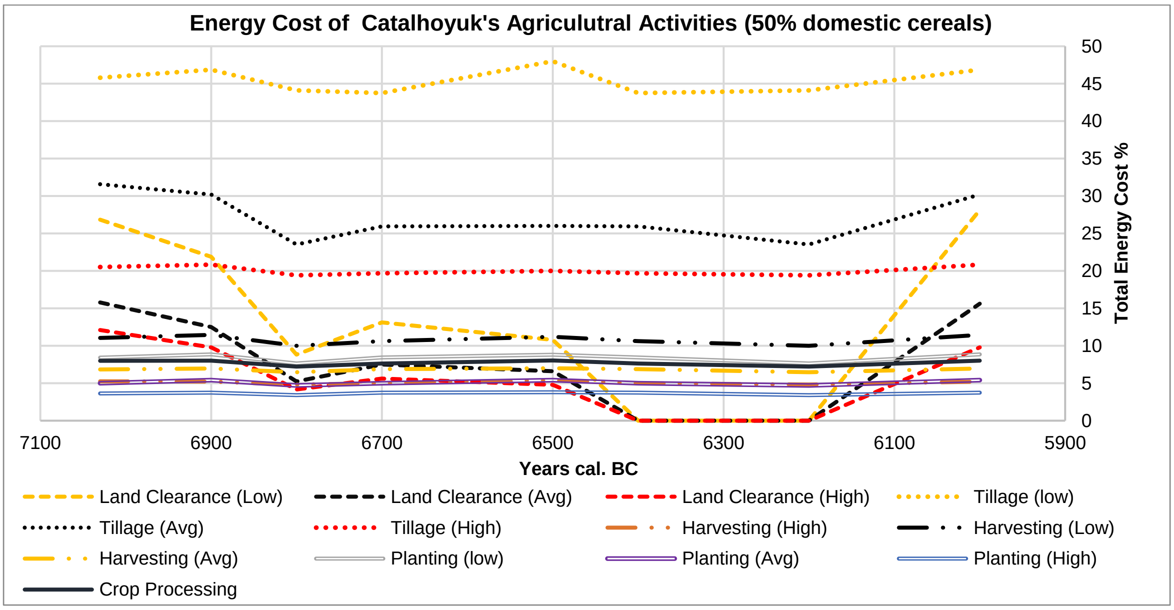

Figure 39 Energy cost of Çatalhöyük's agricultural processes over time, as a percentage of the total available energy. The figures above show the cost of Çatalhöyük's agricultural system, showing the cost of all agricultural processes based on yield and 50% percent reliance on domestic cereals. With a 50% reliance on domestic cereals, agricultural cost primarily scales with land clearance but is also influenced by tillage.

Concentrating on the total cost of agriculture for a 50% reliance on domestic cereals and low yields (Figure 37), we see that during the Early Period with a population increase from 100 to 2000 people, the total cost of agriculture for Çatalhöyük decreases. Referring to Figure 39, although tillage, harvesting, and crop processing costs fluctuate during these population changes, land clearance cost consistently and significantly decreases from a population increase from 100 to 1000 people. Compared to a 75% reliance on domestic cereals and low yields, specifically with a population increase of 100 to 500 people, cost increased whereas in this scenario, cost decreases with a lower reliance on domestic cereals. A lower reliance on domestic cereals requires less agricultural energy input; thus, in this instance, a lower reliance on domestic cereals when needing more land during a time of high population growth seems to improve agricultural costs. Overall, however, land clearance is still the determinant of agricultural cost. At the end of Çatalhöyük's Early Period, with an increase in population from 1000 to 2000 people, Figure 37 indicates that the total agricultural cost decreases (value is 86%). Referring to Figure 39, land clearance costs increase, tillage costs remain constant, and harvesting and planting costs increase slightly. Thus, we should expect cost to increase at this point, yet it decreases by 1%. With a population of 2000 people, more energy is required, especially with low yields, but there is also an increase in the amount of energy received compared to 1000 people. This effectively allows for a slight decrease in agricultural costs instead of an increase. Further, comparing this to the same yield scenario with a 75% reliance on cereals, it is worth noting that a 50% reliance on domestic cereals, with a population of 2000 people and low yields, is *less* costly than a 75% reliance on domestic cereals (agricultural cost of 89% for a population of 2000 people, low yields, Figure 37). Thus, a lower reliance on domestic cereals, in this case seems to improve agricultural costs.

Focusing on Çatalhöyük's Middle Period with a population increase from 2000 to 3000 people (Figure 37), we see a decrease in total agricultural cost. With respect to Figure 39, during Çatalhöyük's Middle Period at this point, there is a slight decrease in land clearance energy costs and an increase in tillage and harvesting costs. Again, land clearance is a greater determinant of overall agricultural cost, thus the cost decrease at this point. Compared to a 75% reliance on domestic cereals, a 50% reliance on domestic cereals, with a population increase to 3000 people and with low yields, is yet again less costly than a 75% reliance on domestic cereals (agricultural cost of 81% for a population of 3000 people, low yields, Figure 37). Thus, a lower reliance on domestic cereals, in this case, seems to improve agricultural cost during Çatalhöyük's Middle Period.

During Çatalhöyük's Late Period, with a population decrease from 3000 to 2000 people (Figure 37), agricultural cost is significantly decreases. Figure 39 explains why this is the case, as land clearance decreases in cost, and, tillage, planting, harvesting, and crop processing costs also decrease. Here, the agricultural cost is primarily determined by land clearance costs, but it is also impacted by the combined effects of tillage, planting, harvesting, and crop processing. Compared to a higher reliance on domestic cereals, in this scenario, we yet again see that a 50% reliance on domestic cereals is less costly than a 75% reliance on domestic cereals. Here, a lower reliance on domestic cereals seems to improve agricultural costs during Çatalhöyük's Middle Period.

During Çatalhöyük's Final Period, with a population decline from 2000 to 1000 people, Figure 37 indicates an increase in agricultural costs. Referring to Figure 39, tillage costs do not change, there are no land clearance costs, and planting costs and harvesting costs decrease slightly. However, what we must also keep in mind is that at this point, *total output* or total energy received from agriculture decreases significantly, along with total losses, as they both scale with population (see Figure 35 and 5.2). Further, the cost is calculated as follows: $(\frac{total\ agricultural\ energy\ input + total\ losses}{total\ agriculutral\ energy\ output})$. Thus, with a decrease in population, although the cost of land clearance is negligible and losses and the cost of tillage, planting, harvesting, and crop processing costs decrease with a decrease in population, the total agricultural energy output significantly decreases, which substantially affects the cost of agriculture, overall. Thus, an overall loss of energy production is costly for Çatalhöyük's agricultural system. In fact, it is just as costly at this point for a 50% reliance on domestic cereals as for a 75% reliance on domestic cereals.

At the end of Çatalhöyük's Final Period, with a decrease in population from 1000 to 500 people, there is an increase in total agricultural costs as demonstrated by Figure 37. Focusing on Figure 39, during this time period for this model, land clearance costs increase along with tillage, planting, harvesting, and crop processing costs. Thus, although total cost primarily seems to scale with land clearance, it is also affected by tillage, planting, harvesting, and crop processing. Additionally, the total agricultural output decreases, thus, the substantial increase in cost.

Regarding average yields and a 50% reliance on domestic cereals (Figure 37), during Çatalhöyük's Early Period and a population increase from 100 to 2000 people, there is an overall decrease in total agricultural cost. Referring to Figure 39, throughout Çatalhöyük's Early Period, land clearance costs consistently decrease, tillage costs decrease to a population of 1000 people then increase with a population of 2000 people, whilst planting energy increases, harvesting energy increases, and crop processing is relatively consistent. Thus, there is a total decrease in agricultural costs, primarily dictated by land clearance. Further, it is worth noting that although overall costs decrease for the Early Period for low and average yield scenarios, average yields are less costly than the low yield scenario. With a higher yield, the energy received from agriculture is more considerable than that of low yields, and less energy input is required. Thus, the cost of agriculture for average yields (which are more productive than low yield scenarios) would aid in lowering agricultural costs.

With respect to Çatalhöyük's Middle Period and a 50% reliance on domestic cereals for average yields, Figure 37 suggests a continued decrease in agricultural cost with a population increase from 2000 to 3000 people. Referring to Figure 39, land clearance costs decrease, and tillage, harvesting, and crop processing increase. Based on Figure 39, we would expect an increase in total agricultural cost, yet we witness the opposite. Again, I believe this is related to the amount of energy received from Çatalhöyük and the amount of land required to sustain Çatalhöyük. With 3000 people, although a significant amount of energy input is required (Figure 35 and Figure 36), losses also peak, and the amount of energy received from agriculture amounts to 5,000,000 megajoules of energy from a 50% reliance on domestic cereals. Compared to a 75% reliance on domestic cereals, it is interesting to note that at this point, a 50% reliance on domestic cereals is more costly by a mere 1%. Here, with average yields, cost does not seem to substantially improve with a 50% reliance on domestic cereals as compared to 75%.

Focusing on Çatalhöyük's Late Period and population decline from 3000 to 2000 people, based on Figure 39, and the fact that land clearance cost is negligible and tillage cost decreases, we expect total agricultural costs to decrease. This is indeed the case. At this point, both land clearance and tillage are the primary determinants of agricultural costs. Further, assessing this scenario with a 75% reliance on domestic cereals, it is interesting to note that with this population decline, a 50% reliance on domestic cereals is less costly than a 75% reliance on domestic cereals. In this case, cost does seem to improve with a lower reliance on domestic cereals.

As Çatalhöyük's population continues to decline during its Final period, we would expect a continued decrease in total agricultural cost with a decrease in population to 1000 people.

Figure 39 indicates there is no land clearance cost, there is a minimal decrease in tillage costs, harvesting costs, planting costs, and even crop processing costs. However, we see an *increase* in total agricultural cost. With such a significant decrease in population, although the cost of land clearance is negligible, other costs decrease, losses decrease, the total agricultural energy output also significantly decreases, all of which seems to substantially affect the cost of Çatalhöyük's agricultural system at this point. Comparing this to a 75% reliance on domestic cereals, a 50% reliance on domestic cereals is more costly in this scenario with average yields. Here, cost does not seem to substantially improve with a 50% reliance on domestic cereals as compared to 75%. We continue to see this increase in total agricultural cost when Çatalhöyük's population decreases to 500 people (Figure 37). This is no surprise, as referring to Figure 39, there is an increase in land clearance costs, tillage costs, harvesting costs, crop processing costs, and even planting costs. Thus, these combined effects help to explain the increase in cost. Analysing this with respect to the same scenario but a 75% reliance on domestic cereals, a 50% reliance on domestic cereals is more costly. Overall, for the Final Period, it seems that with sharp population declines, a larger reliance on domestic cereals improves the cost of Çatalhöyük's agricultural system, at least with average yields.

Focusing on high yields for a 50% reliance on domestic cereals, during Çatalhöyük's Early Period (Figure 37) total agricultural costs decrease for Çatalhöyük from a population of 100 to 1000 people. Referring to Figure 39, land clearance, tillage, harvesting, and crop processing costs decrease throughout Çatalhöyük's Early Period with this population growth, Thus, the cost of agriculture would decrease during this time. At the end of the Early Period, when Çatalhöyük's population increases from 1000 to 2000 people, Figure 37 indicates that total agricultural cost continues to decrease. Figure 39 illustrates that land clearance and tillage cost increase at this point, along with planting, harvesting, and crop processing; thus, we would expect an increase in cost rather than a decrease. However, the increases in cost of these processes are not significantly large. Keeping in mind the increase in energy input, losses, and output, it is clear that in this case, having a higher energy output is beneficial to cost. In fact, for a 50% reliance on domestic cereals for 2000 people, total energy received is 3.2 million megajoules, whereas for 1000 people 1.7 million megajoules are received from agriculture. Thus, the decrease in agricultural cost at the end of the Early Period in this scenario is sensible. It is also worth noting that although overall costs decrease for the Early Period for all yield scenarios, high yields are less costly than either the average or low yield scenarios. With a higher yield, again, the amount of energy received from agriculture is larger than that of low yields, and less energy input is required. Thus, the cost of agriculture for high yields would aid in lowering agricultural costs. Further, comparing this to the same yield scenario with a 75% reliance on cereals, it is worth noting that a 50% reliance on domestic cereals, with a population of 2000 people and high yields (57%), is *less* costly than a 75% reliance on domestic cereals (agricultural cost of 59% for a population of 2000 people, high yields, Figure 37). Thus, in this instance, lower reliance on domestic cereals improves agricultural cost.

This decrease in total agricultural cost continues even through Çatalhöyük's Middle Period (Figure 37), where the population increases from 2000 to 3000 people. Referring to Figure 39, the effects of land clearance more heavily influence the agricultural cost. This is indicated by the fact that during this point in Çatalhöyük's occupation, tillage, harvesting and crop processing increase whereas land clearance decreases (Figure 39). Thus, land clearance seems to determine the agricultural cost at this point. Further, comparing this Middle Period scenario with a 75% reliance on domestic cereals, a 50% reliance on domestic cereals is more costly by a mere 1%. Here, with high yields, cost does not seem to substantially improve with a 50% reliance on domestic cereals as compared to 75%.

During Çatalhöyük's Late period, with a 50% reliance on domestic cereals and high yields and a decrease in population to 2000 people, total agricultural cost decreases (Figure 37). There is no land clearance cost, tillage costs plateau, harvesting costs decrease, and crop processing costs decrease (Figure 39). At this point land clearance is the dominating factor in the agricultural cost.

Focusing on Çatalhöyük's Final Period, with a population decrease to 1000 people, total agricultural cost increases. We would expect a continued decrease in total agricultural cost with a decrease in population. Figure 39 indicates there is no land clearance cost, there is a minimal decrease in tillage costs, harvesting costs, planting costs, and even crop processing costs. However, we see an *increase* in total agricultural cost. With such a significant decrease in population, although the cost of land clearance is negligible, other costs decrease, losses decrease, the total agricultural energy output also significantly decreases, all of which seems to substantially affect the cost Çatalhöyük's agricultural system at this point. Finally, during the end of Çatalhöyük's Final Period, where there is a drop in population to 500 people, Figure 37 indicates that the agricultural cost for a reliance on 50% cereals with high yields, increases. Referring to Figure 39, land clearance costs, tillage costs, planting costs, harvesting costs, and crop processing costs all increase. Combined with the fact that only 190,000 megajoules of energy is being produced (Figure 35), it is no wonder that agricultural cost increases at this point. Comparing this to a 75% reliance on domestic cereals, the cost of agriculture at this point for a 50% reliance on domestic cereals is lower than for a 75% reliance on domestic cereals, thus, in this scenario at the end of Çatalhöyük's Final Period, a lower reliance on domestic cereals seems to be more beneficial for Çatalhöyük.

Overall, there are some consistent patterns for a 50% reliance on domestic cereals. First, high yields are, of course, less costly than lower yields. For a 50% reliance on domestic cereals, agricultural costs range from 81% to 100% for low yields, 61% to 79% for average yields, and 54% to 66% for high yields (Figure 37). In other words, For a 50% reliance on domestic cereals, 54% to 100% of the energy received from agriculture must be invested back into sustaining Çatalhöyük's agricultural system. Further, in some instances, as outlined above, a 50% reliance on domestic cereals is not necessarily less costly than a 75% reliance on domestic cereals.

Further, like a 75% reliance on domestic cereals, land clearance is the primary determinant of agricultural cost, followed by tillage. Although tillage is the most energy-intensive process (Figure 36), more energy input is required to sustain agriculture when more land clearance must occur. However, we have also seen that when land clearance is not a significant factor, tillage is the primary determinant of agricultural cost, harvesting is a secondary determinant of cost, and planting and crop processing seem to come into play with respect to total agricultural cost. As shown in Figure 36, tillage is one of the most energy-intensive processes, followed by harvesting, crop processing, and finally, planting.

Unlike a 75% reliance on domestic cereals, for a 50% reliance on domestic cereals, we see an overall decrease in cost for Çatalhöyük's Early Period, regardless of yield. Similar to a 75% reliance on domestic cereals; however, there is a *decrease* in cost for Çatalhöyük's Middle Period and a substantial increase in agricultural cost for Çatalhöyük's Final Period, regardless of yield. Hitherto, I believe this cost analysis of a 50% reliance on domestic cereals, again, indicates that needing more land to sustain a population during a time of higher growth rate increases agricultural costs for Çatalhöyük's agricultural system, except for if yields are high enough and/or if overall energy input is not significant (i.e., for higher yields and/or a lower reliance on domestic cereals). Conversely, at times with a higher rate of population decline, needing less land and dedicating less energy to agriculture's process does not necessarily improve costs with higher yields because of the substantial decrease in the amount of energy received from agriculture. However, before making any conclusions about this, we must further analyse cost with respect to a 25% reliance on domestic cereals.

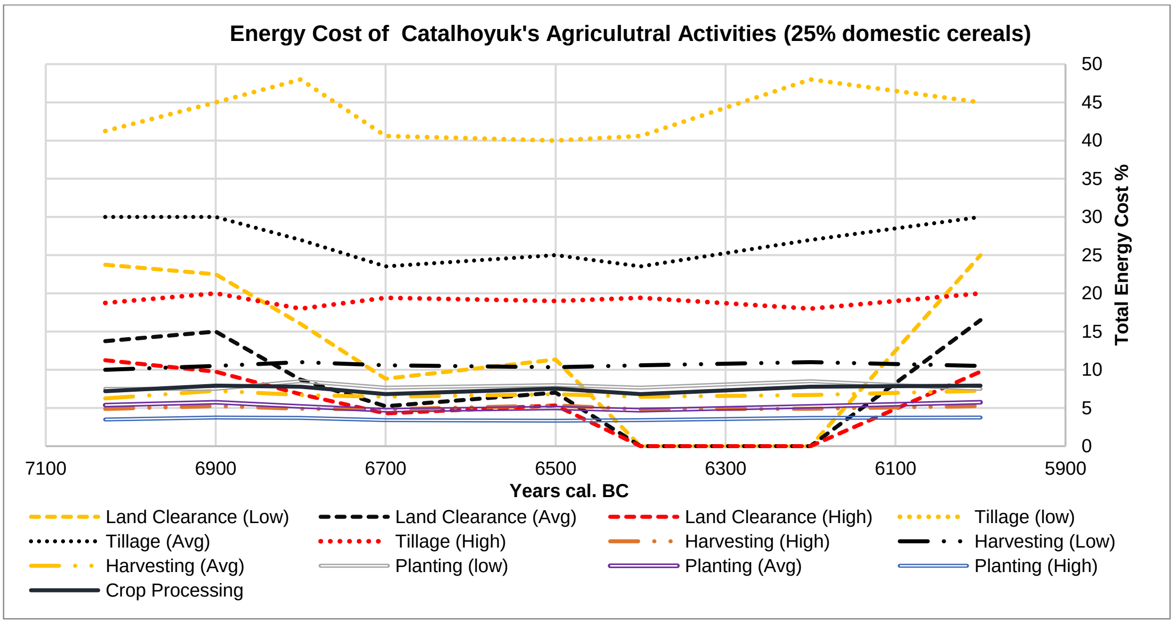

Figure 40 Energy cost of Çatalhöyük's agricultural processes over time, as a percentage of the total available energy. The figures above show the cost of Çatalhöyük's agricultural system, showing the cost of all agricultural processes, based on yield and 25% percent reliance on domestic cereals. With a 25% reliance on domestic cereals, agricultural cost scales with land clearance, but it is also more heavily influenced by tillage, harvesting, and crop processing.

Finally, focusing on a 25% reliance on domestic cereals and low yields, during Çatalhöyük's Early Period, we see a decrease in total agricultural cost with a population growth of 100 to 500 people (Figure 37). Referring to Figure 40, there is a decrease in the cost of land clearance and slight increases in tillage, planting, and crop processing, yet no change in harvesting. In this scenario, land clearance costs are more determinant of agricultural energy costs than any other process. Comparing this to a 75% reliance on domestic cereals and low yields, specifically with a population increase of 100 to 500 people, cost increased whereas in this scenario and with a 50% reliance on domestic cereals cost decreased. Further, a 25% reliance on domestic cereals is less costly than a 50% or 75% reliance on domestic cereals with population growth from 100 to 500 people. A lower reliance on domestic cereals requires less agricultural energy input, even for lower yields; thus, in this instance, a lower reliance on domestic cereals when needing more land during a high population growth rate seems to improve agricultural costs.

With a population increase from 500 to 1000 during Çatalhöyük's Early Period, Figure 37 indicates an increase in agricultural costs. Relating this to Figure 40, there is a significant decrease in land clearance costs and an increase in tillage, planting, crop processing and harvesting costs. In this case, during Çatalhöyük's growth, the combined effects of tillage, planting, and harvesting costs outweigh the decrease in the cost of land clearance. Further, the increase in tillage is quite significant especially when we keep in mind that this energy input requirement is 480,000 megajoules when only 1.0 million megajoules of energy are being directly produced from low yields and a 25% reliance on domestic cereals. Thus, the increase in agricultural cost at this point is sensible. With a population increase to 2000 people at the end of the Early Period, Figure 37 indicates a decrease in total agricultural costs. Relating this to Figure 40, with a population increase to 2000 people, there is a *decrease* in land clearance costs, tillage costs, planting costs, harvesting costs, and even crop processing costs. Amalgamated with the fact that 1,700,000 megajoules of energy are being produced by just 2000 people, the decrease in total agricultural cost is, again, reasonable.

During Çatalhöyük's Middle period, with a population increase of 2000 to 3000, in this scenario with low yields and a 25% reliance on domestic cereals, Figure 37 indicates an increase in agricultural cost. Relating this to Figure 40, with a population of 3000 people, there is an increase in land clearance, planting, and crop processing costs, whereas there is a slight decrease in harvesting and tillage costs. In this case, land clearance is the dominating factor concerning agricultural cost, with planting and crop processing also being contributing factors. Compared to a 50% and 75% reliance on domestic cereals, a 25% reliance on domestic cereals for a population of 3000 people is more costly than either a 50% or 75% reliance on domestic cereals. Here, a lower reliance on domestic cereals in this case does not improve agricultural cost during Çatalhöyük's Middle Period.

Focusing on Çatalhöyük's Late Period with a 25% reliance on domestic cereals and low yields, Figure 37 indicates a drop in agricultural costs with a population decrease of 3000 to 2000 people. Referring to Figure 40, land clearance costs decrease significantly, tillage and harvesting costs increase marginally, whereas planting and crop processing decrease slightly. Here, land clearance cost seems to be the dominating factor concerning total agricultural cost. Comparing to a 50% and 75% reliance on domestic cereals, a 25% reliance on domestic cereals for a population decrease to 2000 people during the Late Period, at least for low yields, is, again, more costly than either a 50% or 75% reliance on domestic cereals. Thus far, a lower reliance on domestic cereals, at least for low yields, does not improve agricultural cost for Çatalhöyük with a significant decrease in population.

Concentrating on Çatalhöyük's Final Period with a population decrease to 1000 people, agricultural cost is slightly increased (Figure 37). Correlating this to Figure 40, although there is no land clearance cost, tillage cost increases, along with planting, harvesting, and crop processing costs. The combined effects of these costs, but especially tillage, seems to be the culprit behind the increase in agricultural cost in this scenario. This increase in agricultural cost increases with a population decline to 500 people in the last parts of Çatalhöyük's Final Period. Again, referring to Figure 40, at this point, land clearance costs increase, however, tillage, planting, and harvesting costs decrease. Land clearance costs increasing at this point, combined with the fact that with a population of 500 people, only 400,000 megajoules of energy is being directly produced from agriculture, is what relates to the increase in the cost of Çatalhöyük's agricultural system within this scenario. Comparing this to a 50% and 75% reliance on domestic cereals, by the end of the Final Period, having a lower reliance on domestic cereals seems to improve costs for Çatalhöyük's agricultural system, at least for low yields.

With regards to average yields and a 25% reliance on domestic cereals, during Çatalhöyük's Early Period, with a population increase from 100 to 500 people, Figure 37 indicates there is a decrease in the cost of agriculture. In Figure 40, land clearance costs and tillage costs decrease, whereas harvesting, planting, and crop processing costs increase slightly. Thus, the agricultural cost at this point is primarily determined by the combined effects of land clearance and tillage. As Çatalhöyük's population increases to 1000 people during the Early Period, the total cost of agriculture decreased (Figure 37). Referring to Figure 40, this is explained by decreases in the costs of land clearance, tillage, planting, harvesting, and crop processes (Figure 40). This decrease in agricultural cost continues to the end of Çatalhöyük's Early Period and the start of its Middle Period (Figure 37). Focusing on Figure 40, land clearance, tillage, planting, harvesting, and crop processing costs all continue to decrease; thus, agricultural cost also decreases.

With a population increase to 3000 people during Çatalhöyük's peak, agricultural cost increases (Figure 37). Relating this to Figure 40, land clearance costs, tillage costs, planting costs, harvesting costs, and crop processing costs all increase at this point; therefore, the cost of Çatalhöyük's agricultural system increases. Compared to a 50% and 75% reliance on domestic cereals, it is interesting to note that at this point, a 25% reliance on domestic cereals is more costly than either a 50% or 75% reliance on domestic cereals. Here, with average yields, cost does not improve with a much lower reliance on domestic cereals.

After Çatalhöyük's peak, when the population decreases from 3000 to 2000 (Figure 37), there is also a decrease in agricultural cost during the Late Period. Referring to Figure 40, land clearance, tillage, harvesting, planting, and crop processing costs all decrease at this point; thus, the cost of Çatalhöyük's agricultural system also decreases. Compared to a 50% and 75% reliance on domestic cereals, it is interesting to note that with this population decline and a 25% reliance on domestic cereals, a 25% reliance is less costly than a 75% reliance on domestic cereals but more costly than a 50% reliance; albeit the difference is only ±1%.

When Çatalhöyük's population decreases to 1000 people during its Final Period, however, agricultural cost slightly increases (Figure 37). Relating this to Figure 40, there is no land clearance cost but tillage, planting, harvesting, and crop processing costs all increase at this point. At the end of Çatalhöyük's Final Period, with a decrease in population to 500 people, however, Figure 37 indicates there is an increase in agricultural cost. Figure 40, indicates an increase in land clearance, tillage, planting, harvesting, and crop processing costs; thus leading to a substantial increase in the total cost of agriculture for Çatalhöyük under these conditions. Analysing this with respect to the same scenario but a 50% and 75% reliance on domestic cereals, a 25% reliance is more costly than a 75% reliance on domestic cereals by a mere 1% but less costly (by 2%) than a 50% reliance. Overall, for the Final Period, it again seems that with sharp population declines, a larger reliance on domestic cereals improves the cost of Çatalhöyük's agricultural system, at least with average yields.

Finally, focusing on a 25% reliance on domestic cereals with high yields, during Çatalhöyük's Early Period and a population increase from 100 to 500 people, Figure 37 shows a decrease in agricultural cost. Relating this to Figure 40, land clearance cost decreases whilst tillage, harvesting, planting, and crop processing increase slightly; thus, the increase in total cost is sensible. Moreover, in this situation, needing more land at a time of higher growth rate does not seem to increase the cost of agriculture, more than likely because with high yields the amount of energy received from agriculture is larger than that of low yields, but less energy input is required. Thus, the cost of agriculture for high yields and a low-reliance scenario aids in lowering agricultural costs. This is further reflected by the fact that at this point, with population growth from 100 to 500 people, a 25% reliance on domestic cereals is less costly than either a 50% or 75% reliance on domestic cereals. At times of higher population growth rate, a lower reliance on domestic cereals but higher yields help to improve agricultural costs.

With a population increase of 500 to 1000 during Çatalhöyük's Early Period, there is a small increase in agricultural cost (Figure 37). Referring to Figure 40, at this point, there is a decrease in land clearance costs, tillage costs, planting costs, harvesting costs, and crop processing costs. Thus, we would expect a decrease in agricultural costs, similar to both a 50% and 75% reliance on domestic cereals during this time. However, for a 50% to 75% reliance on domestic cereals, high yields, and a population increase to 1000 people, total energy output is 1,700,000 megajoules and 2,600,000 megajoules, respectively. The total energy output for this lower reliance on domestic cereals is only 1,000,000 megajoules of energy. Thus, a smaller energy output does not necessarily outweigh the total increase in input or losses of agricultural processes with a lower population growth rate. With a population increase to 2000 people at the end of Çatalhöyük's Early Period and the beginning of its peak Middle Period, there is an increase in agricultural cost (Figure 37). Figure 40, shows a decrease in land clearance, planting, harvesting, and crop processing costs, yet tillage costs remain the same. Again, we would expect more of a decrease in agricultural costs, yet we have a slight increase. I believe this has to do with energy input and output. Although tillage energy does not change, it still requires 330,000 megajoules of energy, whereas only 1,700,000 megajoules of energy are produced. With an increase in losses compared to a population of 1000 people and a smaller energy output than a 50% to 75% reliance on domestic cereals, the total cost will increase rather than decrease in this scenario. Further, compared to a 50% and 75% reliance on cereals, it is worth noting that a 25% reliance on domestic cereals, with a population of 2000 people and high yields (61%), is more costly than both a 75% reliance on domestic cereals (agricultural cost of 59% for a population of 2000 people, high yields, Figure 37) and a 50% reliance on domestic cereals (agricultural cost of 57% for a population of 2000 people, high yields, Figure 37). In this case, a lower reliance on domestic cereals does not seem to improve agricultural cost.

With a population increase from 2000 to 3000 during Çatalhöyük's Middle Period and a 25% reliance on cereals with high yields, Figure 37 indicates there is an increase in agricultural cost. Figure 40 shows that land clearance costs increase, along with harvesting and crop processing costs; tillage costs and harvesting marginally decrease. Thus, with an increase in the cost of agricultural processes but less energy being received from agriculture (as it is a 25% reliance), there will be an increase in agricultural cost during the Middle Period, unlike the decrease witnessed for a 50% and 75% reliance on domestic cereals. Further, comparing this Middle Period scenario with a 50% and 75% reliance on domestic cereals, a 25% reliance on domestic cereals is more costly than 9%. Here, with high yields, cost does not seem to substantially improve with a 25% reliance on domestic cereals

Focusing on Çatalhöyük's Late Period, with a decrease in population to 2000 people, there is a decrease in agricultural cost (Figure 37). Referring to Figure 40, at this point, land clearance costs decrease, tillage costs, harvesting costs, and crop processing costs decrease; thus, there is an overall decrease in agricultural cost.

With a decrease in population to 1000 people during the Final Period, Figure 37 indicates that there is a decrease in agricultural cost within this scenario. At this point, there are no land clearance costs, tillage costs are only marginally lower, yet there is an increase in planting, a small increase in harvesting, and an increase in crop processing costs. Therefore, we would expect an increase in cost; however, we get the opposite. Here, I believe tillage is the dominant factor concerning agricultural cost and is more of a determinant than any other agricultural process. Finally, with a decrease in population to 500 people at the end of the Final Period, Figure 37 indicates an increase in agricultural cost. Referring to Figure 40, there is an increase in land clearance, tillage, planting, and harvesting costs and a marginal increase in crop processing costs. Combined with the fact that less energy is produced (e.g., a drop from 1.0 million megajoules to 400,000 megajoules), this increases total agricultural costs. Comparing this to a 50% and 75% reliance on domestic cereals, the cost of agriculture at this point for a 25% reliance on domestic cereals is lower than for either scenario. In this scenario, at the end of Çatalhöyük's Final period, a lower reliance on domestic cereals seems to be more beneficial for Çatalhöyük.

Generally, for a 25% reliance on domestic cereals, agricultural costs range from 87% to 95% for low yields, 65% to 79% for average yields, and 57% to 62% for high yields (Figure 37). In other words, for a 25% reliance on domestic cereals, 57% to 95% of the energy received from agriculture must be invested back i*nto* sustaining Çatalhöyük's agricultural system. Thus, the Çatalhöyük population is technically receiving either no energy or 46% of the energy produced from its agricultural system. Once again, high yields are less costly than lower yields.

Second, similar to a 50% and 75% reliance on domestic cereals, land clearance is the primary determinant of agricultural cost, followed by tillage. Although tillage is the most energy-intensive process (Figure 36) when more land clearance must occur, more energy input is required to sustain agriculture. However, we have also seen that for a 25% reliance on domestic cereals, harvesting, planting, and crop processing come into play with respect to total agricultural costs. With a smaller reliance on domestic cereals, more agricultural processes seem to influence total agricultural cost although less input is required.

Third, the reliance on domestic cereals in relation to population growth and decline and energy is not necessarily straightforward. The percent reliance on domestic cereals seems to affect costs differently during specific periods of Çatalhöyük's occupation, which is the focus of the remainder of this cost discussion.

With the start of the Early Period (population of 100 people), there is no substantial difference between the percent reliance on domestic cereals, however, there is a difference between yields: low yields are always more costly than high yields. Overall, there is a net decrease in total agricultural costs for the Early Period regardless of yield or percent reliance on domestic cereals, albeit low yields are still more costly than high yields. However, focusing on a point in the Early Period where for a population increase from 100 to 500 growth rate is higher, we do see notable differences between domestic cereal reliance and yield.

Focusing on low yields, a lower reliance on domestic cereals is less costly than a higher reliance on domestic cereals. Here, this indicates that with lower yields, needing more land at a time of higher growth rate cannot be effectively counteracted by a larger reliance on domestic cereals due to the agricultural input requirements. If Çatalhöyük needed to cope with sustaining its population during a high population growth rate with low yielding cereals, a higher reliance on domestic cereals would be unfavourable. A lower reliance on domestic cereals requires less energy to sustain agriculture; thus, in a low yield scenario it is less costly for Çatalhöyük's agricultural system.

Concerning average yields, a higher reliance on domestic cereals at a rate of high population growth is less costly than a lower reliance on domestic cereals. This suggests that with average yield crops, needing more land at a time of higher growth rate can be effectively counteracted by a more significant reliance on domestic cereals, because more agricultural energy is produced. If Çatalhöyük needed to sustain its population during a time of high population growth rate with average yields, a higher reliance on domestic cereals would be favourable for Çatalhöyük. A lower reliance on average yield domestic cereals at this point is more costly than a higher reliance due to receiving less energy output.

Finally, focusing on high yields, a lower reliance on domestic cereals at a rate of high population growth is less costly than a higher reliance on domestic cereals. This suggests that with higher-yielding crops, needing more land at a time of higher growth rate can be effectively counteracted by a smaller reliance on domestic cereals, because less agricultural input energy is required. If Çatalhöyük needed to sustain its population during a time of high population growth rate with high yields, a lower reliance on domestic cereals would be favourable for Çatalhöyük. A higher reliance on high yield domestic cereals at this point is more costly than a lower reliance due to needing to dedicate more energy to sustain agriculture.

For Çatalhöyük's Middle Period (peak), however, there is a different case. At this point in Çatalhöyük's occupation, the growth rate is lower (1.5), yet irrespective of yield or percent reliance on cereals, the amount of land required to sustain a larger population peaks, therefore, the energy input required for agriculture peaks, the potential for losses peaks, the total amount of seed required to sustain agriculture peaks, and the total amount of energy received directly from agriculture peaks (see 5.2, Figure 17, Figure 25, and Figure 35). For a 50% and 75% reliance on domestic cereals there is a net decrease in agricultural costs for all yields for the Middle Period, higher yields being less costly than lower yields. For a 25% reliance on domestic cereals, again, higher yields are less costly than lower yields, but total agricultural costs *increase* for all yields (Figure 37).

The primary factors that differ between domestic cereal reliance here are (1) the scale in the amount of energy output from domestic cereals (i.e., seed and cereal energy) and (2) the amount of land required for agriculture to take place. A higher reliance requires more land, whereas a lower reliance requires less land. Referring to Table 10, at this point, 730 to 1600 hectares of land are required for a 75% reliance on domestic cereals, 520 to 1200 hectares of land are required for a 50% reliance on domestic cereals, and 290 to 600 hectares of land are required for a 25% reliance on domestic cereals. More importantly, however, a 25% reliance on domestic cereals only produces 3.0 million megajoules of energy[13], whereas a 50% reliance produces 5.0 million megajoules of energy and a 75% reliance produces 7.6 million megajoules. Although a lower reliance may allow for less energy input, far less energy is produced than a larger reliance on domestic cereals. This is further indicated by the fact that a 25% reliance on domestic cereals during Çatalhöyük's peak is 10% higher than with a reliance of 50% to 75% domestic cereals This means that at Çatalhöyük's peak, a lower reliance on domestic cereals would have been more costly than a higher reliance on domestic cereals. A higher reliance on high yield domestic cereals at this point would be less costly than a lower reliance due to the substantial amount of energy received from high yields and a high reliance. In other words, when Çatalhöyük was sustaining its peak population, it would have been more beneficial to have a higher reliance on domestic cereals.

Focusing on Çatalhöyük's Late Period, with a population decline from 3000 to 2000 people, there is an overall net decrease in agricultural costs for a 25% and 50% reliance on domestic cereals: the former being a more significant change than the latter. With a 75% reliance on domestic cereals, there is not a very significant change. During the Late Period, regardless of yield or percent reliance on cereals, the amount of land required decreases; therefore, the energy input required for agriculture decreases, losses decrease, the total amount of seed required to sustain agriculture decreases, and the total amount of energy received directly from agriculture decreases (see 5.2, Figure 17, Figure 25, and Figure 35). Again, it is a matter of scale, although we see an opposite trend from the Middle Period. During times of rapid population decline, a lower reliance on domestic cereals would have been less costly to sustain Çatalhöyük than a higher reliance on domestic cereals. With the Late Period, a smaller reliance on domestic cereals when population decreases is less costly than a higher reliance on domestic cereals because less energy is required than previous scenarios, but the loss in energy is not as substantial.

Concentrating on Çatalhöyük's Final Period with a population decline from 2000 to 500 people, the total agricultural costs increase regardless of yield and how reliant the diet is upon cereals. During this period, population decreases for this model; however, land clearance must occur near the end of the Final Period. Thus, costs increase for all scenarios regardless of domestic cereal reliance or yield. However, some scenarios, overall, are more costly than others. High yields and a lower reliance on domestic cereals are the least costly scenarios during this period. During rapid population decline but needing to clear more land, a lower reliance on high yield domestic cereals would have been less costly to sustain Çatalhöyük than a higher

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[13] Seed and total cereal energy, as mathematically, seed energy counts as output.

reliance. In other words, a smaller reliance on domestic cereals is more beneficial for the remaining population than a larger reliance. Conversely, a higher reliance on low yield cereals is the costliest scenario for Çatalhöyük's Final Period.

Clearly, high yields are most beneficial for Çatalhöyük's agricultural system, as they allow for Çatalhöyük to receive more of an energy surplus. Yet, having a higher or smaller reliance with regards to total agricultural cost is very dependent on: the amount of land required, the population growth rate, energy input required, and the amount of energy produced. This cost-analysis of Çatalhöyük's agricultural system highlights the importance of investigating agricultural processes, their relationships to one another, how much energy agriculture requires and produces, and its relation to population growth. We cannot solely focus on energy output with respect to population growth. The relationship between agriculture, energy, and population growth is far more complicated than many of those argued throughout chapter 2 (see White 1943; Chaisson 2003, 2005, 2011, 2013, 2014a, 2014b, 2015; Smil 2000, 2008, 2013, 2017). However, to better understand what is occurring with regards to energy, limits to Çatalhöyük's agricultural system, and its relationship to growth, we must delve into what is known as the Energy Return on Invested Energy of Çatalhöyük's agricultural energy system, otherwise known as EROIE.

7.2.3 Analysing Çatalhöyük's Agricultural Energy Efficiency

The EROIE, or the efficiency ratio, of an energy process or system, is the ratio of total energy input to total energy output; it is utilised in modern energy analyses to understand the efficiency of energetic processes (Hall, 2017, Smil, 2008). If the EROIE of an energy process, source, or system is less than one, obtaining energy from that source is difficult and expensive; energy is *lost,* and there is no energy gain, meaning it is inefficient (Hall, 2017). If the EROIE is equal to one, obtaining energy from that source does not result in a significant energy gain; the energy input and output are equal, and thus, the system, process, or source "breaks even" (Hall, 2017). The greater the EROIE ratio is, the better and more energetically efficient the system. The EROIE ratio was calculated for this model of Çatalhöyük's agricultural energy system to understand its efficiency and how this might have changed as Çatalhöyük's population grew and declined. Figure 41 below demonstrates the EROIE for Çatalhöyük's agricultural system, comparing low, average, and high yielding scenarios for a 25%, 50%, and 75% reliance on domestic cereals for Çatalhöyük's occupation.

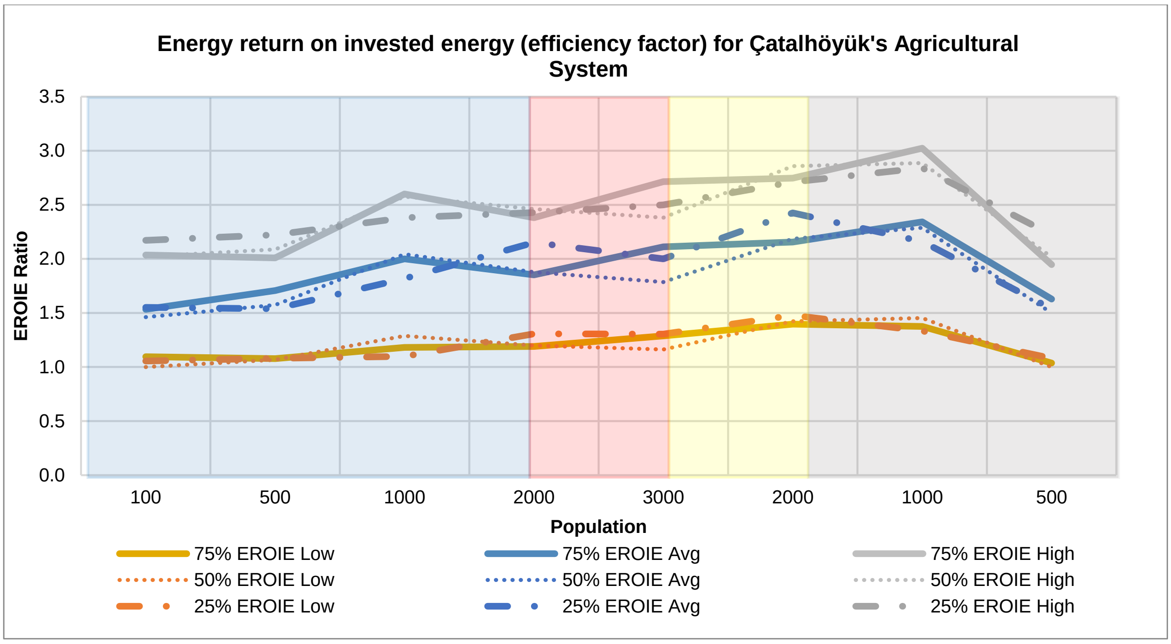


Figure 41: Energy Return on Invested Energy (EROIE, Efficiency Factor) of Çatalhöyük's Agricultural Energy System. This figure demonstrates the EROIE, or efficiency factor, of Çatalhöyük's agricultural energy system based on yield and reliance on domestic cereals. The grey area highlights Çatalhöyük's Early Period, the red area emphasises Çatalhöyük's Middle Period (peak), the yellow area indicates Çatalhöyük's Late Period, and the blue area signifies its Final period as per Figure 10. For Çatalhöyük, low yields are more inefficient than high yields. Further, the importance of yield on efficiency seems to be greater than how much of the diet relies on domestic cereals. The differences between a 25% and 75% reliance on domestic cereals are minimal with respect to efficiency. Çatalhöyük's agricultural system, overall and regardless of yield and domestic cereal reliance, improves over time. It reaches its peak efficiency during its Final Period, with a 75% reliance on domestic cereals and high yields.

Immediately apparent within Figure 41 is that with efficiency, there are subtle differences regarding how much of the diet is reliant upon domestic cereals, but there are substantial differences between yield. High yields are efficient and allow for an energy gain, regardless of how much the diet relies on domestic cereals. Further, with low yields and a smaller population, agriculture at Çatalhöyük would have been less efficient, regardless of yield and domestic cereal reliance. Second, referring to Table 13 (Extra land required to sustain Çatalhöyük's population), efficiency seems to scale with land clearance, highlighted in the variations between domestic cereal reliance. Finally, the percent reliance on domestic cereals impacts efficiency differently during specific periods of Çatalhöyük's occupation, which is the focus of the remainder of this EROIE discussion.

In the beginning of the Early Period (population of 100 people), there is a substantial difference between the yields of domestic cereals; however, there is not a major difference concerning the percent reliance on domestic cereals. Focusing on low yields, there really is no difference between reliance on domestic cereals with respect to efficiency. A higher reliance is just as efficient as a lower reliance. In any scenario at this point, low yields and a small population lead to Çatalhöyük's agricultural system essentially breaking even. With average yields, we see something similar. Average yields are more efficient than low yields; however, the difference between the domestic cereal reliance is again negligible. Focusing on higher yields, which are the most efficient, a 25% reliance on domestic cereals is just slightly more efficient than a higher reliance. However, it should be noted that this difference is only 0.2.

At a point of higher population growth rate, where for this model, Çatalhöyük's population grows from 100 to 500 people, we see some differences between domestic cereal reliance and efficiency. One thing is made abundantly clear: needing more land and dedicating more energy to agricultural processes at a time of higher growth rate affects the cost *and* efficiency for Çatalhöyük's agricultural system.

For low yields, again, there are barely any differences in efficiency between domestic cereal reliance scenarios, but low yields are significantly less efficient than higher yields. Similar to the cost analysis, this indicates that with lower yields, needing more land at a time of higher growth rate cannot be effectively counteracted by a larger reliance on domestic cereals. For average yields and a population increase from 100 to 500, we that a higher reliance on domestic cereals increases slightly in efficiency. Regarding agricultural costs (7.2.2), a higher reliance on domestic cereals at a high population growth rate seems to be less costly than a lower reliance on domestic cereals. Here, efficiency supports this, as a 75% reliance on domestic cereals is more efficient than a 50% reliance, which is also more efficient than a 25% reliance. In this case, with average yields, this supports the claim in the cost analysis that needing more land at a at time of higher growth rate can, with average yields, be effectively counteracted by a larger reliance on domestic cereals because more agricultural energy is produced. With higher yields and a population increase from 100 to 500, we see that although it is a minimal change, a 25% reliance on domestic cereals is more efficient than a 50% reliance on domestic cereals, which is more efficient than a 75% reliance on domestic cereals. The cost analysis at this point and with high yields suggested that a lower reliance on domestic cereals at a rate of high population growth was less costly than a higher reliance on domestic cereals. Here, it is the same for efficiency. A smaller reliance on domestic cereals is more efficient than a higher reliance on domestic cereals. With higher-yielding crops, needing more land at a time of higher growth rate can be effectively counteracted by a smaller reliance on domestic cereals, because less agricultural input energy is required. If Çatalhöyük needed to sustain its population during a time of high population growth rate with high yields, a lower reliance on domestic cereals would be most efficient for Çatalhöyük. Overall, regardless of the yield scenario, here, needing more land and needing to dedicate more energy to agricultural processes at a time of higher growth rate, seems to be a limiting factor for both cost and efficiency within Çatalhöyük's agricultural system.

As Çatalhöyük's population grows to 1000 people during its Early Period, we see that efficiency increases regardless of yield scenario or how much of the diet is reliant on domestic cereals. Again, high yields are far more efficient than low yields. Moreover, concerning all yields, a 50% and 75% reliance on domestic cereals are more efficient than 25% reliance on domestic cereals to sustain a population of 1000 people. Although more energy is required for a population of 1000 people, simultaneously, more energy is produced. This is especially the case with a higher reliance on domestic cereals, and thus, here, a higher reliance is more efficient for Çatalhöyük.

When Çatalhöyük's population reaches 2000 at the end of Çatalhöyük's Early Period, we witness that for all yield scenarios, a lower reliance on domestic cereals becomes more efficient than a higher reliance. With a population of 2000, the amount of extra land required (see Table 13) for a 50% to 75% reliance on domestic cereals is nearly triple the land required for a 25% reliance on domestic cereals. Thus, the amount of land and energy required to sustain a lower reliance on domestic cereals with high yields is significantly lower than either a 50% or 75% reliance on domestic cereals. Although more land is required to sustain a growing population, because less land is required to sustain a lower reliance, efficiency improves for a lower reliance.

For Çatalhöyük's Middle Period (peak), the growth rate is lower (1.5). Yet, irrespective of yield or percent reliance on cereals, the amount of land required to sustain a larger population, peaks, therefore, the energy input required for agriculture peaks, the potential for losses peaks, the total amount of seed required to sustain agriculture peaks, and the total amount of energy received directly from agriculture peaks (see 5.2, Figure 17, Figure 25, and Figure 35). Thus, we may expect efficiency to decrease. Referring to Figure 41, efficiency increases for a

75% reliance on domestic cereals for all yield scenarios. For high yields, efficiency increases for a 25% reliance on domestic cereals but decreases for a 50% reliance on domestic cereals. For low and average yields, efficiency decreases for a 25% and 50% reliance on domestic cereals. This is directly related to the land required to sustain Çatalhöyük's population and energy output.

Referring to Table 13, for low yields, 500 hectares of extra land are required to sustain 3000 people for 75% and 50% reliance on domestic cereals. For a 25% reliance on domestic cereals and low yields, 200 hectares of extra land are required to sustain 3000 people. In this case, the same amount of extra land is required for high and average yield scenarios; however, having a higher reliance on domestic cereals is more efficient because it produces more energy output. Concerning a 25% reliance on domestic cereals, having a lower reliance in this case, during a peak is least efficient because less energy is being produced; thus, this cannot effectively counteract the large energy input required of low yields.

For average yields, 350 hectares of land are required for a 75% reliance on domestic cereals, 290 hectares are required for a 50% reliance on domestic cereals, and 190 hectares are required for a 25% reliance on domestic cereals (Table 13). With average yields, less land and energy are required to sustain all dietary scenarios than for low yields; however, both a 25% and 50% reliance on domestic cereals decrease in efficiency during the Middle Period, whereas a 75% reliance in domestic cereals increases. Although the 25% and 50% reliance on domestic cereal scenarios may allow for less energy input, less overall energy is produced as compared to a 75% reliance on domestic cereals. At this point, for average yields, a 75% reliance on domestic cereals is both less costly and more efficient than any other scenario.

For high yields, efficiency increases for a 75% and 25% reliance on domestic cereals but decreases for a 50% reliance. This, again, is related to the amount of land required and agricultural output. For high yields, 240 hectares of extra land are required to sustain a 75% reliance on domestic cereals, 200 hectares of extra land are required for a 50% reliance, and 130 hectares of extra land are required for a 25% reliance. More importantly, however, a 25% reliance on domestic cereals only produces 3.0 million megajoules of energy, whereas a 50% reliance produces 5.0 million megajoules of energy and a 75% reliance produces 7.6 million megajoules. For a 75% reliance on domestic cereals, although more land is required to sustain agriculture for 3000 people, far more energy is produced than a 50% reliance on domestic cereals. With a 25% reliance on domestic cereals, this lower reliance requires the least amount of extra land to sustain; thus, it requires the least amount of energy input which makes it more efficient.

The relationship to cost for Çatalhöyük's Middle Period is quite interesting. During this Middle Period, overall, a high reliance is not only less costly for Çatalhöyük but more efficient. As aforementioned in the previous chapter subsection, for the Middle Period with a 50% and 75% reliance on domestic cereals there is a net decrease in agricultural costs for all yields. However, for a 25% reliance on domestic cereals, again higher yields were less costly than lower yields, but total agricultural costs *increase* for all yields and a 25% reliance on domestic cereals (Figure 37). This indicates that at Çatalhöyük's peak, a higher reliance on domestic cereals is less costly and more efficient than a lower reliance on domestic cereals. In other words, when Çatalhöyük was sustaining its peak population, it would have been more beneficial to have a higher reliance on domestic cereals.

It is interesting to note that Çatalhöyük does not reach its highest efficiency at its peak Middle Period. Instead, Çatalhöyük reaches its peak efficiency later in its occupation, depending on the yield.

For lower yields, Çatalhöyük would reach its peak efficiency during the Final Period with a population of 2000 and 1000 people and a 25%-50% reliance on domestic cereals.

Unsurprisingly, this was also the point at which cost was the lowest for a 25% to 50% reliance on domestic cereals. Consequently, efficiency increases for all domestic cereal reliance scenarios for lower yields, although it is very minimal. Here, because the amount of land clearance required decreases substantially, the total amount of agricultural energy input decreases significantly. Thus, for lower yields, there is an overall increase in efficiency, with a 25% reliance being most efficient due to requiring the least amount of land to sustain agriculture (see Table 10 and Table 13).

For average yields, Çatalhöyük's agricultural system would reach peak efficiency during its Late Period, with a 25% reliance on domestic cereals. Again, at this point, for average yields, cost is lowest; thus, this being the highest efficiency is sensible. Overall, there is an increase in efficiency for all domestic cereal reliance average yield scenarios; however, a 25% reliance is most efficient because it requires the least amount of land to sustain agriculture (see Table 10 and Table 13).

For high yields, Çatalhöyük's agricultural system would reach peak efficiency during its Final Period, with a population of 1000 people. Here, all high-yield domestic cereal reliance scenarios reach their peak efficiency and, unsurprisingly, this is the point at which cost is the lowest (Figure 37). However, a 75% reliance on domestic cereals is most efficient. The amount of energy produced by a higher reliance, combined with a significant decrease in agricultural energy input because of a lack of land clearance, makes a 75% reliance on domestic cereals more efficient.

Finally, focusing on the Final Period population decrease to 500 people, efficiency for all domestic cereal reliance scenarios and yield scenarios decreases. At this point, as described in Figure 36 all agricultural processes except for land clearance decrease, the total energy received from agriculture also decreases, and Figure 37 indicates that cost increases substantially at this point; therefore, the drop in efficiency is sensible. Moreover, lower yields are less efficient than higher yields, and the most efficient scenario at this point is a high yield 25% reliance on domestic cereals. Again, as emphasised in the cost analysis, during times of rapid population decline but needing to clear more land, a lower reliance on high yield domestic cereals would have less costly and more efficient to sustain Çatalhöyük than any other scenario.

Thus far, the agricultural energy inputs required of Çatalhöyük's agricultural system, its costs, and its efficiency demonstrate, first, high yields are consistently more efficient and less costly than any other yield scenario, regardless of how much of the diet is reliant on domestic cereals whereas low yielding crops are the least efficient and most costly. Second, agriculture's efficiency and cost depend on the amount of land required to sustain agriculture (especially land clearance), population growth and decline, yield, and how much of the diet depends on domestic cereals.

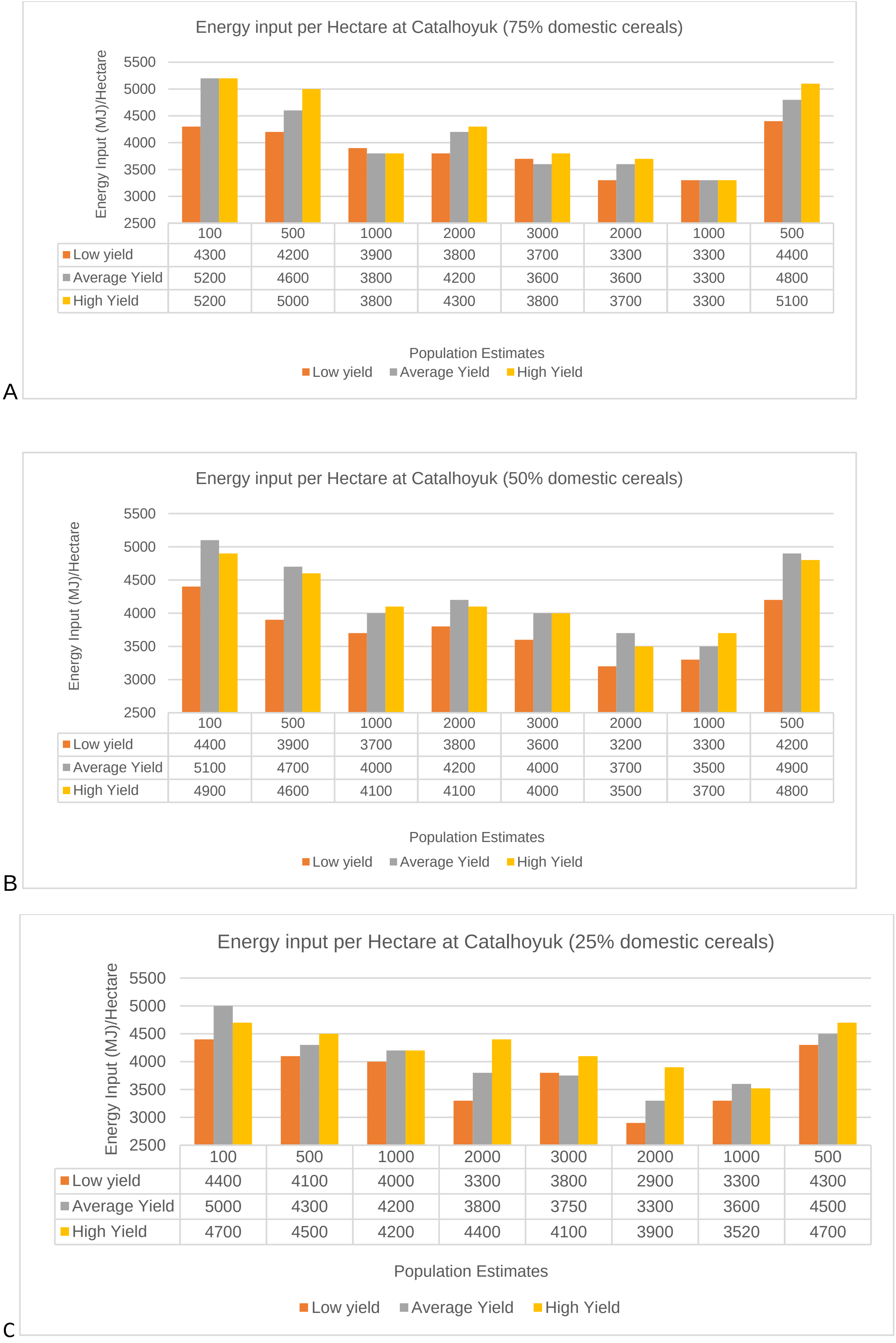
With higher-yielding crops, needing more land during rapid population growth or decline can be made efficient and less costly by utilising a smaller reliance on domestic cereals. With high yields, a lower reliance requires the least amount of extra land to sustain; thus, it requires the least amount of energy input and is most efficient. With average-yielding crops, needing more land and dedicating more energy to agriculture at a time of high population growth or rapid population decline can be counteracted by utilising a more significant reliance on domestic cereals. A larger reliance on domestic cereals for average yields produces more agricultural energy, thus, a higher reliance is more efficient and less costly. Finally, concerning low yields, they do not become efficient (i.e. allow for an energy gain) unless there is a population increase. Further, needing more land at times of higher growth rate and rapid population decline cannot be effectively counteracted by any sort of reliance on domestic cereals, because low yields are too costly and too inefficient to maintain.

The model and analysis thus far have demonstrated and quantified several conclusions surrounding Çatalhöyük's agricultural energy system, the agricultural energy feedback system, and has made significant contributions to understanding feedbacks and lock-ins during the Neolithic. Within Çatalhöyük's agricultural energy system, first, no matter the yield, agriculture requires an energy input from its population. Second, low yield crops require more energy input, are more costly, and are less efficient than high yielding crops. High yields are more beneficial and more efficient for Çatalhöyük. Third, tillage, land clearance, harvesting, and crop processing are Çatalhöyük's most energy-intensive agricultural processes. Fourthly, and most importantly, the efficiency of agriculture at Çatalhöyük initially increases and its cost decreases with population growth. This, to me, seems to be the early workings of the mechanism within the agricultural energy feedback system that encourages population growth and facilitates an increasing or continued reliance upon agriculture. This cost and efficiency aspect of the agricultural energy feedback system at Çatalhöyük is what encourages population growth, facilitates an increasing reliance upon agriculture, and requires additional land. Moreover, Çatalhöyük's agricultural efficiency and cost change throughout its occupation, both of which are, again, determined by the amount of land required. There is also a limit to Çatalhöyük's population growth within its agricultural system, which I believe this data indicates is partially determined by domestic cereal reliance and yield; in other words, land may very well be the limit to Çatalhöyük's growth. Further, once Çatalhöyük's population threshold is reached, it must make its agricultural system to be more productive and more efficient to keep relying upon agriculture to sustain itself. To substantiate this, however, we must delve into the energy requirement per unit hectare of land, presented in the following subsection.

7.2.4 Analysing Çatalhöyük's Agricultural Energy: Energy Input Per Hectare

The energy input per hectare of land required for Çatalhöyük's agricultural system is presented in Figure 42 below. This figure illustrates the energy input required to sustain each hectare of land by domestic cereal reliance and yield. Figure 42 A represents a 75% reliance on domestic cereals, Figure 42 B represents a 50% reliance on domestic cereals, and Figure 42 C represents at 25% reliance on domestic cereals.

Overall, the energy input per hectare of land is *highest* for high-yielding scenarios and lowest for low-yielding ones. This directly correlates with the amount of land which is required. More land is required for low yields; thus, this energy input per hectare will be lower than for high yields, which requires less land. However, what is emphasised in the figure is that no matter the yield the energy input per hectare of land only decreases to a certain extent, the extent to which is dictated by yield, domestic cereal reliance, and thus, land.



	100	500	1000	2000	3000	2000	1000	500
■ Low yield	4300	4200	3900	3800	3700	3300	3300	4400
■ Average Yield	5200	4600	3800	4200	3600	3600	3300	4800
■ High Yield	5200	5000	3800	4300	3800	3700	3300	5100

	100	500	1000	2000	3000	2000	1000	500
■ Low yield	4400	3900	3700	3800	3600	3200	3300	4200
■ Average Yield	5100	4700	4000	4200	4000	3700	3500	4900
■ High Yield	4900	4600	4100	4100	4000	3500	3700	4800

	100	500	1000	2000	3000	2000	1000	500
■ Low yield	4400	4100	4000	3300	3800	2900	3300	4300
■ Average Yield	5000	4300	4200	3800	3750	3300	3600	4500
■ High Yield	4700	4500	4200	4400	4100	3900	3520	4700

Figure 42: Energy Input per Hectare required of Çatalhöyük for a 75% reliance on domestic cereals (A), a 50% reliance on domestic cereals (B), and a 25% reliance on domestic cereals (C). This figure indicates the energy input per hectare of land for Çatalhöyük. Low yield scenarios are the lowest input per hectare because low yields

require more land. High yield scenarios are the highest input per hectare because high yields require less land. However, what is prevalent in this diagram is the significant decrease in input as Çatalhöyük's occupation continues regardless of domestic cereal reliance. For a 75% reliance on domestic cereals, the energy input per hectare of land seems to reach its threshold (i.e. the point at which it no longer improves) at a population of 2000 for high and average yields but a population of 2000 or 3000 for low yields. For a 50% reliance on domestic cereals, the energy input per hectare of land seems to reach its threshold at a population of 2000 people for low, average, and high yields. At a population of 3000 for a higher reliance on domestic cereals, the energy input per hectare improves because more energy is received. After Çatalhöyük's agricultural system reaches its threshold, it must make its agricultural system to be more productive and more efficient to keep relying upon agriculture to sustain itself. With a population of 3000 people, more energy received from a higher reliance on domestic cereals effectively aids in efficiency. For a 25% reliance on domestic cereals, the energy input per hectare of land reaches its threshold at a population of 2000 for high yields and 3000 for low and average yields. For all domestic cereal reliance scenarios, the energy input per hectare improves with a population decrease to 2000 people because less energy input is required due to a lack of land clearance. This makes the system more efficient. At 500 people, regardless of domestic cereal reliance, the total energy input per hectare increases because, as explained in 5.2, land clearance would be required at this point.

For a population of 100 people (7030 cal. BC, Figure 10), energy input per hectare is highest for all yields and no matter the domestic cereal reliance. In fact, the difference between reliance on domestic cereals is roughly only 200 to 500 megajoules per hectare. Essentially, as both cost and efficiency emphasised, sustaining agriculture with a small population is costly and requires significant energy input. As Çatalhöyük's population grows to 1000 people, the energy input per hectare for all yields and domestic cereal reliance scenarios improves. Here, the more people contributing to agriculture, the less of an energetic burden agriculture becomes. This was further emphasised with efficiency (Figure 41) and cost (Figure 38). Within Çatalhöyük's agricultural system regardless of yield or domestic cereal reliance, efficiency initially increases and its cost decreases with population growth. This is the early workings of the mechanism within the agricultural energy feedback system that encourages population growth and facilitates a continued reliance upon agriculture.

When Çatalhöyük's population reaches 2000 people at the end of the Early Period and start of the Middle Period, we see some differences between domestic cereal reliance and yield. Focusing first on a 75% reliance on cereals, when Çatalhöyük's population increases to 2000, the energy input per hectare essentially levels off for low yields, but it increases for high and average yields. For a 50% reliance on domestic cereals, energy input per unit hectare of land levels off for high yields but increases for low and average yields. For a 25% reliance on domestic cereals, the energy requirement per hectare decreases for low and average yields but increases for high yields. As aforementioned, during this point it was also established that a lower reliance on domestic cereals was more efficient than a higher reliance. Although more land is required to sustain a growing population, because less land is required to sustain a lower reliance, efficiency improves for a lower reliance. This is further established by this analysis of energy input per hectare.

Moving on to Çatalhöyük's peak Middle Period, with a population increase from 2000 to 3000, we still see some differences between domestic cereal reliance and yield. With a 75% reliance on domestic cereals, the energy input requirement per hectare decreases for all yield scenarios. At this point, efficiency also increased for a 75% reliance on domestic cereals. With a 50% reliance on domestic cereals, the energy input requirement per hectare decreases for all yields. Efficiency for a 50% reliance on domestic cereals at this point varied. This was due less overall energy being produced as compared to a 75% reliance on domestic cereals. With a 25% reliance on domestic cereals, the energy input per hectare increases for low and average yields but decreases for high yields. Concerning efficiency, for high yields at this point a 25% reliance on domestic cereals increased in efficiency, whereas for low and average yields, a 25% led to a decrease in efficiency. The former was due to an increase in energy output, whereas the former was due to increased energy input. Again, the energy input per hectare also reflects this and suggests that for a 25% reliance on domestic cereals, the threshold is 3000 people for low and average yields, but 2000 people for high yields. These are the points at which the energy input per unit hectare increases. For all domestic cereal reliance and yield scenarios, when Çatalhöyük's population declines, the energy input per hectare continues to decrease until Çatalhöyük reaches a population of 500 in its Final Period. This is the point at which more land is required to clear and sustain this population.

Overall, the patterns we see with a population of 2000-3000 people, I believe indicate that this is Çatalhöyük's threshold for population growth, which is dependent upon domestic cereal reliance and yield (land). Once this threshold was reached during its Middle Period, Çatalhöyük's agricultural system must be more productive or more efficient to keep sustaining agriculture.

Focusing on a 50% to 75% reliance on domestic cereals, this explains why energy input per hectare decreases, efficiency increases (Figure 41), and cost (Figure 37) decreases with a population of 3000 people. The system under these scenarios is more efficient and less costly because more energy is provided. The only reason efficiency, cost, and energy input per hectare continue to improve after Çatalhöyük reaches its threshold (until a population of 500 people) is because of a decrease in population, and thus, the amount of land. Needing less land and dedicating less energy to agriculture's process at a time of population decline helps to improve efficiency within Çatalhöyük's agricultural system.

Concerning a 25% reliance on domestic cereals and a population of 3000 people, this explains (a) why energy input per hectare decreased, efficiency increased (Figure 41), and cost (Figure 37) decreased for high yields, (b) why for low yields, energy input per hectare increases, efficiency plateaus and cost increases, and (c) why for average yields, energy input per hectare increases, cost increases, and efficiency decreases. For the high-yield scenario, more energy is received from agriculture making high yields less costly and more efficient with more people. With this scenario, Çatalhöyük's agricultural system is more efficient and less costly because more energy is provided. More energy is received for the average yield scenario, yet average yields require more land than higher yields, making the system less efficient and more costly. With this scenario, Çatalhöyük's agricultural system is less efficient and more costly because more land is required and less energy is provided. For the low yield scenario, less energy is received overall, and more land is required to sustain lower yields, making the system less efficient and more costly. For the 25% reliance on domestic cereals, the only reason efficiency, cost, and energy input per hectare continue to improve after Çatalhöyük reaches its threshold (until a population of 500 people) is because of a decrease in population, and thus, the amount of land required. Again, needing less land and dedicating less energy to agriculture's process during a population decline helps improve efficiency within Çatalhöyük's agricultural system.

Overall, this indicates that once Çatalhöyük's threshold was reached, its agricultural system had to be more productive and efficient to continue sustaining agriculture and its surplus. Land, again, seems to be tied to Çatalhöyük's growth and decline. Furthermore, these findings for Çatalhöyük's agricultural energy system quantify and demonstrate that agriculture inherently requires significant energy input to sustain it, requires land to support it, and there is a point within agricultural systems which the system must become more efficient, grow or shrink. In other words, this analysis helps to potentially provide quantifiable evidence of why agriculture requires the land colonisation that others have suggested (Barrett, 2011, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski and Weisz, 1999, Rindos, 1980, Shennan, 2018). These findings are a crucial aspect of helping us to disentangle and understand the relationship between population growth, land, and energy, especially during the Neolithic.

Much of this is further substantiated by investigating the EROIE and the average energy required per person per year at Çatalhöyük, presented in Figure 43 below.

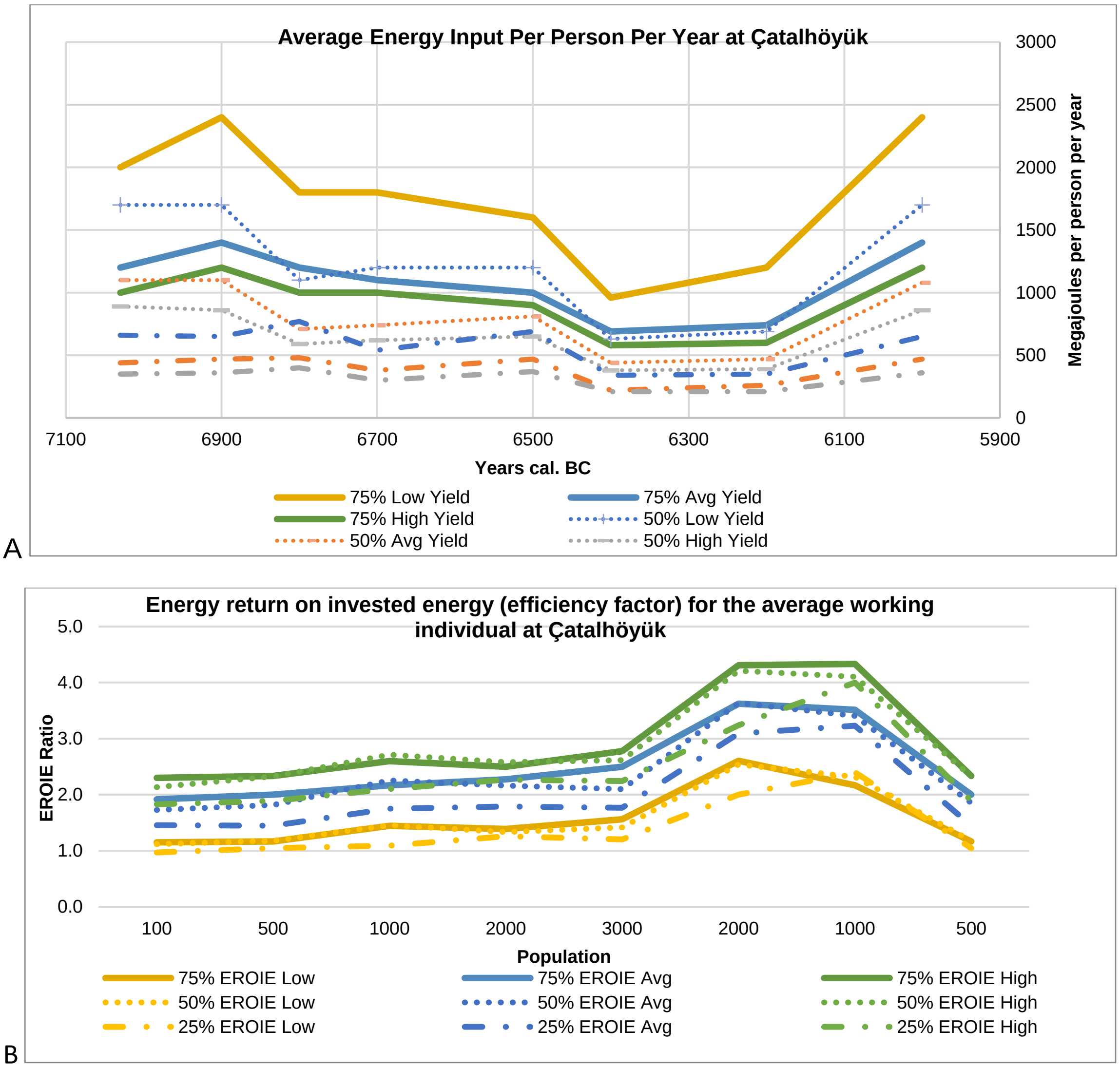


Figure 43 Figure A shows the average yearly input requirement of individuals at Çatalhöyük who were partaking in agricultural activities. High yields require less energy input per person per year, on average, than low yields. Further, a higher reliance on domestic cereals requires far more energy input per year for the individual than a lower reliance on domestic cereals. Figure B shows the EROIE ratio for individuals at Çatalhöyük who were partaking in agricultural activities.

Figure 43 A, indicates the energy input per person per year at Çatalhöyük based on cereal reliance and yield if 75% of the population was performing agricultural labour. Figure 43 B shows the EROIE ratio based on domestic cereal reliance and yield for the average working individual at Çatalhöyük per person per year. Overall, low yields require more energy input and are less efficient than high yields. Further, a higher reliance on domestic cereals requires far more energy input than a lower reliance on domestic cereals. Yet, a higher reliance seems to be more efficient, depending on population growth and reliance on domestic cereals.

For Çatalhöyük's Early Period (7100 cal. BC to 6700 cal. BC, 100 to 2000 people), again, the same pattern is prevalent as before, efficiency increases with Çatalhöyük's population growth; simultaneously, agriculture requires less energy input for the average individual per year. Regarding efficiency, during Çatalhöyük's Early Period, efficiency is much higher for the average individual than the overall group for high yields and average yields. For lower yields, the efficiency for the average individual compared to the overall group is closer in value. Having a growing population with higher yields makes agriculture more efficient and easier than for the group.

For Çatalhöyük's Middle Period (6700 cal. BC to 6500 cal. BC, 2000 to 3000 people), Çatalhöyük's energy efficiency decreases slightly, and the average energy requirement per person per year increases slightly, or plateaus (i.e., does not improve). Regarding efficiency, during Çatalhöyük's Middle Period, efficiency is relatively similar for the average individual than the overall group for all yields and no matter the reliance on domestic cereals. This, again, suggests that Çatalhöyük's threshold is 2000-3000 people.

Once Çatalhöyük reaches its Late Period, the individual energy required per year decreases regardless of yield or domestic cereal reliance, as land clearance energy is not required and the population decreases. As a result, efficiency at this point for the average working individual at Çatalhöyük increases substantially. In fact, the efficiency at this point for the average working individual at Çatalhöyük is nearly double what it is for Çatalhöyük, as a group. It becomes far more efficient and less energy intensive for the average individual to participate in agriculture, *because* the population declines and no additional land is needed to sustain the population. This occurs up until a population of 500 people, where we see efficiency decrease and the amount of energy required for the average individual working at Çatalhöyük increase substantially.

The data presented above for average individuals at Çatalhöyük suggests that throughout Çatalhöyük's occupation, but particularly during its peak population, differences between household access to land, resources, differences in seed storage, may be significant. Further, it demonstrates the need for group effort in agriculture in order to partake in it. Although this thesis does not strive to explain the origins of the Neolithic itself as this is beyond the scope of this thesis, this shows that the energetic perspective in this thesis opens more avenues towards such understandings.

Thus far, the figures and data from the model demonstrate the agricultural energy feedback system at work (Figure 1). Agriculture at Çatalhöyük would have allowed for an energy surplus; however, with the lowest yields, agriculture would have broken even or barely provided an energy surplus for Çatalhöyük. According to the agricultural energy feedback system posited in chapter 1, providing an energy surplus inherently aids in population growth. As discussed in chapter 3, this population growth is evidenced archaeologically at Çatalhöyük. Çatalhöyük's own bioarchaeological data indicates that its increase in population was driven by fertility and birthrate, one of the direct results of reliance upon domestic plants (Larsen, Knüsel et al., 2019). As agriculture provided this surplus energy to Çatalhöyük and its population grew, the energy cost of agriculture decreased. Energetically, agriculture provided an energy surplus, its cost and efficiency improved, and the energy input per hectare of land decreased with Çatalhöyük's growth, at least up to its Early Period (emphasised in Figure 43). Figure 37, Figure 41 and Figure 43 demonstrate that Çatalhöyük's Neolithic agricultural system had within it an internal mechanism that promoted an increasing reliance upon agriculture. This was directly tied to a combination of energy surplus, energy cost and efficiency being enhanced due to population growth and investing more energy into agricultural processes. However, this cost and efficiency changes substantially throughout its Middle Period, with a peak population of 2000-3000 people, and is driven by land clearance and tillage, as well as yield and how reliant upon domestic cereals the diet was, i.e., land. Çatalhöyük's agricultural processes required more energy as its population grew, as indicated by Figure 35 and Figure 36. This energy input requirement would have been highest during Çatalhöyük's peak. Çatalhöyük's archaeological evidence corroborates this, as bioarchaeological evidence (chapter 3) indicated high levels of crowding and increases in fertility, birthrate, physiological stress, and the presence of illnesses during this period (Hodder, 2014b, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019). This bioarchaeological evidence overall confirmed that with more people present at Çatalhöyük, people were working harder, living a vigorously active lifestyle, and likely investing more time and energy into daily processes, including agricultural ones; the energy model in this analysis substantiates this.

Further, this finding overall also helps to explain limits to growth within Çatalhöyük's agricultural system, which is 2000 to 3000 people. At this point, the cost and efficiency seem to plateau, no matter the yield, and the energy input per hectare of land also plateaus and does not improve. At this point, the differences between yield scenarios and energy input per hectare are also minimal. This finding is critical for understanding the relationship between population growth, land, and energy, not just at Çatalhöyük, but also during the Neolithic. Once this threshold was reached, there were conflicts in energy balances both within and outside of agriculture. The agricultural system must be made more efficient and productive, or more land is required. Çatalhöyük had to find ways of balancing energy conflicts and sustaining itself, hence, the changes we see during Çatalhöyük's Middle Period.

Additionally, this analysis has quantified and proved the existence of a positive energy feedback system between agriculture, surplus energy, and population growth, and, identified limits to this feedback system's growth. This has significant implications, as it quantifies a mechanism that can be tied to why the Neolithic Revolution came with population growth, surplus production, new land requirements, changes in nutrition, workload, mobility, social interaction, and, new ensembles of activities, behaviours, and technologies (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995).

7.3 THE AGRICULTURAL ENERGY FEEDBACK SYSTEM AT ÇATALHÖYÜK

Another aspect of the agricultural energy feedback system, as stated in chapter 1 and emphasised throughout this thesis, was that agriculture's processes depend on one another's success and energy input from populations. If one agricultural process fails, the system and the subsequent energy flows of which it is a part, can break down. Agriculture is only successful when its processes are successful and agriculturally based societies must maintain this success by inputting energy into agriculture's processes. Agriculture as a system comes with the caveat that agricultural processes, together, are dependent upon one another's success to produce an energetic surplus. This aspect of agriculture has not been fully recognised, as outlined in chapter 2 (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski and Weisz, 1999, Odum, 2007, Odum and Odum, 1977, Smil, 2017) nor has it been quantified. This aspect of agriculture is essential, as it only further enhances the cost and efficiency aspect of the agricultural energy feedback system; thus, it aids in facilitating an continuing reliance upon agriculture. This effectively "traps" societies into relying upon it. Thus, considering the inputs and outputs of Çatalhöyük's agricultural energy system, the focus of this chapter section, allows for us to understand how this could happen within Çatalhöyük, and has broader implications for understanding the Neolithic and the spread of agriculture, more generally.

Chapters 5 and 6 quantified the minimum energy requirements of Çatalhöyük's agricultural energy system, including the amount of cereal energy required for Çatalhöyük's population through time and the agricultural energy investment required for each agricultural process. The previous chapter subsection utilised this data to demonstrate that within Çatalhöyük (1) low yield crops require more energy input, are more costly, and less efficient than high yielding crops (2) demonstrated that tillage, harvesting, land clearance, and crop processing are energy-intensive agricultural processes, (3) showed a higher reliance on domestic cereals requires higher energy input but produces a large amount of energy whilst a lower reliance on domestic cereals requires a low energy input but produces a smaller amount of energy, (4) initially agriculture's efficiency increases and its cost decreases with population growth, but this cost and efficiency change throughout Çatalhöyük's occupation depending on population growth and decline and the amount of land required to sustain agriculture (land required, yield, and how much of the diet is reliant upon domestic cereals) and (5) Çatalhöyük's threshold for population growth was indeed 2000-3000 people; once this threshold was reached its agricultural system had to be made to be more sufficient to keep relying upon agriculture. Having quantified and modelled the energy inputs of Çatalhöyük's agricultural system, it is now possible better understand how these inputs fit within Çatalhöyük's agricultural energy system: how this energy flows through the system, how it changes in relation to Çatalhöyük's changing population, and how the agricultural inputs modelled tie in with the archaeological data at hand. These are the primary issues upon which this chapter subsection will focus. For this dissertation, it was not possible within the timeframe allowed for the final corrections to include an analysis of every aspect of population growth or to include average yield scenarios. Thus, the remaining interpretations within this chapter subsection focus exclusively on low and high yields for the beginning and midpoint of the Early Period and Çatalhöyük's Middle Period.

Referring to Figure 16 in Chapter 3, section 3.4, which represents Çatalhöyük's agricultural energy system, to function, Çatalhöyük as an entity had to invest energy into multiple processes to grow domestic crops and to extract energy from them. The first agricultural processes to take place before domestic crops can grow are land clearance, tillage, and planting. After plants grow, the energy from the crops can only be extracted via harvesting, then subsequently threshing, winnowing, sieving, and pounding or grinding, all of which also require energy input from Çatalhöyük peoples. The energy from domestic crops is extracted in the form of grain and returned to Çatalhöyük via curation, defined for this analysis as food, further food processing, and cooking (Atalay and Hastorf, 2006). However, in order to grow agricultural crops for the next year, a portion of the grain must be stored as seed. Therefore, this energy does not go directly back into sustaining Çatalhöyük, but instead, goes back into sustaining Çatalhöyük's agricultural system via planting.

Figure 44 represents Çatalhöyük's agricultural energy system at a population of 100, for low (A) and high (B) yield scenarios for a 75% reliance on domestic cereals. Figure 45 and Figure 46 represent the same population and yield scenarios, but for a 50% and 25% reliance on domestic cereals. Figure 47, Figure 48, and Figure 49 represent low (A) and high (B) yield scenarios for Çatalhöyük's agricultural system for a population of 2000 people for a 75%, 50%, and 25% reliance on domestic cereals, respectively. Figures Figure 50 to Figure 52 represent Çatalhöyük's agricultural system with low (A) and high (B) yields for a population of 3000 people, again for a 75% (Figure 50), 50% (Figure 51) and 25% (Figure 52) reliance on domestic cereals.

Figure 44 to Figure 46 are the most indicative of the beginning of Çatalhöyük's Early Period (pre-peak, 7100-6700 BCE). Figure 47 to Figure 49 represent the end of Çatalhöyük's Early Period and the beginning of its Middle Period (peak, 6700-6500 BCE). Figures Figure 50 to Figure 52 correspond to the end of Çatalhöyük's Middle Period.

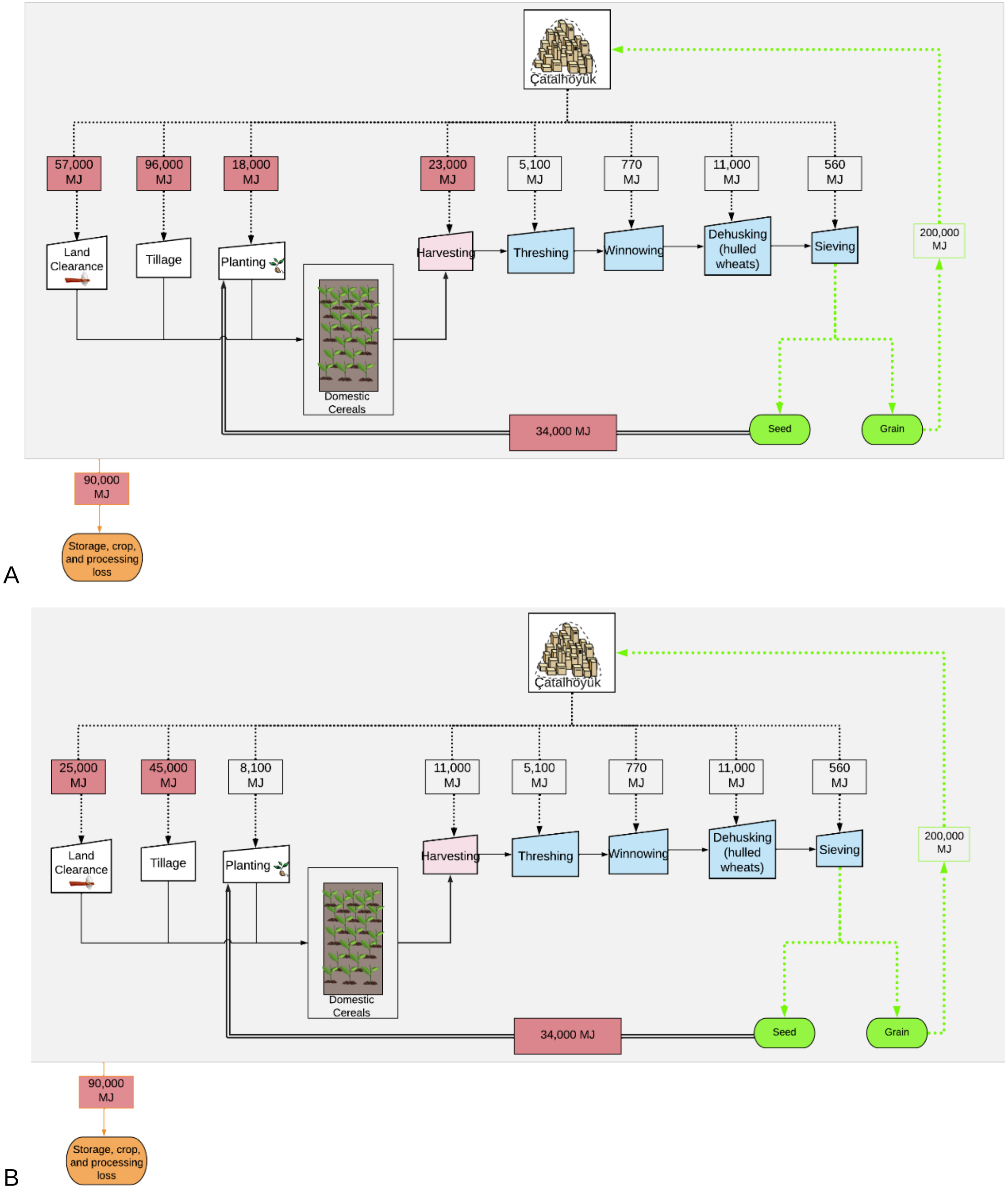


Figure 44: Çatalhöyük's Agricultural System at low (a), and high yields (b), for a population of 100 people, 75% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 12,000MJ) processes than for other yield scenarios.

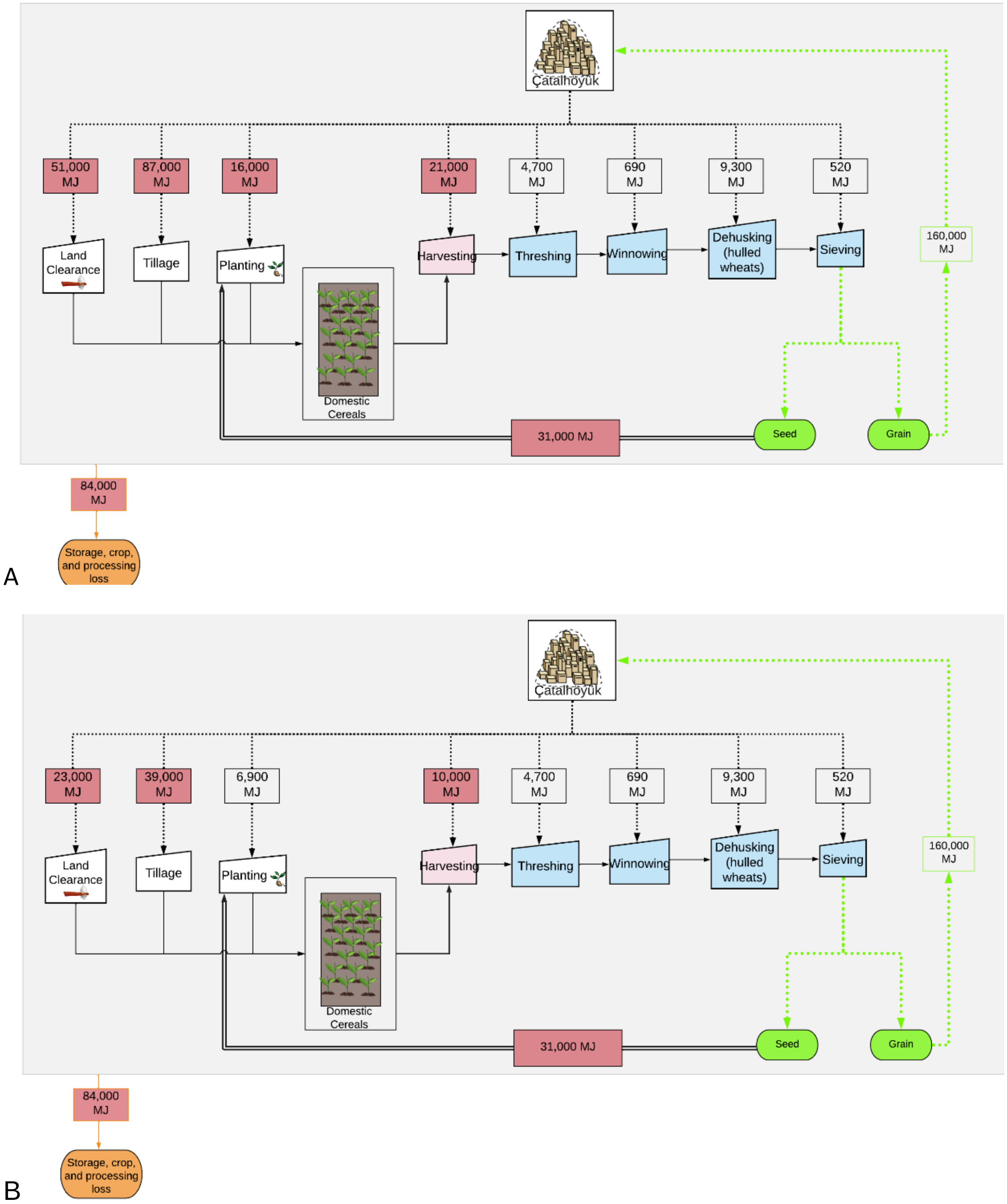


Figure 45: Çatalhöyük's Agricultural System at low (a) and high yields (b) for a population of 100 people, 50% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 9,500 MJ) processes than for other yield scenarios.

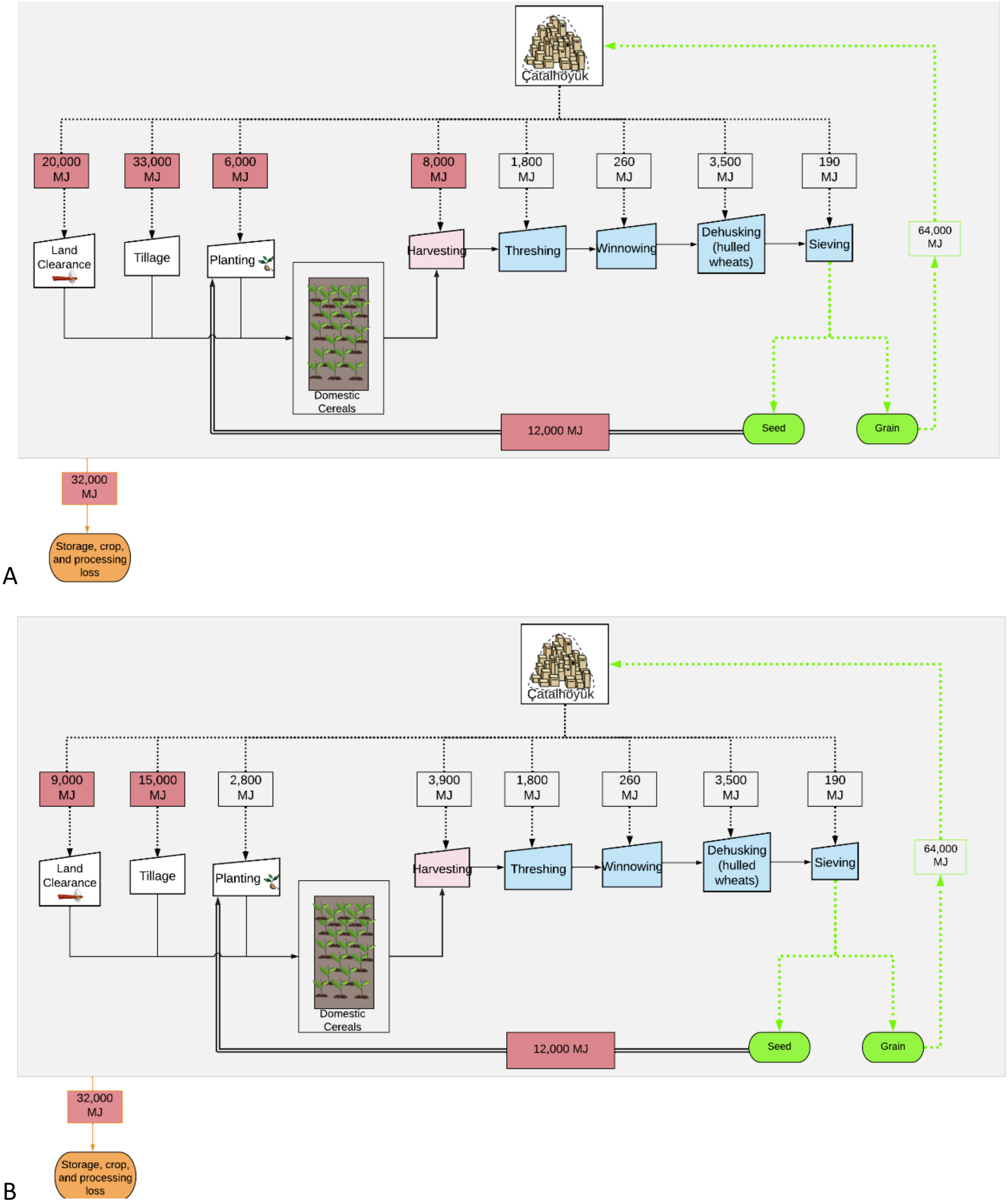


Figure 46: Çatalhöyük's Agricultural System at low (a) and high yields (b) for a population of 100 people, 25% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 4,000MJ) processes than for other yield scenarios

Focusing first on Figure 44 to Figure 46, no matter the scenario, losses are significant, as their energetic values are equal to sustaining half of Çatalhöyük's population for this model, regardless of domestic cereal reliance or yield. Although this is related to the amount this model assumes for losses (see losses in 5.2.), this emphasises that accounting for losses would have been an essential aspect within Çatalhöyük's agricultural system early on in its occupation. Further, storage is another important characteristic to note; the amount of seed storage required to sustain agriculture at this point is equal to sustaining roughly 15% of the population. Even with this minimum population estimate of 100 people, seed requirement was important within Çatalhöyük's agricultural system, especially in its early days. Finally, tillage and land clearance are all, no matter the yield or domestic cereal reliance, energy-intensive processes. This implies that from the beginning, land and access to land were important aspects of Çatalhöyük's agricultural system. Again, and as argued by Fischer-Kowalski and co-authors, and Rindos, agriculture within this Neolithic system is limited by land, even from its onset (Fischer-Kowalski and Haberl, 1997, Rindos, 1980). Furthermore, threshing, winnowing, dehusking and sieving are considered separately in this analysis; however, combining their energy inputs, crop processing is indeed energy-intensive, regardless of yield and domestic cereal reliance. Again, from its onset, crop processing would have been energy-intensive for Çatalhöyük regardless of yield and how much of the diet relies upon domestic cereals.

Keeping in mind efficiency, Figure 41 in the previous section emphasised that low yields were far less efficient than higher yields. Furthermore, it was noted with low yields that a larger reliance on domestic cereals was just as (in)efficient as a smaller reliance on domestic cereals; Figure 44 to Figure 46 seem to substantiate this. However, focusing on high yields for a 75% reliance on domestic cereals (Figure 44), only land clearance, tillage, and crop processing in toto are energy-intensive. For a 50% reliance on domestic cereals, land clearance, tillage, crop processing, and harvesting are energy-intensive. For a 25% reliance on domestic cereals, tillage, land clearance, and crop processing are energy-intensive.

Despite the energy required for agriculture in all yield scenarios, there is still the potential for energy surplus for all scenarios, aside from a low yield 50% reliance on domestic cereals (Figure 37 and Figure 41). However, even in this case, Çatalhöyük breaks even and does not *lose* energy. Assuming a 75% reliance on emmer, einkorn, free-threshing wheat, and barley (as established in 5.2, also Figure 17,) there is the possibility of an energy surplus. For a 75% reliance on domestic cereals, this energy surplus equates to 6% to 37% of the total energy received, for a 50% reliance on domestic cereals this surplus is up to 0% to 34% of the total energy received, and for a 25% reliance on domestic cereals, it is 5% to 39% of the total energy received—an energy gain which can be utilised for activities other than sustaining agriculture.

Figure 47 to Figure 49 show Çatalhöyük's agricultural energy system at a population of 2000 people, for low (A) and high yield (B) scenarios for a 75% (Figure 47), 50% (Figure 48), and 25% (Figure 49) reliance on domestic cereals. This model is the most indicative of the end of Çatalhöyük's Early Period and the beginning of its Middle Period (peak, 6700-6500 BCE). As discussed in 7.2.2, by the end of the Early Period there was a net decrease in total agricultural costs and improvement in efficiency regardless of yield or percent reliance on domestic cereals; albeit low yields were still costlier than high yields (Figure 37). It is at this point where the agricultural energy feedback system is accelerated, as the energy cost and efficiency of Çatalhöyük's agricultural system starts to improve, Çatalhöyük would be investing more energy into its agricultural processes, and would receive more an energy surplus, regardless of yield or domestic cereal reliance.

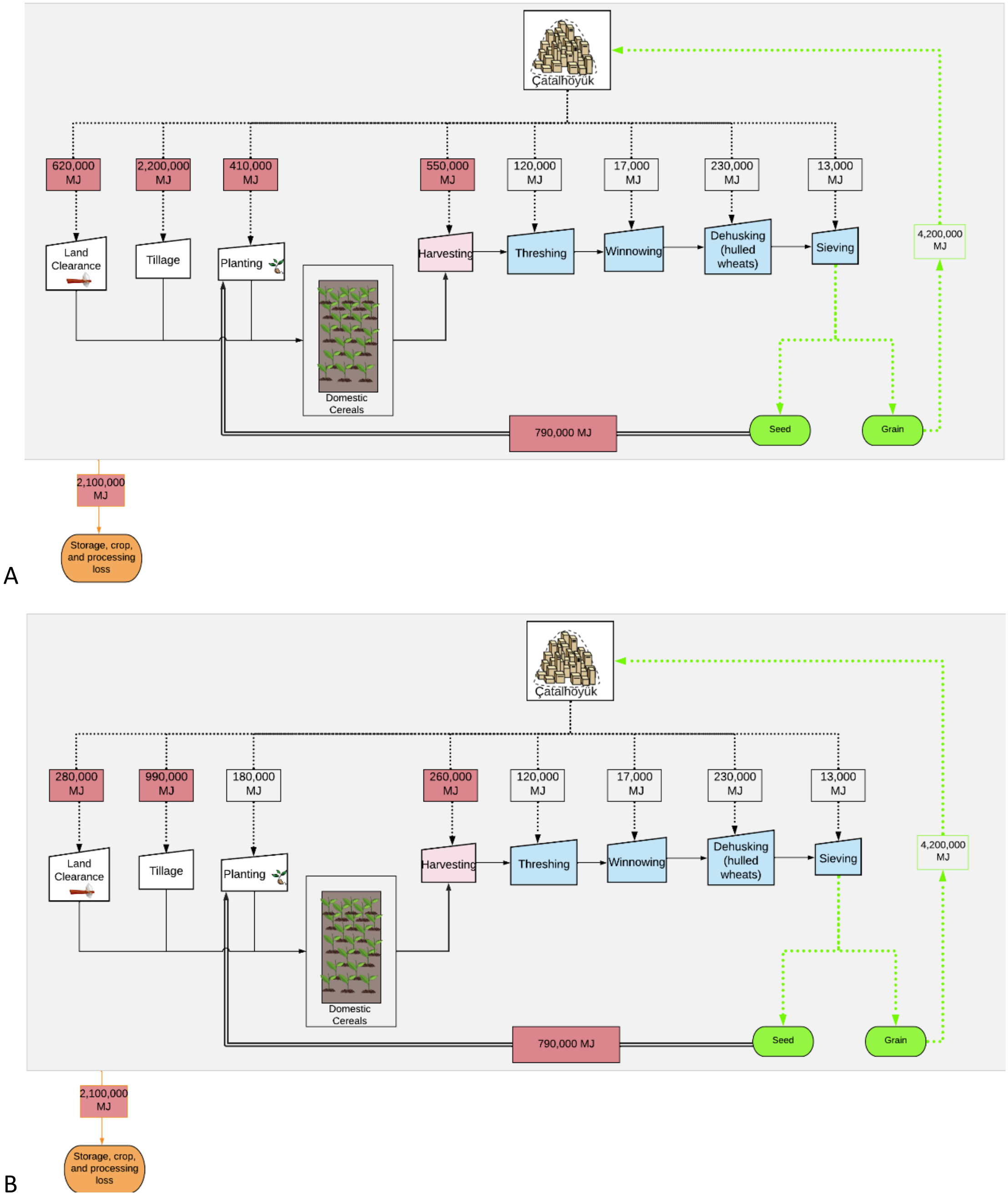


Figure 47: Çatalhöyük's Agricultural System at low (a) and high yields (b) for a population of 2000 people, 75% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 250,000MJ) processes than for other yield scenarios

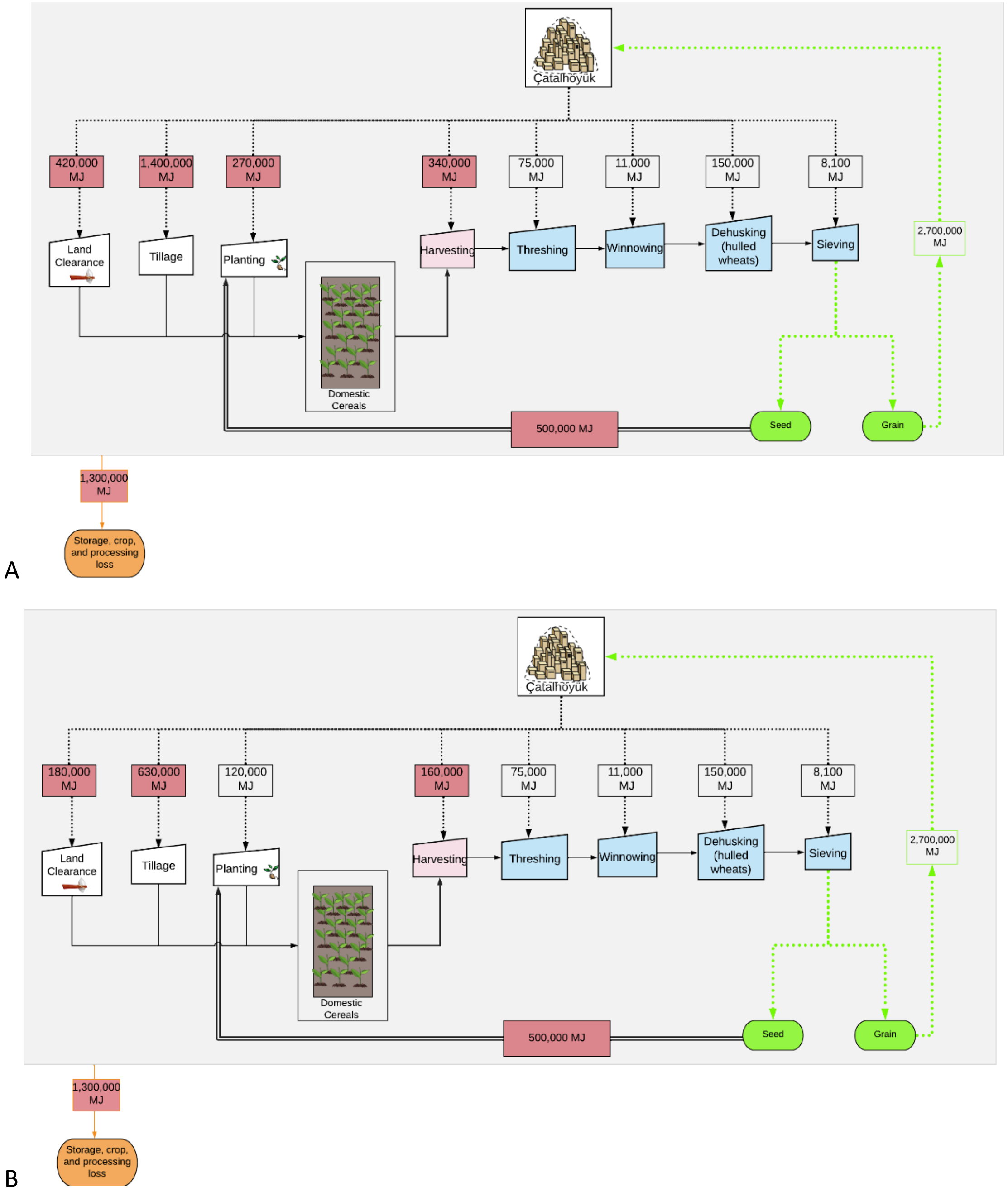


Figure 48: Çatalhöyük's Agricultural System at low (a) and high yields (b) for a population of 2000 people, 50% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 160,000MJ) processes than for other yield scenarios

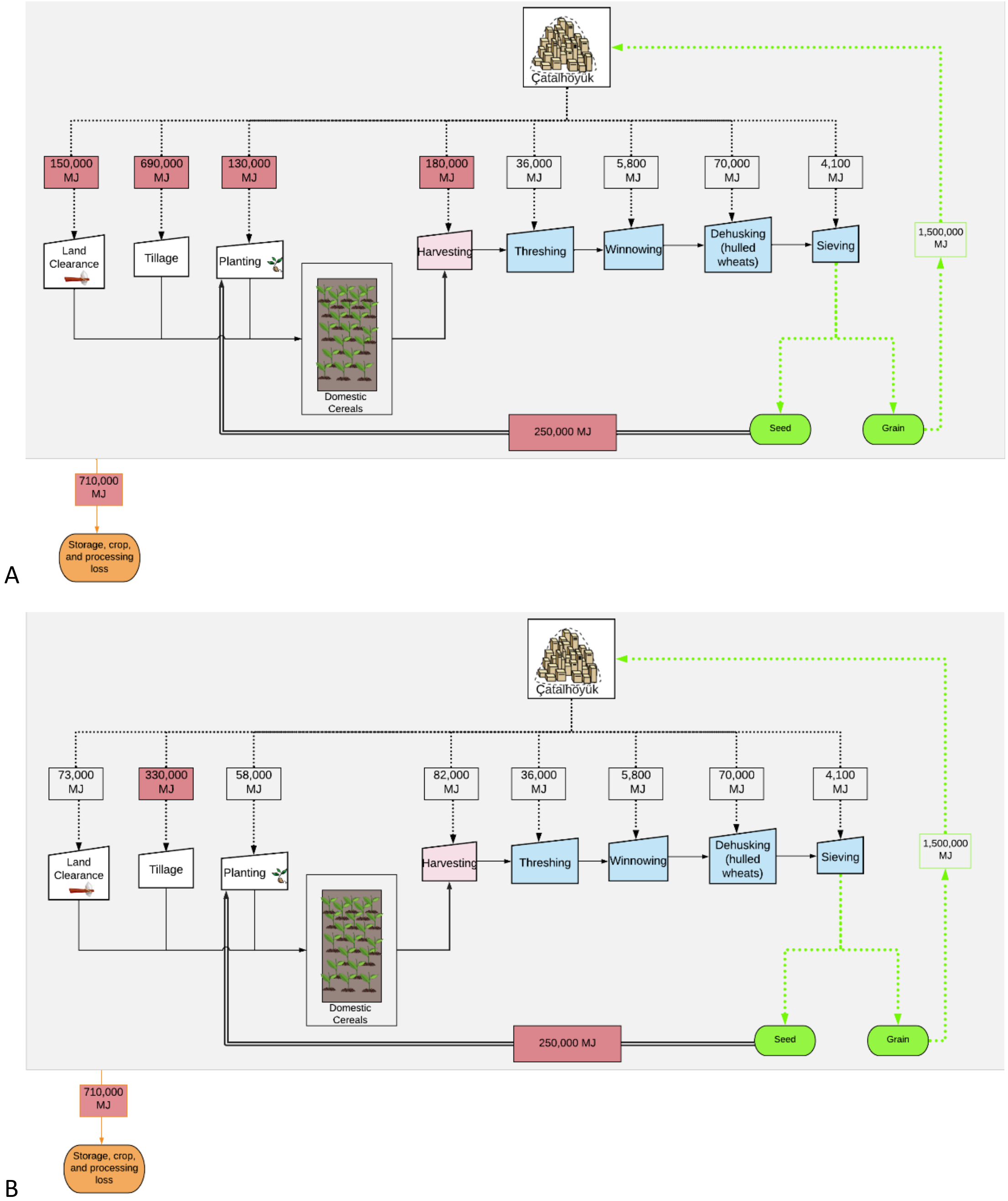


Figure 49: Çatalhöyük's Agricultural System at low (a), and high yields (b) for a population of 2000 people, 25% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 85,000MJ) processes than for other yield scenarios

For all scenarios in Figure 47 to Figure 49, regardless of yield or domestic cereal reliance, seed requirement and losses are significant. This, of course, makes sense, as with having three times as many people, more cereal energy is required; therefore, more seed storage will also be required and the potential for losses increases. Furthermore, regardless of yield and cereal reliance, crop processing is energy-intensive. Focusing on low yields, it is worth noting that for a 25% to 75% reliance on domestic cereals, land clearance, tillage, harvesting, crop processing, and planting are all energy intensive processes. Most agricultural processes scale with population; however, these are still significant findings within this point in Çatalhöyük's growth, because it indicates that losses in addition to keeping and storing seed, planting seed adequately, and harvesting crops on time are not just energetically significant, but, crucial to maintaining agriculture with low yields. Finally, the same pattern arises; high yield scenarios are less energy-intensive than low-yield scenarios. In other words, high yield scenarios have less energy-intensive agricultural processes than low yield scenarios.

We witness some differences between a higher and lower reliance on domestic cereals, focusing on higher yields. For both a 75% (Figure 47) and 50% (Figure 48) reliance on domestic cereals, land clearance, tillage, harvesting, and crop processing are energy-intensive. Furthermore, it is at this point for the first time for a 50% and 75% reliance on high yield domestic cereals, and more energy processes are intensive than the beginning of Çatalhöyük's occupation. This, as expressed in previous subsections, I believe, emphasises that for a 50% to 75% reliance on domestic cereals, 2000 people is the absolute threshold for Çatalhöyük. Once this threshold was reached, Çatalhöyük's agricultural system must be made to be more efficient to keep relying upon agriculture.

For a 25% (Figure 49) reliance on domestic cereals, only tillage and crop processing are energy-intensive with Çatalhöyük's population of 2000. With respect to efficiency, as discussed in 7.2.3, (Figure 41) for all yield scenarios, a lower reliance on domestic cereals becomes more efficient than a higher reliance. This model shows why; because, at this point, with a lower reliance on domestic cereals, less of agriculture's processes are considered to be intensive. Furthermore, with a population of 2000 people, the amount of extra land required for a higher reliance on domestic cereals is nearly triple the land required for a 25% reliance on domestic cereals. Although more land is required to sustain a growing population, efficiency improves because a lower reliance requires the least amount of land.

By the end of Çatalhöyük's Early Period and the Start of the Middle Period, despite the energy required for agriculture in all yield scenarios, there is still the potential for energy surplus for all scenarios (Figure 37 and Figure 41). For a 75% reliance on domestic cereals this energy surplus is 11% to 41% of the total energy received, for a 50% reliance on domestic cereals this surplus is up to 14% to 43% of the total energy received, and for a 25% reliance on domestic cereals, it is 13% to 39% of the total energy received. Overall, with an increase in population to 2000 people, there is an energy gain no matter the yield situation or reliance on domestic cereals. With even more of an energy surplus than before, this energy can be returned to Çatalhöyük and invested in other activities such as ritual, materials, or trade, as opposed to sustaining this agricultural system.

Focusing on the end of Çatalhöyük's Middle Period, figures Figure 50 to Figure 52 represent Çatalhöyük's agricultural system with low (A) and high (B) yields for a population of 3000 people, again for a 75% (Figure 50), 50% (Figure 51) and 25% (Figure 52) reliance on domestic cereals.

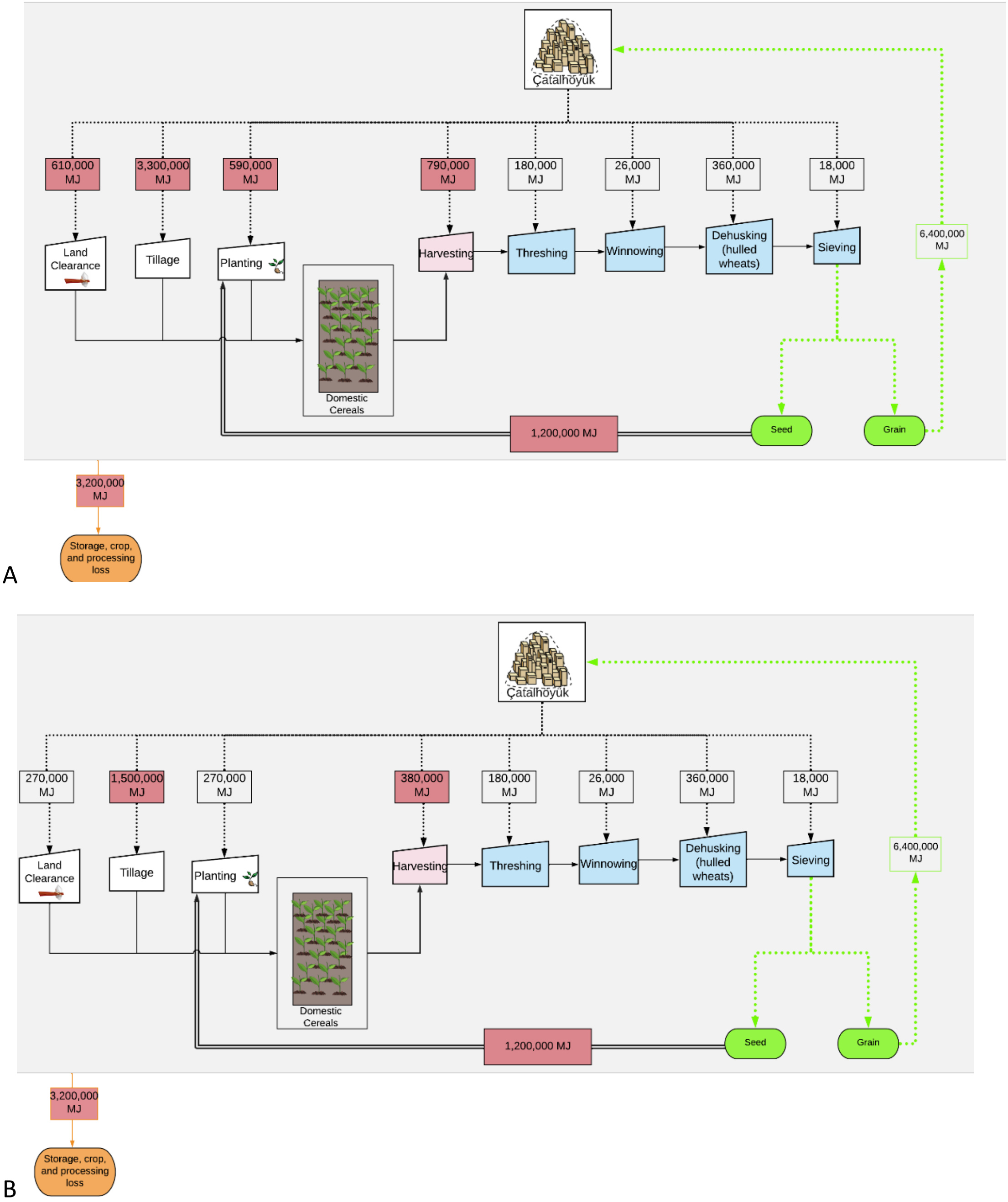


Figure 50: Çatalhöyük's Agricultural System at low (a) and high yields (c) for a population of 3000 people, 75% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 380,000MJ) processes than for other yield scenarios

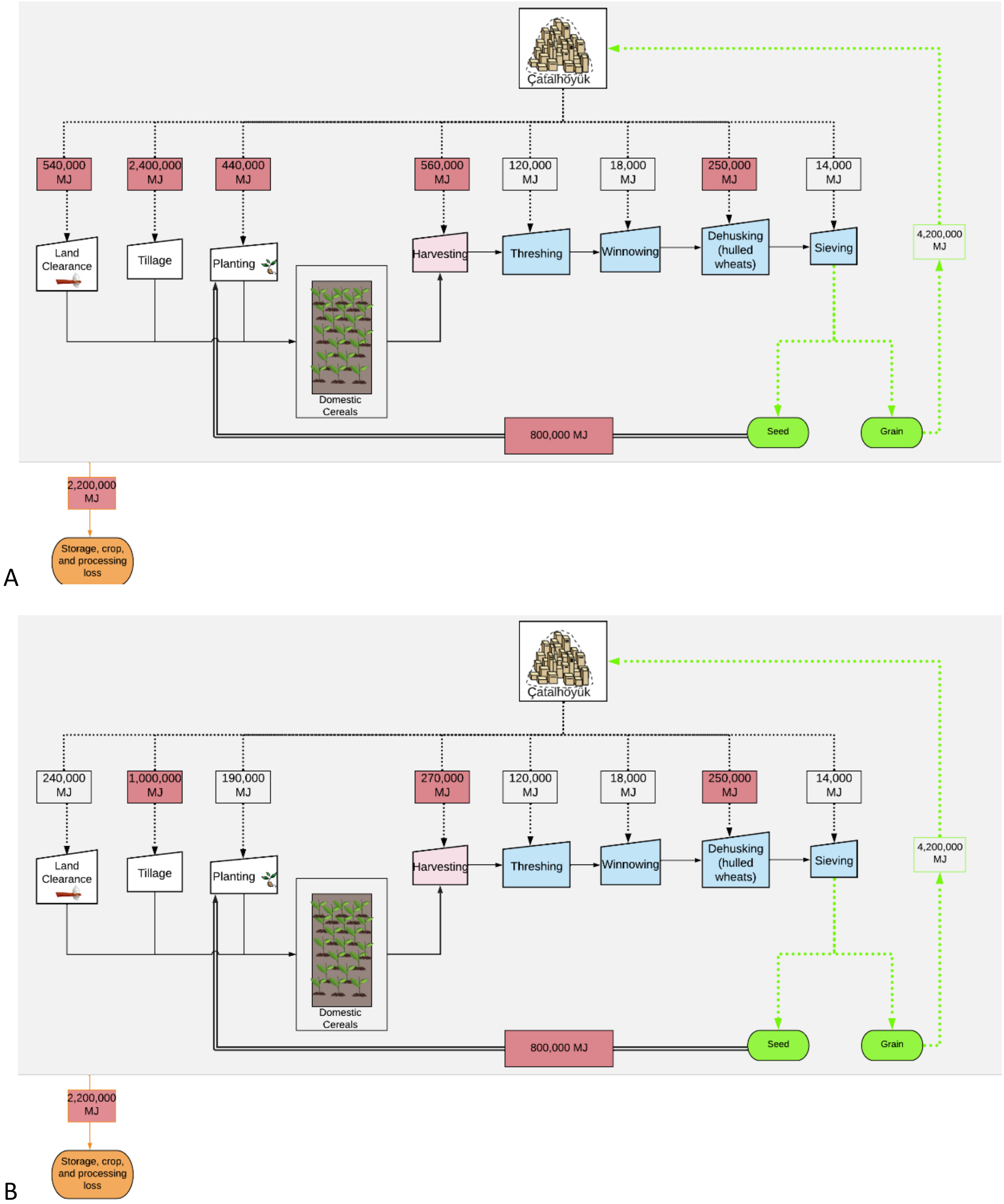


Figure 51: Çatalhöyük's Agricultural System at low (a) and high yields (b) for a population of 3000 people, 50% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 250,000MJ) processes than for other yield scenarios

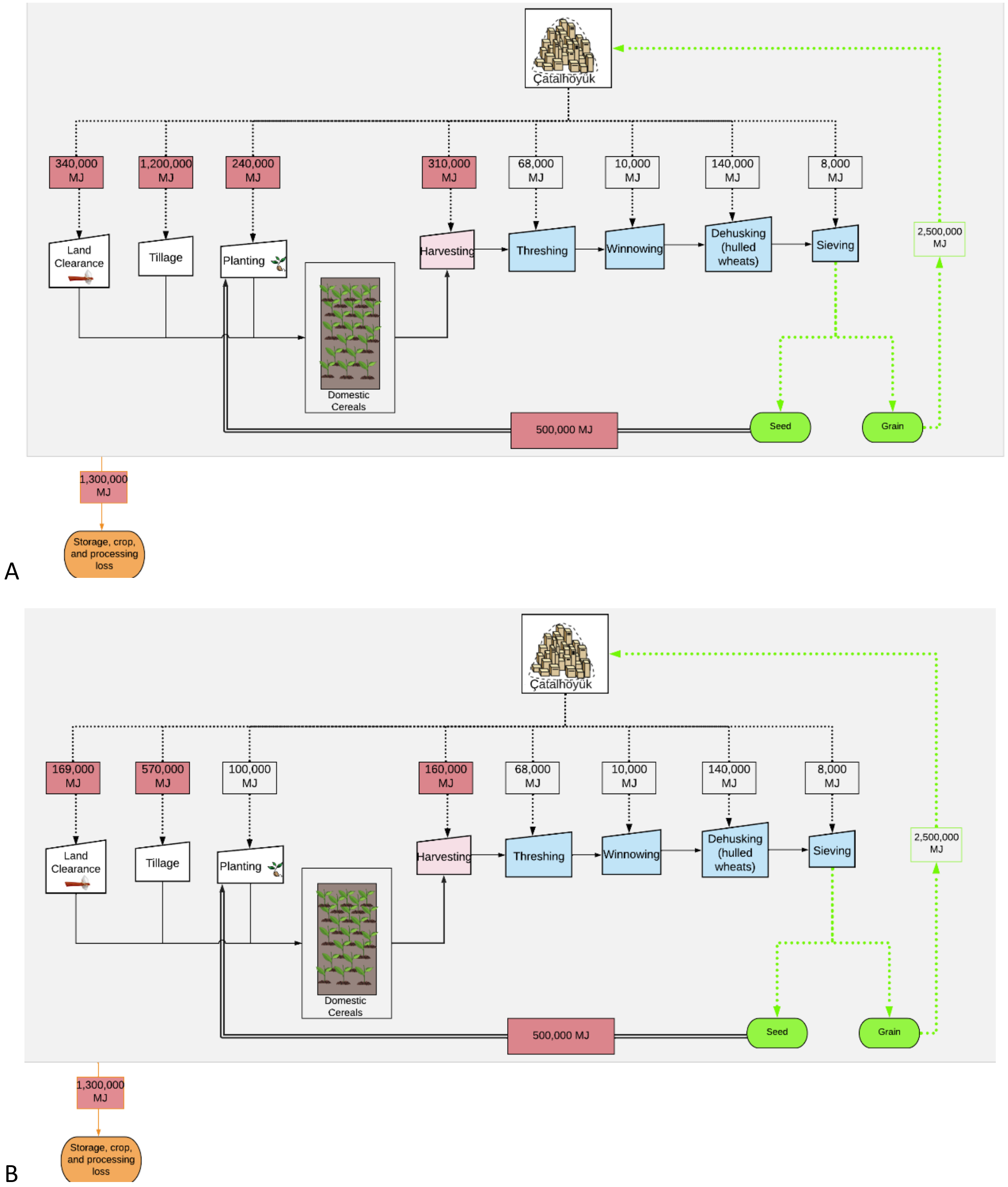


Figure 52: Çatalhöyük's Agricultural System at low(a) and high yields (b) for a population of 3000 people, 25% reliance on domestic cereals. All energy values are shown in Megajoules per year. With low yields, Çatalhöyük's agricultural processes are more intensive (greater or equal to 150,000MJ) processes than for other yield scenarios

As discussed in the previous chapter, during the Middle Period with a population of 3000 people, the energy input required for agriculture peaks, the potential for losses peaks, the total amount of seed required to sustain agriculture peaks, and the total amount of energy received directly from agriculture peaks (see 5.2, Figure 17, Figure 25, and Figure 35). With respect to the amount of energy surplus available to Çatalhöyük at this point with low and high yields, for a 75% reliance on domestic cereals, this energy surplus is 17% to 45% of 6.4 million megajoules of energy received from agriculture, for a 50% reliance on domestic cereals this surplus is 19% to 46% of the 4.2 million megajoules received, and for a 25% reliance on domestic cereals, this energy surplus is 10% to 37% of the 2.5 million megajoules received. There is an energy gain no matter the yield situation or reliance on domestic cereals; thus, his energy can be returned to Çatalhöyük and invested in other activities such as ritual, materials, or trade, for example, as opposed to sustaining this agricultural system. However, what is more important here is the energy intensity and efficiency.

Focusing first on low yields, for a 25%-75% reliance on domestic cereals land clearance, tillage, planting, harvesting, and crop processing are all energy-intensive processes. However, it must be noted that at this point, regardless of yield scenario, for a 50% reliance on domestic cereals, dehusking energy itself is energy-intensive. As discussed in 6.2.2 (Figure 33), dehusking energy requires more input than either threshing, winnowing, or sieving energy, even though this is just for *two* crops. The dehusking energy of emmer and einkorn is quite significant at this point with a 50% reliance on domestic cereals, no matter the yield. However, it is only at this point in Çatalhöyük's occupation where it is becoming relevant.

Concerning high yields, regardless of domestic cereal reliance, tillage, harvesting, and crop processing are all energy-intensive processes. For a 50% reliance on domestic cereals, as mentioned above, dehusking becomes energy-intensive on its own. For a 25% reliance on domestic cereals, land clearance becomes energy intensive, unlike a 50% and 75% reliance. Even with high yields, more of agriculture's processes are becoming intensive. For the first time for a 25% reliance on domestic cereals and high yields, more energy processes are intensive than at the beginning of Çatalhöyük's occupation. At Çatalhöyük's population peak, a lower reliance on domestic cereals becomes energy-intensive regardless of yield. This, as expressed in previous subsections, I believe, emphasises that for a 25% reliance on domestic cereals, 3000 people is the absolute threshold for Çatalhöyük. Once this threshold was reached, Çatalhöyük's agricultural system must be made to be more efficient to keep relying upon agriculture.

Overall, these Figure 44 to Figure 52 demonstrate the following: low yield crops require more energy input, are more costly, and less efficient than high yielding crops, agriculture's efficiency initially increases, and its costs decrease with population growth, these costs and efficiency improvements depend on when additional land clearance is needed in a time of high population growth rate, tillage, land clearance, and crop processing are energy-intensive agricultural processes, and, no matter the population or yield scenario, agriculture's processes are inherently dependent upon one another's success and require an energy investment from Çatalhöyük's population. Further, if one agricultural process fails, land clearance or tillage is inadequate, planting is unsuccessful, the harvest fails, or if seed storage fails, the entire agricultural system and the subsequent flows of which it is a part can completely break down. Throughout Çatalhöyük's growth, with more agricultural processes becoming more intensive, the data analyses presented here demonstrates that the potential for energy conflicts between these activities, clearing more land to sustain agriculture and Çatalhöyük's population, and continuing to devote energy to all of agriculture's other processes would have occurred. Çatalhöyük would have had to adjust and make changes to avoid such energy (and time) conflicts. This is, in essence, all pointing to the presence of the agricultural energy feedback system.

7.4 ENERGY AND ARCHAEOLOGY AT ÇATALHÖYÜK

It is important to consider how these agricultural energy models fit in with Çatalhöyük's archaeological data. During Çatalhöyük's Middle Period (peak, 6700-6500 BCE), population estimates range between 2000-3000 people (chapter 3). Radical changes occurred during this period in terms of Çatalhöyük's health, diet, relationships to both plants and animals within the Çatalhöyük household (physical and symbolic changes), religiosity, resource procurement, and material production (Hodder, 2014b). These changes and Çatalhöyük's need for less labour, greater efficiency in daily processes, and an expansion of resource catchment zones were, as I argued in chapter 3, the result of the inner workings of the agricultural energy feedback system. In providing more energy, agriculture at Çatalhöyük facilitated population growth and increased fertility. Population growth helps to improve agriculture's efficiency and cost, which itself encourages an increasing reliance upon agriculture (and population growth) and necessitates additional land. Further, the fact that agriculture is dependent on both the success of its agricultural processes and human energy input only further facilitates this feedback. Whilst this occurred, Çatalhöyük had to dedicate more energy to agriculture to keep it sustained. As more resources were required, simultaneously, Çatalhöyük was altering and impacting its own environment, which it *also* had to adjust to forcing Çatalhöyük to expand its resource catchment area. Whilst all this was occurring, Çatalhöyük saw changes in diet and nutrition, plant relationships, resource procurement strategies, and even in animal relationships (Hodder, 2014b, Larsen, Knüsel et al., 2019, Pearson, Buitenhuis et al., 2007). I argue that these changes in themselves represent the energy conflicts between balancing agriculture activities and non-agricultural activities, in other words, maintaining efficiency and sustaining Çatalhöyük's agricultural system. Çatalhöyük would have, and did, make adjustments and changes to avoid or control such energy (and time) conflicts. This is quantifiable evidence of the agricultural energy feedback system at work, and the archaeological data at Çatalhöyük further indicates this.

For this chapter subsection, I will specifically focus on changes in domestic crops, relate these to the energy model at hand, and relate these to other changes occurring during this time at Çatalhöyük (e.g., herd management, cooking methods, clay resourcing, and potential over-exploitation of the surrounding environment).

Focusing first on the changes crop resources over time, as established in chapter 3, section 3.3, emmer, einkorn, free-threshing wheat, naked barley were the domestic cereals upon which Çatalhöyük was most dependent during its Early period. During the Middle Period, however, Çatalhöyük peoples relied more upon free-threshing wheat, hulled barley, decreased their reliance upon einkorn, and utilised a new crop, NGW ("new" glume wheat), which replaced emmer. Utilising the quantifications from chapters 4 to 6, I will show that many of these changes can be linked to the energy input requirements of these crops.

Within section 5.1, it was demonstrated and emphasised that domestic cereals differ by yield and therefore the land requirements for Çatalhöyük's domestic crops were calculated based on low, average, and high yield values, as well as how much of the diet was reliant on domestic cereals (Table 9 and Figure 19). Because of this, since crops differ by calorific value, yield, and crop processing steps, domestic cereals were quantified as separate entities. A recognition of these differences is missing from much society-energy literature and energy models of past (and present) agricultural energy models (chapter 0, e.g., Chaisson 2014, Smil 2008, Smil 2017, Fischer-Kowalski et. al. 2014). Consequently, the energy model developed here is particularly apt for energetically comparing Çatalhöyük's domestic cereals. As mentioned in the preceding chapter subsection, the Energy Return on Invested Energy

(EROIE), of an energy process is the ratio of total energy input to total energy output (Hall, 2017, Smil, 2008). The EROIE ratio was calculated for each domestic cereal within this model of Çatalhöyük to understand each cereal's efficiency and how this might have changed as Çatalhöyük's population grew over time. Figure 53 below demonstrates the EROIE for barley, emmer, einkorn, and free-threshing wheat, depending on domestic cereal reliance and low and high yields for Çatalhöyük's occupation over time. For this dissertation, it was not possible within the timeframe allowed for the final corrections to include average yield scenarios for this dissertation. Thus, the remaining interpretations within this chapter subsection focus exclusively on low and high yields.

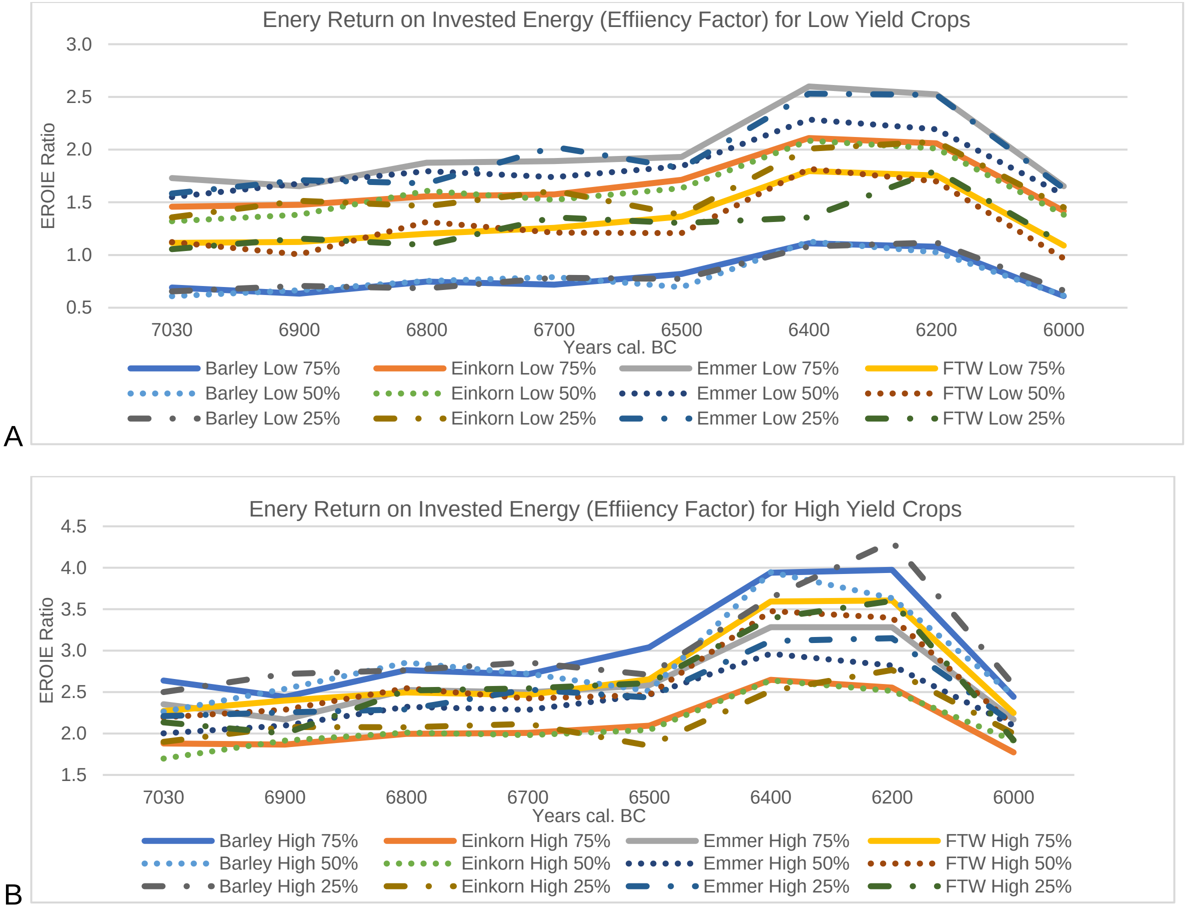
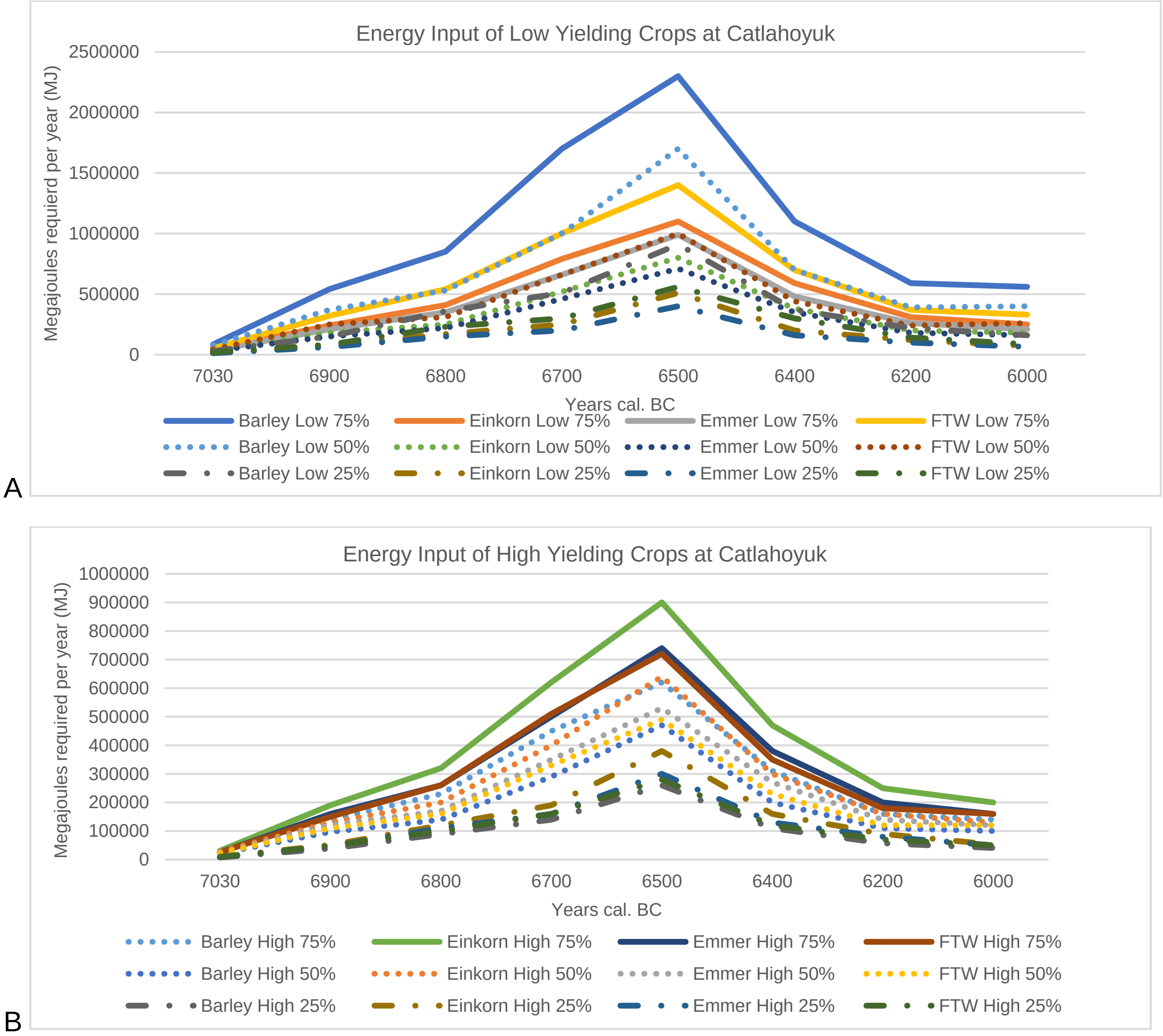


Figure 53 The Energy Return on Invested Energy. This diagram demonstrates the EROIE of domestic cereals at Çatalhöyük, according to yield. A represents the EROIE of low yielding crops and B represents the EROIE of high yielding crops. High yielding crops are always more efficient than low yielding crops. Further, cereal type is more indicative of efficiency than reliance on domestic cereals. For low yields, barley, regardless of domestic cereal reliance, is the least efficient domestic cereal, whereas emmer is the most efficient of low yielding crops. For high yields, the most efficient crop is free threshing wheat or barley, whereas the least efficient crop, irrespective of domestic cereal reliance, is einkorn.

Again, we see that high yield crops are more efficient than low yielding crops. All of Çatalhöyük's crops seem efficient, aside from low-yielding barley, which barely breaks even in terms of energy return. Further evident is that as Çatalhöyük's occupation continues, the efficiency improves. As aforementioned, for this model, after Çatalhöyük reaches its peak, the population decreases. With this decrease in population is a decline in the amount of energy required to sustain a smaller population, and no land clearance energy is required for a population decline from 3000 to 1000 people. Thus, as emphasised in 7.2.3, regardless of yield or cereal reliance, efficiency seems to plateau with a population of 2000-3000 people (6700-6500 cal. BC), but peak efficiency is reached after Çatalhöyük's peak, during its Final Period (6200 cal. BC, population of 1000 people). This is further reflected by Figure 37, Figure

41 and Figure 42, which indicate that at around 2000-3000 people, cost, efficiency, and the energy input per hectare for Çatalhöyük's no longer improve until Çatalhöyük's population decreases. This is the same pattern that we have been seeing throughout this analysis.

Moreover relying upon any of these crops makes energetic sense for Çatalhöyük peoples, as they are all efficient. Efficiency, however, seems to be more influenced by the cereal type rather than how much of the diet depends on domestic cereals. Concerning low yields, barley, regardless of domestic cereal reliance, is the least efficient domestic cereal, whereas emmer is the most efficient low-yielding crop. Focusing on high yields, the most efficient crop is free-threshing wheat with a 25% reliance on domestic cereals, or barley with a 50% reliance on domestic cereals. Irrespective of domestic cereal reliance, however, einkorn is always least efficient concerning high yields. However, efficiency in and of itself does not necessarily inform us about the differences in energy input between these crops. Therefore, Figure 54 below indicates the total energy input of Çatalhöyük's domestic cereals according to domestic cereal reliance and low and high yield.



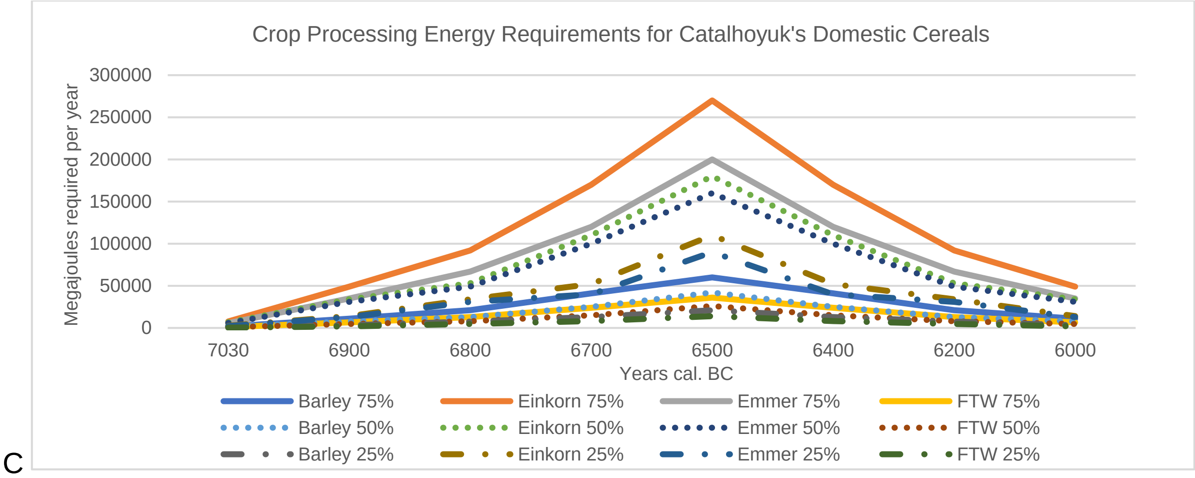


Figure 54 Total Energy Input of Çatalhöyük's Crops. Total Energy Input of Çatalhöyük's Crops. A represents the input for low yield scenarios, B shows the input for high yield scenarios, C indicates the total crop processing energy (threshing, winnowing, sieving, dehusking). Çatalhöyük's crop energy input scales with population growth over time. As more energy was required to keep Çatalhöyük sustained as it grew, more energy and time had to be dedicated to agriculture and its processes. To account for agriculture's extra time and energy requirements, decreasing their reliance upon einkorn, an energy intensive domestic cereal, would help alleviate some of this energetic pressure faced by Çatalhöyük peoples. Increasing their reliance upon free-threshing wheat, which is overall not nearly as energy-intensive as einkorn, makes energetic sense.

Referring to Figure 54, no matter the yield, more and more energy input is required for Çatalhöyük's crops up until its peak (2000-3000 people, 6700 to 6500 cal. BC), where the energy input declines with Çatalhöyük's population decrease in the Late and Final Periods. The notable increase at 6500 cal. BC, is again, due to the amount of land required to sustain a larger population reaching its peak; therefore, the energy input required for agriculture peaks; along with the potential for losses, the total amount of seed required to sustain agriculture, and the total amount of energy received directly from agriculture (see 5.2, Figure 17, Figure 25, and Figure 35). Furthermore, this is related to the energy intensity of agricultural activities (previous section, Figures Figure 50 to Figure 52) and the fact that crop energy input scales with Çatalhöyük's population growth. The previous section indicated (see Figure 44 to Figure 46) that crop processing activities combined were energy-intensive even with a minimum population of 100 people. If we consider crop processes separately, dehusking starts to come into play with a population of 3000 and a 50% reliance on domestic cereals, But, for a 25% reliance (Figure 52) and 75% reliance (Figure 50) on domestic cereals, dehusking is just shy of becoming energy-intensive on its own. Again, it is at the point of 2000 to 3000 people where Çatalhöyük's has energy conflicts between dedicating energy to agricultural activities and energetic conflicts outside of the agricultural energy system. This energy analysis not only allows us to investigate crop differences, but the data presented in Figure 54 substantiates the agricultural energy feedback system and provides quantifiable evidence for why Çatalhöyük would change its reliance on crops during its Middle East Period.

Focusing on Figure 54 and differences between yield scenarios, what is most prevalent in either low or high yields is that a higher reliance requires more energy input. For low yield scenarios, a higher reliance on barley and free-threshing wheat are the most energy intensive crops. In contrast, with a 25% reliance on any domestic cereal is the least energy-intensive situation. For high yield scenarios, a high reliance on einkorn, emmer, and free-threshing wheat are the most energy-intensive crops, whereas a low reliance on any of these crops is the least energy-intensive. Regardless of how much of the diet is reliant on domestic cereals, however, we see that einkorn is consistently the most energy-intensive crop, followed by either emmer or barley. Einkorn would have been quite an energy-intensive crop, especially reflected in the total crop processing energy (Figure 54 C). Einkorn requires far more energy input regarding crop processing than the other Çatalhöyük domestic cereals, even though it is an efficient crop overall (Figure 53). Free-threshing wheat and barley are similar to one another; they are the least intensive crops to process. Depending upon the yield, they are also energetically efficient crops for Çatalhöyük's agricultural system. Overall, the data presented in Figure 54 provides quantifiable evidence for why, during its peak, Çatalhöyük decreased its reliance upon einkorn, the NGW which replaced emmer, and a hulled barley.

The increasing reliance upon free-threshing wheat and decrease in einkorn are linked directly to energy input. As described in sections 3.3 and 6.2, hulled wheats, especially einkorn, require significantly more energy to process compared to free-threshing wheats and barleys. Figure 54 quantitatively and energetically demonstrates that overall, einkorn is more energy-intensive for Çatalhöyük's agricultural system, especially with regards to crop processing. As described in 3.3, this corresponds with the preference towards less labour-intensive processing and a need for more efficiency as suggested by the Çatalhöyük Research Project and provides another strand of evidence which corroborates that the agricultural energy feedback system was occurring at Çatalhöyük. Einkorn was too energy-intensive and is one of the least efficient crops; thus, the move away from it was one of the ways Çatalhöyük could have aided in lessening the energy conflicts and burdens the Çatalhöyük peoples faced during its peak.

The appearance of the NGW, a hulled wheat, and two-row hulled barley during the Middle Period, as described in 3.3, is a curious case and has been deemed as a response to the 8.2kya drying event during the end of Çatalhöyük's occupation (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017) (also see Figure 10). The Çatalhöyük team interpreted the presence and use of both the NGW and two-rowed hulled barley as related to this event because the NGW is a hardy crop, and this and the hulled barley were potentially drought resistant; the NGW is also particularly suited to Çatalhöyük's culinary tradition (Bogaard, Filipović et al., 2017: 22). These domestic cereals came into play during Çatalhöyük's Middle Period and became the preferred cereals by Çatalhöyük 's Late Period (Bogaard, Charles et al., 2013, Bogaard, Filipović et al., 2017, Russell and Bogaard, 2014: 64-65). Although we do not have calorific or yield data on this NGW we can utilise the energy model within this thesis to make some assumptions to better understand this NGW at Çatalhöyük (Czajkowska, Bogaard et al., 2020, Jones, Valamoti et al., 2000). This NGW is now considered to be a significant crop within prehistoric Eurasian agriculture and has significant implications for understanding the spread of agriculture within southwest Asia to Europe (Czajkowska, Bogaard et al., 2020). Modern DNA research on this NGW indicates that this NGW within southwest Asia were cultivated as "metapopulations," essentially fitting in with a colonisation aspect of the spread of agriculture (Czajkowska, Bogaard et al., 2020: 7-8). Thus, understanding the energetic aspects of this NGW at Çatalhöyük aids to our broader understanding of the spread of agriculture in the Neolithic.

If we assume, drawing from data within chapters 5 and 6, this NGW is calorically, yield, and crop processing-wise, similar to emmer, and, if we assume the barley is processed similarly to other hulled cereals modelled here (specifically dehusking), these crops would be roughly as energy-intensive as emmer. According to the models produced within this thesis, if the NGW is indeed like emmer, the NGW is still less energetically intensive overall compared to einkorn; therefore, relying more upon the NGW and instead decreasing reliance upon einkorn makes energetic sense and still fits within the agricultural feedback system model at hand. The hulled barley would also be less energy-intensive than einkorn and be energetically similar to emmer. Moreover, Figure 53 indicates that with both low and high yields, if the NGW and the hulled barleys are indeed similar to emmer, these crops would be very efficient during Çatalhöyük's Late period, regardless of low or high yields.

Further, as established in 6.2, hulled species, although they do take more effort to process, have a significant advantage to naked species: hulled species are better protected during storage and allow for "spreading the labour" of crop processing steps, since dehusking does not have to occur at the same time as threshing (Halstead, 2014: 178). Therefore, although these hulled species may be more energy-intensive than free-threshing wheat, they do have storage and labour advantages.

Referring back to Figure 44, Figure 45, and Figure 46, Çatalhöyük's agricultural system at low and high yields with a population of 100 people, even at this *minimum* population estimate, indicates that seed storage was significant (75% reliance: 34,000 megajoules, 50% reliance: 31,000 megajoules, and 25% reliance: 12,000 megajoules) and the potential for losses is also significant (75% reliance: 90,000 megajoules, 50% reliance: 84,000 megajoules, and 25% reliance: 32,000 megajoules). The importance of storage and losses only increase over time, as Çatalhöyük's population reaches its population threshold of 2000-3000 people. Thus, by omitting einkorn, a very energy-intensive hulled cereal, and increasing their reliance on cereals like NGW and hulled barley that are more drought-resistant, more resistant to storage failures, help to spread labour costs, and are less energy-intensive than einkorn, makes those crops more compatible with managing potential risk whilst easing and balancing the energetic pressures of faced by Çatalhöyük during its peak. Regarding the spread of agriculture from south-west Asia to the Aegean, archaeological evidence indicates a preference of glume wheats and hulled barleys over wild hulled barley and einkorn; these were available throughout these areas; however, peoples did not subsist upon them (Shennan, 2018: 68-70). Wright's (1994) work argued that pounding and grinding (dehusking) are labour-intensive processing methods that would have been required to make wild cereals edible, and their labour requirements have been vastly underestimated. Again, the energy analysis within this thesis indicates and quantifies why glume wheats and hulled barleys might have been preferred and the agricultural energy feedback system provides a mechanism for why they might have spread, being related to efficiency and energy intensity. Such an understanding of crops at Çatalhöyük, and for the spread of agriculture in the Neolithic more generally, could not have taken place without investigating these crops and Çatalhöyük's agricultural system, energetically.

Another aspect of agriculture at Çatalhöyük which requires discussion is storage. Even with a population of 100 people (the minimum population for this model), and 2000 people (Çatalhöyük's minimum peak estimates), seed storage energy was vital for Çatalhöyük's agricultural system. This implies that keeping, storing, and setting seed aside was energetically important within Çatalhöyük's agricultural system. If seed storage fails, the entire agricultural system and subsequent flows of which it is a part breaks down. Storing seed for the next year's crop is *crucial;* although seedcorn energy does not directly sustain Çatalhöyük, it is recycled back into sustaining agriculture the next year. As emphasised throughout this thesis, agricultural processes are interdependent and entangled within one another. Storage itself highlights the interdependencies of agriculture's processes. Agriculture cannot take place without seedcorn; if no seedcorn is available, planting the next year cannot take place. Further, having enough seed for the next year's crop cannot occur without having a successful harvest. A harvest is not successful if harvested too late or if the harvest is unsuccessful, if tillage is inadequate, or if storage is insufficient. In order to subsist from agriculture, one must have seedcorn, and agriculture's processes have to be successful. Even with minimum peak estimates, Çatalhöyük's agricultural processes depended on one another, and seedcorn would have been pivotal; seedcorn was important even within this Neolithic system. Moreover, discussions of the interdependencies of agriculture's processes are something that the archaeological community is neglecting. The model developed here has helped bring this issue to light.

One of the primary aspects of the agricultural energy feedback system is that agriculture affects environmental changes, *and vice versa.* Agriculture is sensitive to changes, especially environmental ones. All of agriculture's processes depend upon one another's success, all its processes must be successful in order to produce an energy surplus, and if external factors, including a drying event or the potential over-exploitation of Çatalhöyük's immediate environment disrupts agriculture or its processes, the system itself has great potential to fail, or, it becomes more difficult to sustain. Regarding the over-exploitation of Çatalhöyük's immediate environment, this was explained and discussed in section 3.3, but it is worth assessing this with regard to the energy model at hand.

During the Middle Period, Çatalhöyük depleted its backswamp clays due to its growing population and houses needing more structural support as a result of this (Doherty, 2013). With the clay extraction for Çatalhöyük also came the invasive plant species, *Phragmites australis* (common reed), which is well documented at Çatalhöyük, especially during Çatalhöyük's Middle and Late period; it actually is dominant over other sedges and grasses in the archaeobotanical assemblage (Roberts, Boyer et al., 2007, Ryan, 2013, Sadvari, Charles et al., 2017: 171). However, Çatalhöyük peoples did utilise reed in basketry, fuel, and construction, the clay extraction pits and the pockets of wetter areas which Çatalhöyük's excessive clay extraction pits would have caused and allowed this invasive species to thrive (Roberts, Boyer et al., 2007, Ryan, 2013: 188-189). *Phragmites* had major implications for Çatalhöyük's people, including altering wild plant taxa upon which they relied, thus, forcing Çatalhöyük's inhabitants to forage farther from the site for wild plant resources (Sadvari, Charles et al., 2017 :171-172). Occurring at the same time was Çatalhöyük's decreasing reliance upon and use of acorn (Asouti, 2005b, Asouti, 2013, Bogaard, Filipović et al., 2017, Filipović, 2014). As Çatalhöyük's houses increased in number and become sturdier, during the Middle Period, Çatalhöyük's wood source was primarily juniper, a sturdier and more durable wood; the presence of juniper is also possibly indicative of a "low-intensity" human impact on the landscape due to herding and logging throughout the area, which is indirectly supported by Çatalhöyük's increasing reuse of timbers over time (Asouti and Austin, 2005: 14-15). Essentially, as Çatalhöyük's population grew and its herds grew, they likely overexploited oak, their herds overgrazed lands, and thus Çatalhöyük aided in low-intensity deforestation, resulting in their reliance upon juniper (Asouti and Austin, 2005: 14-15). Whilst this was occurring, zooarchaeological and bioarchaeological evidence indicates that people and animals were becoming more mobile and, Çatalhöyük's resources catchment zone was expanded (Fairbairn, Asouti et al., 2002, Henton, 2013, Henton, 2010, Hillson, Larsen et al., 2013, Larsen, Hillson et al., 2015). This increase in mobility at Çatalhöyük is surmised to be directly related to Çatalhöyük reaching its peak population numbers during the Middle period; as Çatalhöyük's population increased and its occupation continued, the resource catchment area also had to expand (Hillson, Larsen et al., 2013, Larsen, Hillson et al., 2015: 33). As Çatalhöyük's population grew, so did energy pressures and energy requirements.

Although crop yield was based on low, average, and high ethnographic and historical yields and by crop type (see section 5.2), presently, the yield of the Neolithic crops at Çatalhöyük is unknown. However, it may be safe to assume average to higher yield scenarios are representative of Çatalhöyük's agricultural system. One of the ways it is possible to retrieve past crop yields within archaeological contexts is via carbon isotope discrimination (Δ), as there is a positive correlation between Δ and productivity across cereals cultivated specifically in the Mediterranean (Araus, Slafer et al., 2003: 685). Araus et al. utilised Δ from fossil grains to predict yields of ancient cultivars and used this same approach to "predict" modern yields. Their analysis indicated that the formula and model was accurate, and, that Neolithic agricultural practices, at least in the Mediterranean, may have produced greater yields than originally expected (Araus, Slafer et al., 2003: 689-691). In fact, the predicted Neolithic yields were similar to modern yields with losses from pests and diseases (which the energy model here, includes) (Araus, Slafer et al., 2003: 689-691). Thus, it is probable that Neolithic yields at Çatalhöyük during its Early Period could be more reminiscent of the higher yield scenarios in the energy model of this thesis. Overall, the energy model at hand, regardless of yield scenario, indicates that an energy surplus would have occurred. In providing an energy surplus, this inherently aids in population growth, which we know occurred during Çatalhöyük's Middle Period. Either way, however, utilising Δ of domestic cereals at Çatalhöyük could be a promising avenue by which to refine this energy model.

Archaeobotanical evidence in the form of weed seeds in dung indicates that Çatalhöyük inhabitants expanded their herds across the landscape over time to allow flocks to graze, or Çatalhöyük's inhabitants themselves collected fodder across the landscape for their herds (Fairbairn, Asouti et al., 2002, Henton, 2013, Henton, 2010: 166, 197). Further, during the Middle Period, there is evidence of greater intervention in herd management in the form of early birthing for lambs, evidence of penning on site, and increased herding labour (Bogaard, Henton et al., 2014, Henton, 2013, Russell and Martin, 2005, Russell, Twiss et al., 2013). It is estimated that Çatalhöyük's flocks reached the thousands; this would have posed a significant energy input and a real and significant threat to cereals as an energy source (Cribb, 1987, Russell and Bogaard, 2014: 66). Having herds in the thousands, which is estimated for Çatalhöyük during its Middle period, posed a threat to cereals as an energy source (see chapter 3, section 3). Either way, as more cereal energy was required for Çatalhöyük and its domestic herds grew to the thousands, an increasing reliance upon domestic cereals, which Çatalhöyük experienced, required more protection of crops from growing herds in the form of either collecting natural fodder from across the landscape, or, herding domestic caprines more widely across the landscape. Finally, Çatalhöyük's reliance upon less energy intensive crops (free-threshing wheat, the NGW and hulled barley, as posited above) and wild plants (bitter vetch) in addition to using clay pots for cooking during its peak, also indicates the need for freeing up time, labour and energy and, thus, allowing for more multitasking (Atalay and Hastorf, 2006 :309). In other words, this is direct evidence of Çatalhöyük attempting to account for and deal with energy input requirements occurring during its Middle Period and other energetic conflicts with herding, ritual, and trade, for example. All of this evidence, along with the data analysis above, indicates that the agricultural energy feedback system was occurring at Çatalhöyük. Such an understanding of Çatalhöyük, could not have taken place without investigating and modelling Çatalhöyük' agricultural energy system.

The diagram below (Figure 55) shows how the agricultural energy feedback system at Çatalhöyük might have occurred. Agriculture provided a surplus of energy to Çatalhöyük and facilitated population growth while simultaneously, Çatalhöyük required more energy to keep itself sustained. As this occurred, Çatalhöyük became increasingly more invested in agriculture, due to increased efficiency and decreased costs with population growth, the dependencies of agriculture's processes on one another and requiring human energetic input, whilst requiring more resources to keep Çatalhöyük, as an entity, sustained. As more and more resources were required, Çatalhöyük was also altering and impacting its own environment which it *also* had to adjust to, thus forcing Çatalhöyük to expand its resource catchment area. Çatalhöyük saw changes in diet and nutrition, plant relationships, resource procurement, and even in animal relationships (Hodder, 2014b, Larsen, Knüsel et al., 2019, Pearson, Buitenhuis et al., 2007). The agricultural energy feedback system was indeed at work within Çatalhöyük, and the modelling of its agricultural energy system demonstrates its occurrences and quantifies it energetically. This thesis has demonstrated the energy requirement of agriculture for a Neolithic society, and quantifies and proves the existence of a positive energy feedback between agriculture, surplus energy, and population growth discussed by many throughout chapter 2 (White 1943; Chaisson 2003, 2005, 2011, 2013, 2014a, 2014b, 2015; Smil 2000, 2008, 2013, 2017; Odum and Pinkerton 1955, Odum and Odum 1977, Odum 1977, 2007; Fischer-Kowalski and Haberl 2007, 1997, Fischer-Kowalski et al. 2014, Fischer-Kowalski and Weisz 1999, Lenton and Watson 2011, Lenton et al. 2021; Rappaport 1971; Barrett 2011). Thus, this thesis provides a quantifiable reason and a mechanism as to why the Neolithic Revolution came with population growth, surplus production, new land requirements, changes in nutrition, workload, mobility, social interaction, and, new ensembles of activities, behaviours, and technologies (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995).

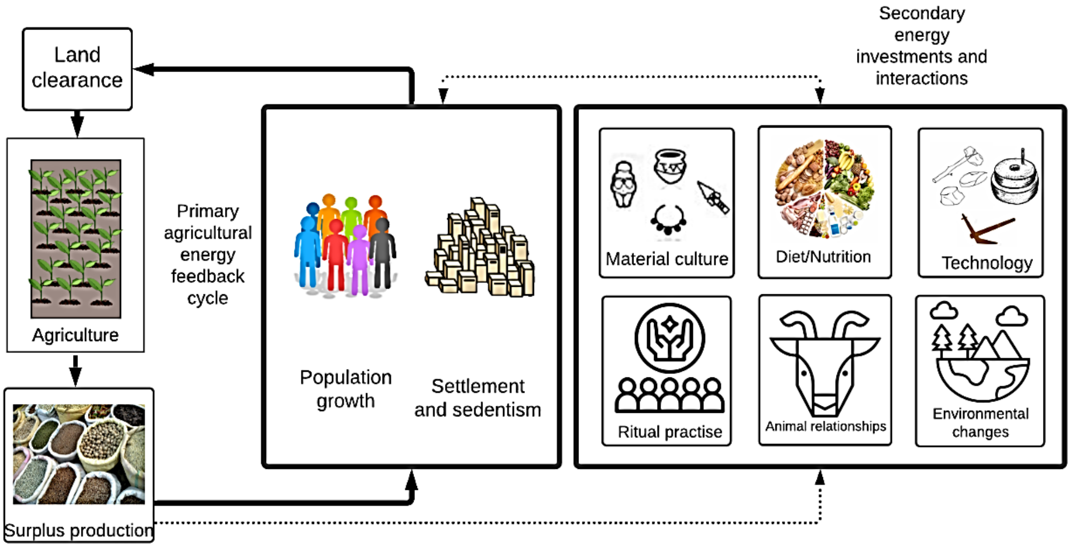


Figure 55: The Agricultural Energy Feedback System at Çatalhöyük, indicating the feedback between agriculture, surplus energy, and population growth. The initial increasing efficiency and decreasing costs with agriculture and population growth is the mechanism that drives surplus production and new land requirements. With a growing population, however, comes the need for more energetic resources to sustain both the growing population and agriculture. The efficiency and cost of agriculture change as a population gets larger and reaches its threshold, depending on how much of the diet relies upon domestic cereals, and yield. Population growth and requirements, then, are not limitless. Changes in population density, increasing the efficiency of processes, and, changes in activities, behaviours, technologies, workloads, and mobility seem to result from maintaining agriculture and sustaining or improving its efficiency whilst balancing energy conflicts.

7.5 AGRICULTURE AND ENERGY: NEXT STEPS

The model established in this thesis (Chapters 4-7.4) indicates that the agricultural energy feedback system was occurring at Çatalhöyük and has successfully demonstrated quantifying our past relationships with agricultural energy using archaeological data and methods, analyses, and perspectives, is not only possible but necessary. The lack of quantifications of past energy systems prior to this thesis, meant that the unintended or unanticipated consequences of past human actions concerning the environment were not recognised (van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). Such consequences likely directly relate to the Global Climate Change issues we have today, but we are not incorporating these timescales or understandings into models or analyses (van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). Further, omitting quantifications of past energy systems means failing to incorporate the deep history of humanity's relationship to energy (Malm and Hornborg, 2014, Steffen, Broadgate et al., 2015). As a result, we must have a richer, more contextualised understanding of how our unsustainability and the global climate change problem developed. Although this thesis does not provide all the answers to such a "wicked problem", it does provide a way forward for archaeology to contribute more broadly to energy sustainability issues and understandings (Steffen, Sanderson et al., 2004, van der Leeuw, Costanza et al., 2011).

Further, archaeology has always sought to understand the relationship between agriculture, population growth, and sedentism, limits to population growth, and understanding the mechanisms behind the Neolithic and the spread of agriculture (chapter 0). The Neolithic and the spread of agriculture itself is directly related to humanity's relationship with energy. Agriculture is inherently dependent upon energy use; it was during the Neolithic, as well. Quantifying our past relationships with agricultural energy, using archaeological data, methods, analyses and perspectives, as this thesis has done, has presented and quantified this, whilst bringing to light energetic dependencies of agriculture and its processes. Moreover, in utilising an energetic approach to understanding agriculture at Çatalhöyük, this thesis provides a mechanism as to why the Neolithic and agriculture came with population growth, surplus production, new land requirements, changes in nutrition, workload, mobility, social interaction, and, new ensembles of activities, behaviours, and technologies (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995). Further, this thesis quantifies and successfully demonstrates why agriculture is associated with land colonisation others have suggested (Barrett, 2011, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski and Weisz, 1999, Rindos, 1980, Shennan, 2018). Agriculture has within it a positive energy feedback between surplus energy, population growth, and its processes, and traps societies into relying upon it. This could not have occurred without investigating and modelling a Neolithic agricultural energy system, utilising archaeological data, methods, and conclusions.

However, no model is perfect, and there are areas that could be developed further and some outstanding questions.

First, as outlined in 5.2, for the sake of modelling and data visualisation, this energy model represented Çatalhöyük's population growth and decline being linear with time, and thus most of the agricultural processes at hand are represented this way. However, it would be quite interesting to see what occurs when the population is *not* linear, let us say, during multiple periods of stable population growth. When this happens, there would be a yearly energy surplus, which could be utilised to invest in other activities such as ritual, materials, herding, or technology; how does this affect agriculture and its efficiency or how much more energetic tension could this cause between devoting energy to agriculture, and balancing other additional activities?

As described in 5.2, this thesis explicitly focused on agriculture and the domestic cereal reliance aspect of the diet. To quantify and model Çatalhöyük's agricultural energy system, this dissertation recalculated Çatalhöyük data through the lens of a modern human energy requirements framework, the 2004 Human Energy Requirements Expert Consultation (henceforth referred to as the HERE consultation). However, the HERE consultation is not solely focused on agricultural activities. Collecting wood, making mudbricks, gathering plants by hand via squatting, hunting birds, fishing, and tending, feeding, milking, and grooming animals (by hand) are just some of the activities which are included in the HERE consultation (James, 1990, UNU, 2004). Thus, utilising the methodology established within this thesis could and should be applied to modelling other human-animal and human-plant relationships, tool production, clay exploitation, and feasting, for example would be another avenue by which to expand this energy model. What are the effects of Çatalhöyük's agriculture on other energy flows at Çatalhöyük? How does this fit in and *energetically* affect relationships with clay, obsidian, human-animal relationships, or technology? How entangled do these energy flows become, and how reliant upon one another do they become? We know such changes occurred, and I have linked them to the agricultural energy, efficiency, cost, and land requirements in this thesis, however, understanding these other energy flows in themselves can help us to draw a more holistic picture of Çatalhöyük's *overall* energy system, and potentially point us towards understandings of Neolithic energy systems more generally. Further, seasonality was not addressed within this energy model, but it is certainly an issue that warrants discussion. All the agricultural activities modelled here did not take place at the same time, but instead, occurred throughout the year; herding, hunting, gathering, food processing, and feasting also would have occurred at different times throughout the year. Modelling the entirety of Çatalhöyük's energy system and understanding the energetic ebbs and flows throughout the year is absolutely an avenue for future research. Although this thesis was primarily focused upon agricultural energy and creating an agricultural energy baseline for a Neolithic society, it opens an entire avenue for research on energetically modelling and understanding how energy plays a role throughout Neolithic societies, more generally.

Alternatively, modelling the Çatalhöyük data with a fluctuating population baseline would also be beneficial and improve our understandings of these relationships, and changes occurring at Çatalhöyük. For example, as discussed and outlined in 5.2, Çatalhöyük's diet was based upon age at Çatalhöyük, and there were multiple age-based dietary transitions for individuals at Çatalhöyük (Pearson and Meskell, 2015, Pearson, Haddow et al., 2015). Younger adults had access to plants or animals from different parts of the surrounding landscape, and/or they consumed a greater quantity of meat from wild equids and boar; older individuals seemed to have consumed a greater quantity of meat from sheep and cattle (Pearson, Haddow et al., 2015: 224). Utilising the methodology in this thesis, it would be possible to measure the energetic differences in diet between subsets of Çatalhöyük's population. Further, it should be noted that the number of people participating in agricultural labour would have varied year to year. As described in Chapter 5, it is unfeasible that the entire Çatalhöyük population would have been partaking in all agricultural activities. This is something we also see ethnographically (Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000, Halstead, 2014). This analysis primarily focused on investigating Çatalhöyük's energy, as an entity, but did present data of how much energy would have been required of the average person participating in agriculture at Çatalhöyük (Figure 34 and Figure 43). Other quantifications in this thesis, available in the appendix, including how much energy would have been required for the average person if 25%, 50%, and 100% of Çatalhöyük's population were participating in agriculture were completed but were not analysed. It would be interesting to further investigate what happens to Çatalhöyük's agricultural system when, in some years, less of the population was available to complete the agricultural labour. Moreover, although this thesis did not seek to understand the origins of the Neolithic itself, this aspect provides another avenue towards investigating why individuals may (or may not) adopt agriculture as a subsistence lifeway.

The energy model presented made the following assumptions: all agricultural processes are successful regardless of yield, storage is always successful, losses are average, a 25%, 50%, and 75% reliance upon four domestic cereals, and Çatalhöyük peoples having equal access to land (chapter 5). Ethnographically, we know that all agricultural processes are not always successful, yield varies by season, and losses also vary by season (Evans, 1993, Gregg, 1988, Halstead, 2014). What happens to Çatalhöyük's agricultural energy system when, for example, harvesting, planting, or tillage, fail. What happens when storage, harvesting, and processing losses are more than what this model assumes? How much extra energy surplus would there be if these losses are far less? How do changes in these agricultural energy flows affect the rest of the energy system and subsequent flows of which they are a part? Regarding equal access to land, what happens energetically when there is unequal access to land and resources needed to perform these activities? This model could and should be expanded to include such issues.

Additionally, we know that by Çatalhöyük's Middle Period, there is evidence of greater intervention in herd management in the form of early birthing for lambs and increased herding labour (Bogaard, Henton et al., 2014, Henton, 2013, Russell and Martin, 2005, Russell, Twiss et al., 2013). Çatalhöyük's environment allowed for its population to accommodate long-lived plots *and* viable seasonal grazing areas for its herds (Charles, Doherty et al., 2014: 86). Furthermore, a common theme throughout Neolithic sites is that agriculture and animal husbandry reinforce one another (Bogaard, 2004, Larsen, Hillson et al., 2015, Larsen, Knüsel et al., 2019). Meat, as we know from Çatalhöyük's isotopic research, was a major and important component of Çatalhöyük diet (Bogaard, Ater et al., 2019, Bogaard, Filipović et al., 2017, Filipović, 2014, Hillson, Larsen et al., 2013: 354, Pearson and Meskell, 2015: 468-472, Pearson, Haddow et al., 2015: 223-224). Animals then were a crucial part of Çatalhöyük, especially caprines. Thus, modelling domestic cereal reliance within this thesis alongside animal herding and meat consumption in relation to one another is an obvious next step to expanding this model. Further, this model focused on four domestic cereals and assumed a 25%-75% dietary reliance upon them. Further, lentils were another domestic legume which was not modelled for this thesis; what happens when we decrease this dietary cereal percentage and/or tie in lentils? It would be interesting to see how lentil subsistence ties in with Çatalhöyük's agricultural energy and how this plays into Çatalhöyük's overall energy system.

Finally, although the lack of manuring was addressed in 5.4.2, it is worth considering the lack of it, weeding, and further cereal processing in this model. The quantifications in this analysis do not account for manuring, weeding, or further cereal processing. The lack of weeding is mostly tied to the manuring, as weeding would have been more important if manuring occurred. Evidence of manuring at Çatalhöyük is questionable, but it would be very interesting to see how manuring, and subsequently weeding, would have affected not only Çatalhöyük's agricultural energy system but also how this might have enhanced and further entangled animals within Çatalhöyük's *overall* energy system. Spreading manure and weeding are also activities the HERE consultation includes in its human energy requirements analyses; thus, thus, again, utilising the methodology established within this thesis could and should be applied to modelling both of these potential scenarios (James, 1990, UNU, 2004).

With regards to further cereal processing, i.e., further grinding of cereals to flour, gruels, etcetera, these were not fully investigated within this thesis. This was because foodways in themselves are dependent upon individual and family preferences, the local environment, taboos, traditions, nutritional needs, and can even differ by age group or gender (Atalay and Hastorf, 2006, Ertuĝ-Yaras 1997, Halstead, 2014, Hastorf, 2017). Further, as mentioned in 5.2, Çatalhöyük's isotopic analyses indicate that children, adolescents, younger adults, and older adults consumed different foods (Pearson and Meskell, 2015). Infants were breastfed, and by three years old, they were fully weaned; children aged 5 to 10 had a different diet compared to other adolescents and adults, and, once a person reached young adulthood, the diet changed again; this transition was maintained until old age (Pearson, Haddow et al., 2015: 224). Although differences between gender were limited, age differences between diets were significant at Çatalhöyük (Pearson and Meskell, 2015). Thus, it would be interesting to model the dietary differences in age groups and, the energy differences between further cereal processing and even cooking, as it is well known ethnographically that grinding wheat, einkorn, barley, and emmer all vary with respect to how they are consumed (Ertuĝ-Yaras 1997, Ertuğ-Yaras, 2000, Hillman, 1983, Hillman, 1984, Wright, 1994). For example, within chapter 2 (2.3.4), Kemp (1971) focused on understanding the patterns of energy flow within an Inuit group on Baffin Island (currently Nunavik) and its relationship to social and economic activities (2.3.4) (Kemp, 1971). His work identified previously unidentified entanglements, including social controls tied to foodways (Kemp, 1971). Taking such an energetic approach to households within Çatalhöyük, utilising the methodology outlined in this thesis, provides yet another avenue for future research to investigate energy and foodways within household contexts.

Overall, the energy model presented can absolutely be enhanced in multiple ways and provides many avenues for future research. More importantly, the model presented throughout this chapter has allowed us to make several conclusions regarding Çatalhöyük which help us to understand the broader Asian Neolithic .

In amalgamating the data within chapters 4 to 6, this chapter identified fundamental energetic differences between agricultural processes. Tillage, harvesting, land clearance, and crop processing were designated as energy-intensive. Regarding yield, low yield crops require more energy input, are more costly, and less efficient than high yielding crops and, higher yields also allow for more of an additional energy surplus, regardless of population growth rate. Further, a higher reliance on domestic cereals requires more energy to sustain agriculture as compared to lower reliance on cereals. Moreover, a higher reliance on domestic cereals allows for more energy to be received from agriculture than a lower reliance on domestic cereals. This chapter also demonstrated and quantified energetic reasons as to why Çatalhöyük changed their cereal crop reliance towards more durable, efficient, less energy-intensive crops. The presence and use of the NGW, two-row hulled barley, and free-threshing wheat can all be linked to energy and balancing energy flows. Relating this to the broader Neolithic, these crops have significant implications for understanding the spread of agriculture from southwest Asia to Europe. This thesis provides quantifiable evidence for why these crops would have been utilised *and* could have potentially spread. Connected to this, this thesis quantified and proved the existence of the agricultural energy feedback system at Çatalhöyük. The data presented identified, quantified, and successfully demonstrated that agriculture has energy feedbacks and dependencies which aid in population growth and enforce a reliance upon agriculture. Further, with regards to population growth, this chapter demonstrated and quantified that agriculture's efficiency initially increases and its cost decreases. This improved cost and efficiency is the mechanism of agriculture which effectively aids in population growth and enforces a reliance upon agriculture. The improved cost and efficiency are most beneficial if agriculture has enough people participating, enough land, and sufficiently high yields. Cost and efficiency begin to plateau when additional land clearance is needed during a time of high population rate; there is indeed a limit to Çatalhöyük's agricultural system, which was 2000 to 3000 people. Once this threshold was reached, efficiency and cost no longer improve, the amount of surplus energy available begins to decrease, and the agricultural system had to be made to be more efficient to keep relying on agriculture. In other words, Çatalhöyük had to adjust to energy tensions and make its system more efficient. The changes witnessed during Çatalhöyük's Middle period are Çatalhöyük adjusting to these energy tensions.

By considering the inputs and outputs of Çatalhöyük' agricultural system, this chapter demonstrated agriculture's processes being dependent on one another's success *and* energy input from Çatalhöyük's population. Agriculture as a system comes with the caveat that agricultural processes, together, are dependent upon one another's success to produce an energetic surplus. If any agricultural process fails, the system and the subsequent energy flows of which it is a part, can break down. This aspect of agriculture is crucial, as it aids in facilitating an increasing reliance upon agriculture. This effectively "traps" societies into relying upon it. However, once the agricultural system reaches its threshold, the system must be made to be more efficient to keep relying upon agriculture. Agriculture at Çatalhöyük could become more efficient and less costly, especially at times of needing more land during rapid population growth or population decline, by utilising a smaller reliance on high yielding cereals, or a larger reliance on average yielding cereals. A lower reliance on high yielding cereals requires the least amount of extra land to sustain agriculture whereas a larger reliance on average yielding cereals produces more agricultural energy; both of which improve cost and efficiency. For Çatalhöyük, efficiency improvements were attempted via the changes in the Middle Period. Moreover, after its peak, Çatalhöyük seems to have made its system more efficient via population decline, which resulted in more efficiency, fewer costs, and less agricultural energy input required. Combined, these findings for Çatalhöyük's agricultural energy system are crucial, as they quantify and demonstrate that agriculture requires land colonisation which others have suggested, indicate limits to growth, and, explain why the Neolithic came with population growth, surplus production, new land requirements, changes in nutrition, workload, mobility, social interaction, and, new ensembles of activities, behaviours, and technologies: the struggle to balance energy input, energy use, and energy output (Despina and Relaki, 2020, Düring, 2013, Flannery, 1973, Fuller, Allaby et al., 2010, Kennett and Winterhalder, 2006, Larsen, Hillson et al., 2015 :28, Larsen, 2015, Larson, Piperno et al., 2014, Riehl, Zeidi et al., 2013, Smith, 1995). Energy and balancing energy input, output, and use have always been enduring problems for humanity. This thesis has provided a way for archaeological data, methods, and analyses to model and thus, better understand how processes of energy extraction flow and function and potentially lock us into specific trajectories.

8 CHAPTER 8: DISCUSSION AND CONCLUSIONS

Chapter 1 introduced the agricultural energy feedback system (Figure 1). This agricultural energy feedback system argues that agriculture comes with energy feedbacks that aid in population growth and essentially foster and enforce a reliance upon agriculture. Agriculture itself provides a surplus of energy, thereby aiding in population growth. This growing population, however, requires more energy to keep it sustained. The society at hand, in this case, Neolithic Çatalhöyük, must dedicate more energy to agricultural processes to support itself and its energetic surplus, whilst a plethora of unintended consequences occurs, including permanent changes to the environment alongside changes in diet and nutrition, material culture, technology, animal relationships, and even ritual practise. An agricultural-based society like Çatalhöyük becomes increasingly reliant upon agriculture due to an energy surplus which can only be provided and sustained by investing energy into its processes. At the same time, the population growth which occurs alongside agriculture improves the energy cost and efficiency of agriculture; this cost and efficiency improvement are a crucial mechanism within the agricultural energy feedback system.

Chapter 2 of this thesis presented why a methodology to quantify energy use in the past was required. More specifically, White (1943) argued that agriculture provided excess energy to people, forced mobile populations to become sedentary, and initiated a feedback that allowed for industrial society as we know it. Odum demonstrated that agriculture was not necessarily sustainable as an energy system, as it traps societies into depending on a limited set of energy resources (Odum, 2007, Odum and Odum, 1977). Further, population ebbs and flows, he argued, were the direct result of populations attempting to balance energy flows (Odum, 2007, Odum and Odum, 1977). Fischer-Kowalski and colleagues (Fischer-Kowalski and Haberl 2007, 1997, Fischer-Kowalski et al. 2014), similar to Rindos (1980), argue that agriculture depletes natural resources, requires a hard, laborious life, and agriculture is limited by land and agricultural productivity (Fischer-Kowalski and Haberl, 1997: 68). Like Shennan (2007, 2018), Fischer-Kowalski recognises the colonising aspect of agriculture and argue that this plays a significant role in the spread of agriculture, and fully recognise the existence of the agricultural energy feedback system; they were the first to bring these concepts together (Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski, Krausnmann et al., 2014, Fischer-Kowalski and Weisz, 1999). Lenton and colleagues explain that agriculture provides energy yet requires significant labour and high productivity levels and suggests a sort of positive feedback between energy, agriculture, and agricultural labour (Lenton and Watson, 2011, Lenton, Kohler et al., 2021). Redman and colleagues' utilisation of adaptive cycles as positive feedback systems argued that accumulating a surplus and maintaining efficiency aids in enabling the emergence of complex society (Redman and Kinzig, 2003). Barrett (2011) posited that farming ecologies reproduce themselves via increased energy investment in labour organisations either through more energy from domestic resources, greater levels of energy efficiency in labour organisation, and changes in energy storage, or a combination of these energy relationships (Barrett, 2011: 76). Drawing from these authors and expanding upon them, this thesis posited the agricultural energy feedback system and energetically modelled it. Energy models are in need of archaeological data, narratives and analyses, and an understanding of the agricultural energy feedback system is required.

Chapter 3 of this thesis presented Çatalhöyük as a case study and argued that the agricultural energy feedback system was occurring at Çatalhöyük. I argued that Çatalhöyük's need for less labour, greater efficiency in daily processes, and an expansion of resource catchment zones resulted from the inner workings of the agricultural energy feedback system. Further, Çatalhöyük makes an excellent case study not just because of the data available from the site, but because Çatalhöyük is known to be one of the sources of the western expansion of agriculture. Thus, understanding the agricultural energy relationships at Çatalhöyük allows for a better understanding of the spread of agriculture during the Neolithic (Barrett, 2011, Barrett, 2016, Barrett, 2019, Shennan, 2018).

Chapters 4-6 established a methodology and quantifications addressing agricultural energy at Çatalhöyük by utilising archaeological data and methods. Chapter 4 established an energy methodology to quantify energy systems in the past, applying Çatalhöyük's (bio)archaeological data to a modern human energy requirements framework. This energy methodology was applied in chapters 5 and 6 to quantify the energy of Çatalhöyük's agricultural energy system. More specifically, chapter 5 focused on land preparation, calculated the amount of land Çatalhöyük's population would have required based on a 75% reliance upon four domestic cereals, and from here, quantified land clearance, tillage, and planting energy for Çatalhöyük. Chapter 6 focused on harvesting and crop processing and calculated the agricultural energy required from Çatalhöyük for these agricultural activities, Çatalhöyük's minimum populational energy requirements, required agricultural energy input for each agricultural process, and land requirements were also quantified and related to Çatalhöyük's population growth and development through time (also see Chapter 3). Thus, the work completed throughout chapters 4-6 provides a mechanism for Çatalhöyük's growth, development, and limits with respect to agriculture during the Neolithic. Further, chapters 4-6 quantified the energy requirements of this Neolithic agricultural energy system and demonstrated the human energy inputs required of agriculture and that being reliant upon agriculture means effectively being dependent upon its success. To ensure agriculture's success, societies reliant upon it must continuously invest energy in its processes, sustain it, and, be efficient at doing so; these processes must be successful, and societies must continuously extract resources by acquiring more resources, including more land.

Chapter 7 combined analysed and interpreted the energy of agricultural processes quantified within chapters 5 and 6 and identified energetic differences between agricultural processes. Chapter 7 provide crucial findings within this thesis. First, low yield crops require more energy input, are more costly, and are less efficient than high yielding crops. Second, agriculture's efficiency and cost initially improve with population growth. This improved cost and efficiency is the mechanism of the agricultural energy feedback system aiding in population growth and enforcing a reliance upon agriculture. However, this efficiency and cost plateau when additional land clearance is needed with a high population growth rate; this is the point within agricultural systems that requires expansion and land colonisation. In other words, this thesis has also determined limits within a Neolithic agricultural system. For Çatalhöyük, once this limit was reached, the amount of additional surplus energy from Çatalhöyük begins to decrease, no matter the yield and Çatalhöyük had to adjust to energy tensions. The changes Çatalhöyük underwent during the Middle period are Çatalhöyük adjusting to these energy tensions. Third, tillage, harvesting, land clearance, crop processing, and storage are energetically demanding processes, thus, are crucial to the success of agricultural systems. Fourth, there are energetic reasons why free-threshing wheat, certain glume wheats, and barleys were preferred during the Neolithic. The changes in cereal crop reliance at Çatalhöyük, for more durable, efficient, and less energy-intensive crops, has significant implications for understanding the spread of agriculture from southwest Asia to Europe. Furthermore, the agricultural energy feedback system is the mechanism that might have accelerated their spread during the Neolithic. Fifthly, this chapter provided quantifiable evidence of the existence of the agricultural energy feedback system at Çatalhöyük.

Finally, chapter 7 also presented that agricultural processes, together, are dependent upon one another's success and require human input to sustain agriculture additional surplus energy. This aspect of agriculture has not been fully recognised, as outlined in chapter 2 (Fischer-Kowalkski and Haberl, 2007, Fischer-Kowalski and Haberl, 1997, Fischer-Kowalski and Weisz, 1999, Odum, 2007, Odum and Odum, 1977, Smil, 2017) nor has it been quantified, until now. This aspect of agriculture is essential, as it forces an increasing reliance upon agriculture, "trapping" societies into relying upon it. Investigating Çatalhöyük's Neolithic agricultural energy system, overall, has allowed for quantifiable reasons for why agriculture requires land colonisation and explains why the Neolithic came with population growth, production increases and new land requirements. Additionally, this has helped us gain an understanding of how the spread of agriculture is related to energy and our struggle to balance energy input, use, and outputs.

This final chapter discusses the energy methodology and energy analysis at hand and provides overall conclusions. Agriculture, as a system, comes with the caveat that its processes become increasingly dependent on one another's success to produce an energetic surplus; high yielding crops are more efficient at providing this surplus. Agriculture's efficiency and cost initially improve with population growth. However, this efficiency and cost plateau when additional land clearance is needed in a time of high population growth rate; at this point, agricultural systems require expansion. Tillage, harvesting, land clearance, crop processing and storage are energetically demanding; thus, they are crucial to understanding the success of agricultural systems. Energy provides quantifiable evidence for why certain glume wheats, barleys and free-threshing wheats were preferred, and the agricultural energy feedback system is the mechanism that facilitated their spread during the Neolithic. Section 8.1 discusses broader research themes surrounding the thesis, including both archaeological and sustainability issues. Finally, 8.2 concludes the methodology and energy analysis presented within this thesis.

8.1 DISCUSSION: ARCHAEOLOGY AND BEYOND

The new methodology created and enacted in this thesis sought to understand how agricultural energy flows functioned at Çatalhöyük, and more importantly, for the broader Neolithic. This thesis demonstrated that agricultural systems are constructed as energy feedback systems that aid population growth and enforce a reliance upon agriculture. This thesis analysed the development of these sparsely studied energy flows, feedbacks, and dependencies, which I termed the *agricultural energy feedback system*. The agricultural energy feedback system posited, modelled, and proved here provides a mechanism that explains the spread of agriculture, why agriculture requires additional land, what encourages population growth, and explains limits to population growth during the Neolithic.

In modelling Çatalhöyük's agricultural system, this thesis brought attention to the roles of crop yield, domestic cereal reliance, and the more energetically demanding aspects of agricultural cycles, i.e., tillage, harvesting, land clearance, crop processing, and storage. As demonstrated in this thesis, the caveat of agricultural systems is that agricultural processes, together, become increasingly dependent upon one another's success to produce an energetic surplus. This is one of the crucial aspects of agriculture that has been overlooked (chapter 2), until now. Quantifying the energy requirement of agricultural processes at Çatalhöyük has provided an avenue to understanding this, but more importantly, it has aided in understanding the uptake of domestication and agriculture.

In bringing to light and quantifying the human energetic requirements of agriculture's processes, this thesis demonstrated that agriculture as a system requires significant energy input. Many have argued that the energy output received from agriculture was the cause of its spread, subsequent social developments, and changes in nutrition, social interaction, mobility, workload, and increases in production (Chaisson, 2014b, Odum, 2007, Odum and Odum, 1977, White, 1943). However, by neglecting the activities required to perform agriculture, this mistakes causes and effects; energy output on its own does not facilitate the spread of agriculture, population growth, or necessitate additional land. Instead, its spread, population growth, and land requirements are intertwined with input requirements of agriculture's processes, outputs, crop yields, energy cost and efficiency, as posited by the agricultural energy feedback system. Agriculture depends on energy, and it always has. Moreover, to be most beneficial or successful to the population, agriculture requires high yields, population growth, and adequate access to land. The agricultural energy feedback system posited here demonstrates and quantifies this energetically. This thesis and the development of the agricultural energy feedback system enhances calls for understanding and comparing the labour differences of agricultural processes (Fuller, Allaby et al., 2010, Halstead, 2014, Wright, 1994).

Çatalhöyük itself is a remarkable case study. Its expert-led excavations, substantial and detailed archaeological evidence, stratigraphic sequencing, and 1400 years of occupation with no breaks in stratigraphic sequencing have undoubtedly allowed for valuable perspective on modelling energy relationships in the past. Using Çatalhöyük's archaeological data, it was possible to quantify and present a past agricultural energy system. However, some may argue that the energy methodology developed and presented could not be replicated in other archaeological case studies. Although this is a genuine concern, I categorically disagree.

The work and methodology within this thesis *can* be applied to archaeological sites more generally. Extremely fine-grained data was not required to inform the analysis at hand. Referring to chapter 4, baseline requirements were based on Çatalhöyük's bioarchaeological data, but more importantly, *routinely collected* bioarchaeological data such as stature estimates, body mass estimates, age estimates, biomechanics, and the presence of osteoarthritis; these are all routinely collected data wherever skeletal remains are present (Elliott, Kurki et al., 2016, Jeanson, Santos et al., 2017, Larsen, 2015). Isotopic data helped to better inform the model in this thesis, especially dietary requirements and mobility, but it was not the most pivotal foundation to this analysis; routinely collected archaeological data was. The foundation of the model in this thesis, e.g. chapters 5 and 6, was based on ethnographic data, experimental archaeological data, and routinely collected archaeological data; all of these are for determining that the Çatalhöyük population was a relatively healthy one with access to adequate nutrition and opportunity for normal development (Larsen, Hillson et al., 2015: 50). Archaeobotanical data allowed for determining what kind of cereals were present at Çatalhöyük, how they were planted, harvested, processed, and even stored (chapter 6).

Further, combining archaeobotanical data, bioarchaeological data, ethnographic analysis and experimental archaeological data allowed for determining how much energy would have been required for Çatalhöyük's population to complete agricultural tasks; this was fundamental to creating and enacting the methodology in this thesis. Çatalhöyük's stone tool data and analysis, combined with experimental archaeological data and ethnographic data, allowed for determining rates of land clearing, tillage, harvesting, and dehusking. Architectural data, i.e., permanent storage in the form of bins, provided average storage capacity, which allowed for determining whether or not storage requirements in this model could have been stored at Çatalhöyük. Although the paleoenvironmental data at Çatalhöyük is rich and detailed, again, this is not data that is exclusive *only* to Çatalhöyük. Paleoenvironmental data is crucial to most archaeological sites and assemblages and, again, is routine within archaeological sites (Faith and Lyman, 2019, Hassan, 1978, Kaufman, Kelly et al., 2018). The model enacted and presented within this thesis reframes archaeological data and methods to a modern human energy requirements framework (Figure 56). If anything, I believe this energy methodology has highlighted how crucial archaeological data is for informing this energy methodology, especially the roles of bioarchaeological, archaeobotanical, and experimental archaeological data.

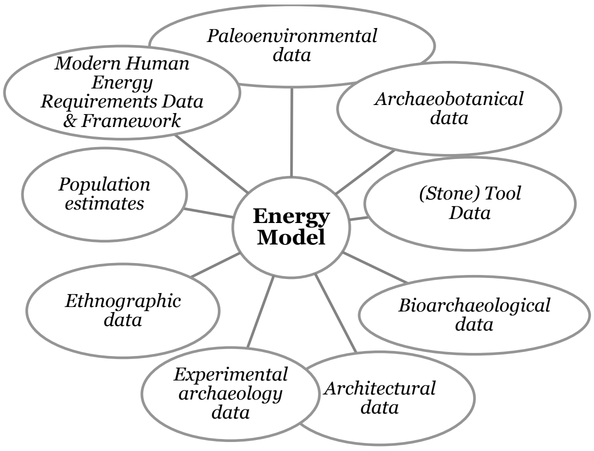


Figure 56: This figure presents the data utilised throughout the energy model within this thesis. Utilising archaeological data and methods is crucial to informing energy models in the past. Here I would like to emphasise that the archaeological data used for the energy model in this thesis is based on routinely collected archaeological data, common in archaeological methods, and is applied to a modern human energy requirements framework. The energy methodology presented in this thesis is not exclusive to Çatalhöyük.

I would argue that this thesis also provides an exciting opportunity for more theoretical aspects of archaeology. The model and quantifications within this thesis can be applied to and expand Ian Hodder's entanglement perspective of Çatalhöyük. Entanglement attempts to understand and disentangle how human-thing, human-human, thing-thing, and thing-human relationships and dependencies develop (Hodder, 2012, Hodder, 2016: 11). Çatalhöyük, he argues, is full of entanglements between humans, materials, the environment, animals, plants, and labour (Hodder, 2012, Hodder, 2016, Hodder, 2021a). Hodder has argued for viewing Çatalhöyük's population growth as the result of Çatalhöyük's response to coping with labour demands and practical entanglements (Hodder, 2016: 33-34, Hodder, 2021a: 276-280). Using clay extraction as an example, Hodder argues that as Çatalhöyük's population grew, it needed more supportive houses; building more supportive houses required digging deeper into the sands for mudbrick houses which required more work, as did travelling to obtain oak and juniper and transporting the timbers to better support these houses (Hodder, 2016: 33-34, Hodder, 2021a: 276-280). Thicker walls and two story-houses required more labour, in addition to the increased use of domestic sheep, an increasing reliance upon domestic cereals, as did the use of *Phragmites* caused by Çatalhöyük's clay exploitation which helped to push Çatalhöyük to expand its resource catchment areas in response to *Phragmites* invasion (Hodder, 2016: 33-34, Hodder, 2021a: 276-280). Hodder suggests that by delving into the practical entanglements at Çatalhöyük, we can understand the broader processes occurring during the Neolithic, i.e. the intensification of agriculture, the domestication of animals, settlement aggregation, and changing social structures; all of these are actually the *by-products* of local, practical entanglements (Hodder, 2016, Hodder, 2021a).

What is missing from this view of entanglement, however, is energy. Energy is the mechanism tied to Çatalhöyük's population growth and its entanglements. The agricultural energy feedback system posited and modelled in this thesis is itself an entanglement of energy dependencies within agriculture. Moreover, this thesis indicates that the intensification of agriculture, settlement aggregation in agricultural societies, are the by-products of energy use and extraction and can be quantified. This thesis provides an avenue to model Hodder's entanglements energetically and helps to explain why, as Hodder describes,

> "[humans and things] are dependent on each other in ways that are entrapping and asymmetrical…that things are so caught up in other things and in other human-thing dependencies, that daily practices are directed down specific pathways, that humans are drawn in specific directions that create further entanglements" (Hodder, 2016: 9).

As argued in chapter 1, although this thesis focuses on agricultural processes and agricultural energy, the advantage of taking an energetic approach is that *everything* has and uses energy. Within this thesis, energy allowed people, materials, crops and the landscape to be brought together into one framework. Similarly, it is also possible to energetically model other human, plant, and animal relationships, environmental feedbacks, tool production flows, or even ritual flows. This thesis provides a foundation for quantifying and examining these relationships on the same scale, making it possible to better understand other energy flows' entanglements and identify other energetic dependencies or feedbacks.

I would also argue that energetically modelling the agricultural energy feedback system utilising an archaeological case study, as this thesis does, allows us to empirically model some aspects of human adaptive cycles. I am not suggesting that the agricultural energy feedback system is the comprehensive answer to this understanding, however, it is a step towards empirically modelling and understanding the role energy plays within adaptive systems and opens the door to more, exciting modelling opportunities. In this case, utilising energy from an archaeological approach provides a crucial piece of the puzzle towards understanding adaptive cycles and resiliency within human systems. In resiliency terms, this thesis is specifically focused on the role of agricultural energy surplus and efficiency, however, what other adaptive cycles and feedbacks are there with other subsistence practices? What role do human-animal relationships play in the adaptive feedback cycle, for example? By utilising an adaptive framework and modelling adaptive cycles in the past from an energetic point of view, archaeology can aid in helping us to understand *how* humans set their own future, control their own destinies, and manipulate their own resiliency.

In creating a methodology that is based upon archaeological data, this thesis provides a potential avenue for archaeologists to contribute to today's sustainability and energy issues. As argued in this thesis, the need to fully understand and recognise our relationship with nature and energy requires studying the world through an interdisciplinary lens; a lens that includes archaeological narratives, analyses, and data (Hudson, 2012). Archaeologist Sander van der Leeuw has consistently suggested that we need to consider the emergence of our problems today and use our past to learn for the future (van der Leeuw, 2012 :110-116). Human action on the Earth system, including human action in the past, has unprecedented effects and unintended consequences for our environment today (van der Leeuw, 2012 :106). This thesis demonstrated that agricultural activities like land clearance and tillage indefinitely alter the energy systems of which they are a part. These are both activities that are required and, as identified in this thesis, are energy-intensive. Further, they have unintended and long-lasting consequences, especially if done incorrectly or too often (5.3 and 5.4). Some of the longer-term issues with tillage, for example, includes exposing topsoil to erosion, recompacting topsoil, reducing the strength and trafficability of soil, disrupting macrofauna (i.e. earthworms), decreasing soil microbial life and organic matter, and quick soil carbon release (Halstead, 2014: 46-47, 261-268, Van Alfen, 2014: 101, 191-193, van den Akker and Soane, 2005). The potential for damage caused by tillage is significant, and, overall, the entire soil cycle and the hydrologic cycle is altered as a consequence of tilling. Tillage and land clearance, as agricultural processes, emphasise that for humans to benefit from agriculture, they must invest energy into agricultural processes *and* alter the environment and its cycles—the hydrologic, soil, and atmospheric cycles. These agricultural processes were also occurring in the Neolithic. Çatalhöyük's archaeological evidence indicates Çatalhöyük had a direct impact upon the environment, however the long-term effects of Neolithic Çatalhöyük's impacts upon the region today have not been thoroughly investigated, but they absolutely should be. This thesis makes clear that consequences and changes in energy flows and systems occurred even from the onset of the "Agricultural Revolution," and we must discuss and investigate them. We have been accumulating these unanticipated consequences for thousands of years but are not incorporating these timescales or understandings into models or analyses (van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). This thesis provides one way of incorporating and better understanding the unintended or unanticipated consequences of past human decisions and actions upon the environment through an energy analysis (van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016).

Finally, this energy analysis at Çatalhöyük has stimulated a much-needed discussion of energy and archaeological discourse. Energy clearly plays a role in population growth and subsistence pathways. However, archaeology has not been considering the processes of energy extraction by which societies grow. One of the fundamental questions our discipline has always had is *how* or *why did societies grow*. This thesis demonstrates how and that energy extraction and our relationships with energy plays a fundamental role. Archaeologists need to investigate this more thoroughly, and this thesis provides a methodology to do so. Limits to societal growth are far more related to energy, energy efficiency, and energy flows than given credit. Within Çatalhöyük's agricultural system, this limit seems to be related to land, suggesting that land is something that requires more investigation not only at Çatalhöyük, but for the Neolithic more broadly. Agriculture alters human and environmental flows and did so during the Neolithic; because of the work within this thesis, we understand how this occurred.

8.2 CONCLUSIONS

Investigating the Neolithic from an energy point of view has allowed for new, exciting perspectives and conclusions on the Neolithic, a pivotal turning point in humanity's history

First, Çatalhöyük's agricultural system, and agriculture more generally, has the potential to provide a substantial energy surplus even at lower yields; this is now energetically modelled for a Neolithic agricultural system. Further, high yielding crops allow for more of an additional surplus of energy while having limited costs and higher efficiency. Even within this Neolithic system, agriculture seems to work best with high yields.

Second, Çatalhöyük's agriculture system, assuming a 25% to 75% reliance on four domestic cereals, requires significant energy input from Çatalhöyük's population to sustain it. Further, agricultural inputs vary depending on the process at hand, the amount of land upon which agriculture is occurring, crop yield, and the population. The model and thesis here allowed us to see the energy input required of agriculture, investigate agricultural processes, and compare agricultural processes on the same scale. This thesis also demonstrated the energy differences between Neolithic domestic cereals and provided quantifiable reasons for why certain barleys, free-threshing wheats, and certain glume wheats were preferred, whilst the agricultural energy feedback system provides the mechanism for why they spread. Because agricultural processes were modelled and compared, it was possible to establish these differences between crops and agricultural processes and understand the agricultural energy feedback system's inner workings within a Neolithic system. As demonstrated throughout chapter 2, although agriculture's output was emphasised by many and even heeded as one of the foundational aspects in relation to societal development (Chaisson, 2014b, Odum, 2007, Odum and Odum, 1977, White, 1943), quite often agriculture's inputs were often neglected or disregarded, the input of agricultural processes was rarely calculated or modelled separately especially for past agricultural energy systems. Thus, discussions and modelling of the agricultural energy feedback system were missing. This thesis enacted an energy methodology and quantified the agricultural inputs of Neolithic Çatalhöyük's agricultural system, utilised archaeological data and methods to do so, and demonstrated the importance of considering such inputs. Overall, this model indicates that agriculture, even in the Neolithic, required a significant amount of energy to keep it sustained.

Akin to this, this thesis demonstrated that within Çatalhöyük's agricultural system, and likely within agriculture more generally, as population growth occurs, the cost of agriculture initially decreases and becomes more efficient regardless of low or high yield scenarios. This is because having more people spreads the energy input required of agriculture. However, this cost and efficiency plateau when a population’s threshold is reached, i.e. additional land clearance is needed in a time of high population growth rate; at this point, agricultural systems are required to be more efficient. Thus, Çatalhöyük's agricultural system has a limit.

Cost and efficiency are most affected and controlled by land clearance and tillage. Chapter 7 section 7.3 emphasised that even at a population of 100, regardless of yield scenario, land clearance and tillage are energy-intensive processes, and storage is energetically demanding (Figure 44, Figure 45, and Figure 46). Even with 100 people, the agricultural energy feedback system was occurring or, at the very least, beginning to occur. As the energy cost and efficiency of Çatalhöyük's system started to improve, i.e., when its population grew, Çatalhöyük would have been investing more energy into more agricultural processes, and it would have received a substantial energy surplus, no matter the yield. However, once Çatalhöyük's population reached 2000 to 3000 people when the growth rate is greater than one Çatalhöyük's must invest more energy into land clearance than the previous year, decreasing the surplus received from agriculture and its processes. Needing more land, especially at a time of higher growth rate, seems to be the limiting factor within Çatalhöyük's agricultural system. Further, at these points (2000 to 3000 people), nearly every agricultural process becomes energy intensive and it is increasingly difficult to keep agriculture sustained and functioning (Figure 50, Figure 51, and Figure 52). The need for seed, successful planting, tilling, a successful harvest, and dehusking all become energetically demanding. Further, once this threshold was reached, there were conflicts in energy both within and outside of agriculture; Çatalhöyük had to find ways of balancing energy conflicts between maintaining agriculture, herding, gathering and foraging, feasting, other ritual activities, trade and exchange, and the like.

Agriculture is inherently dependent upon energy; balancing energy input, energy use, and energy output has always been a struggle, as this thesis indicates, and is even a struggle today. Across human communities today, we see a struggle to balance available energy with energy use and the cultural, social, and economic dynamics which maintain and sustain social coherence, material acquisition, and community needs (Bates, Petrie et al., 2017, van der Leeuw, 2012, van der Leeuw, Costanza et al., 2011, Verburg, Dearing et al., 2016). This was also the case at Neolithic Çatalhöyük and is an enduring problem for humanity. Regarding today's sustainability issues, this work has indicated how intricate and sensitive agriculture as a system is and was during the Neolithic. All of agriculture's processes depend upon one another's success, all its processes must be successful to produce a large energy surplus, and high yielding crops seem to work best. If any external factors such as disease which burdens the population, weather events, climate change, storage failures, severe crop failures, decreasing yields, or social conflict disrupt these agricultural processes, the system itself can fail. As demonstrated by this thesis, archaeology can and needs to model and better understand energy use in the past.

Archaeology deals with many aspects of energy use; we just do so in the past. As a discipline, archaeology is the scientific study of humankind's past, the study of our environmental, material, social, political, and cultural relationships throughout time and geographical space. Archaeology illuminates the diversity of these complicated relationships and interactions while at the same time promoting cultural understanding of human variation, something which is missing from most energy models which do not come from an archaeological perspective. This thesis indicates that archaeology has the tools, the data, and the methods at its disposal to help us better understand how processes of energy extraction flow, function and potentially lock us into unsustainable trajectories, opening a door to understanding how these lock-ins might have occurred, as far back as the Neolithic.

9 APPENDIX

For this dissertation, it was not possible within the timeframe allowed for the final corrections to include an updated appendix. Thus, the calculations within this appendix include calculations for a population of 1000, 3500, 5000, and 8000 people. This appendix provides all data calculations made for this thesis based on Cessford's 2005 estimates as opposed to Bernardini and Shachner 2018.

9.1 CEREAL REQUIREMENTS FOR ÇATALHÖYÜK

Table 29: Cereal Requirements for Çatalhöyük. This table presents the amount of cereals required to sustain Çatalhöyük at various population estimates. This was calculated based on data presented in Chapter 4.

Population	1000	3500	5000	8000
Total calories needed (population x kcals/day)	1800000	6300000	9000000	14000000
75% of kcals from cereals per day	1400000	4700000	6800000	11000000
18.75% of cereal kcals per day (divided evenly;)	350000	1200000	1700000	2800000
18.75% of cereal kcals per year (18.75% cereal cals * 365 days)	130000000	440000000	620000000	1000000000
18.75% of cereal in Megajoules per year [kcals per year x 4184)/(1e+6) to Megajoules]	540000	1800000	2600000	4200000

9.2 TOTAL LOSSES

This section of the appendix presents the calculated losses, in both kilograms and megajoules per year, which were accounted for in this thesis.

9.2.1 Crop Losses for Çatalhöyük

Table 30 Crop losses. This table presents the cereal losses for this model (20%) in kilograms per year, based on population estimate and crop.

	1000	3500	5000	8000
Free-Threshing Wheat	8400	28000	40000	64000
Barley	7400	26000	36000	58000
Emmer	8200	28000	38000	62000
Einkorn	7600	26000	36000	58000
Total loss	32000	110000	150000	240000

Table 31 Crop losses. This table presents the cereal losses for this model (20%) in megajoules per year, based on population estimate and crop.

	1000	3500	5000	8000
Free-Threshing Wheat	110000	360000	520000	830000
Barley	110000	380000	530000	850000
Emmer	110000	370000	510000	830000
Einkorn	110000	370000	510000	830000
Total	440000	1500000	2100000	3300000

9.2.2 Processing Losses for Çatalhöyük

Table 32 Processing losses. This table presents the cereal losses for this model (20%) in kilograms per year, based on population estimate and crop.

	1000	3500	5000	8000
Free-Threshing Wheat	8400	28000	40000	64000
Barley	7400	26000	36000	58000
Emmer	8200	28000	38000	62000
Einkorn	7600	26000	36000	58000
Total loss	32000	110000	150000	240000

Table 33 Processing losses. This table presents the cereal losses for this model (20%) in megajoules per year, based on population estimate and crop.

	1000	3500	5000	8000
Free-Threshing Wheat	110000	360000	520000	830000
Barley	110000	380000	530000	850000
Emmer	110000	370000	510000	830000
Einkorn	110000	370000	510000	830000

9.2.3 Storage Losses for Çatalhöyük

Table 34 Storage losses. This table presents the cereal losses for this model (10%) in kilograms per year, based on population estimate and crop.

Population	1000	3500	5000	8000
Free-Threshing Wheat	4200	14000	20000	32000
Barley	3700	13000	18000	29000
Emmer	4100	14000	19000	31000
Einkorn	3800	13000	18000	29000
Total storage loss	15800	54000	75000	120000

Table 35 Storage losses. This table presents the cereal losses for this model (10%) in Megajoules per year, based on population estimate and crop.

Population	1000	3500	5000	8000
Free-Threshing Wheat	54000	180000	260000	420000
Barley	54000	190000	260000	420000
Emmer	55000	190000	250000	420000

Einkorn	54000	180000	260000	410000
Total storage loss	220000	740000	1000000	1700000

9.3 SEED REQUIREMENTS FOR ÇATALHÖYÜK

The tables within this subsection of the appendix present the total amount of seed required by crop and population.

Table 36: Total seed requirements and seed storage, assuming 20% of seed required per year. This table presents the total seed requirements and total seed storage based on Çatalhöyük's population and crop.

Population	1000	3500	5000	8000
Wheat	8400	28000	40000	64000
Barley	7400	26000	36000	58000
Emmer	8200	28000	38000	62000
Einkorn	7600	26000	36000	58000
Total seed required	32000	110000	150000	240000

9.4 GRAIN REQUIRED FOR ÇATALHÖYÜK

The tables within this subsection of the appendix present the total amount of grain required by crop and population.

Table 37: Total Kilograms of grain required per year to account for loss and seed storage. This table presents the number of kilograms of seed required per year to account for all losses and seed storage.

Population	1000	3500	5000	8000
Free-Threshing Wheat (kcals converted to kg)	71000	240000	340000	550000
Barley (kcals converted to kg)	63000	210000	300000	490000
Emmer (kcals converted to kg)	69000	230000	330000	530000
Einkorn (kcals converted to kg)	65000	220000	310000	500000
Total kilograms required	270000	900000	1300000	2100000

Table 38 Total Megajoules of cereal needed per year to account for losses and seed storage. 1 kilocalorie is equal to 4184 joules (J) or 0.004184 megajoules (MJ), 1 megajoule (MJ) is equal to 1000000 joules (J)

Population	1000	3500	5000	8000
Free-Threshing Wheat Energy MJ	920000	3100000	4400000	7100000
Barley Energy MJ	920000	3100000	4400000	7200000
Emmer Energy MJ	920000	3100000	4400000	7100000
Einkorn Energy MJ	920000	3100000	4400000	7100000
Total	3700000	12000000	18000000	29000000

9.5 LAND REQUIREMENTS

The tables within this subsection of the appendix present the amount of land required by crop and population, depending on yield scenario.

Table 39 Land requirement by crop and population, based on low-yields. This table presents the low-yield scenario, the land in hectares (ha), and square kilometres (km2) per year.

	ha	km2	ha	km2	ha	km2	ha	km2
Population	1000		3500		5000		8000	
Free-Threshing Wheat	150	1.5	500	5.0	710	7.1	1100	11
Barley	250	2.5	840	8.4	1200	12.0	2000	20
Emmer	81	0.8	270	2.7	390	3.9	620	6
Einkorn	93	0.9	310	3.1	440	4.4	710	7
Total land (ha)	570		1900		2700		4400	

Table 40 Land requirement by crop and population, based on average-yields. This table presents the average-yield scenario, the land in hectares (ha), and square kilometres (km2) per year.

	ha	km2	ha	km2	ha	km2	ha	km2
Population	1000		3500		5000		8000	
Free-Threshing Wheat	96	1.0	320	3.2	460	4.6	740	7.4
Barley	100	1.0	340	3.4	480	4.8	780	7.8
Emmer	66	0.7	220	2.2	320	3.2	510	5.1
Einkorn	78	0.8	260	2.6	370	3.7	600	6.0
Total land (ha)	340		1100		1600		2600	

Table 41 Land requirement by crop and population, based on high-yields. This table presents the high-yield scenario, the land in hectares (ha), and square kilometres (km2) per year.

	ha	km2	ha	km2	ha	km2	ha	km2
Population	1000		3500		5000		8000	
Free-Threshing Wheat	71	0.7	240	2.4	340	3.4	550	5.5
Barley	63	0.6	210	2.1	300	3.0	490	4.9
Emmer	56	0.6	190	1.9	270	2.7	430	4.3
Einkorn	67	0.7	230	2.3	320	3.2	520	5.2
Total land (ha)	260		870		1200		2000	

Table 42: Total Amount of Land needed, based on a 75% reliance on cereals, by population, and yield scenario and including losses and seed storage

Population	1000	3500	5000	8000
Low yield—amount of land needed	570 ha	1900 ha	2700 ha	4400 ha
Average yield—amount of land needed	340 ha	1100 ha	1600 ha	2600 ha
High yield—amount of land needed	260 ha	870 ha	1200 ha	2000 ha

Table 43: Extra land required to sustain Çatalhöyük's population: based on a 75% reliance on cereals, by population, and yield scenario and including losses and seed storage.

Population	1000	3500	5000	8000
	Initial land required	Extra land required		
Low yield	540 ha	1300 ha	800 ha	1700 ha
Average yield	320 ha	760 ha	500 ha	1000 ha
High yield	240 ha	610 ha	330 ha	800 ha

9.6 AGRICULTURAL ENERGY OF LAND CLEARANCE, TILLAGE, AND PLANTING BASED ON CEREAL AND POPULATION

The sections within this appendix chapter focus on land clearance energy, tillage energy, and planting energy depending on crop, crop yield, and population. The data within this appendix was used for calculations throughout Chapter 5.

9.7 LAND CLEARANCE

9.7.1 Land Clearance Energy of Barley, depending on yield scenario.

The tables below present required energy input for land clearance for Barley, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

*Table 44: Barley Land Clearance, **Low Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	130000	300000	180000	410000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***300000***	***690000***	***410000***	***940000***
land clearance work hours per person per year-100% of population working (total work hours/(100% population))]	130	86	36	51
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	300	200	82	120

land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	170	110	48	68
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*390*	*250*	*110*	*160*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	260	170	72	100
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*600*	*390*	*160*	*230*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	520	340	140	210
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*1200*	*780*	*320*	*480*

Table 45: Barley Land Clearance, ***Average Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	50000	120000	72000	150000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***110000***	***270000***	***160000***	***340000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	50	34	14	19
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	115	79	33	43
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	67	46	19	25
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*150*	*100*	*44*	*57*

land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	100	69	29	38
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*230*	*160*	*66*	*86*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	200	140	58	75
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*460*	*320*	*130*	*170*

Table 46 Barley Land Clearance, High yield

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	32000	75000	46000	97000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***73000***	***170000***	***110000***	***220000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	32	21	9	12
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	73	49	21	28
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	43	29	12	16
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*98*	*65*	*28*	*37*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	64	43	18	24
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*150*	*98*	*42*	*56*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	130	86	37	49

Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*300*	*200*	*84*	*110*

9.7.2 Land Clearance Energy of Free-Threshing Wheat, depending on yield scenario.

The tables below present required energy input for land clearance for Free-Threshing Wheat, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 47: Free-Threshing Land Clearance, ***Low Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	77000	180000	110000	200000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***180000***	***410000***	***250000***	***460000***
land clearance work hours per person per year-100% of population working (total work hours/(100% population))]	77	51	22	25
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	180	120	50	57
land clearance work hours per person per year-75% of population working (total work hours/(75% population))]	100	69	29	33
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*230*	*160*	*67*	*76*
land clearance work hours per person per year-50% of population working (total work hours/(50% population))]	154	103	44	50
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*350*	*240*	*100*	*110*
land clearance work hours per person per year-25% of population working (total work hours/(25% population))]	310	210	88	100

Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*710*	*480*	*200*	*230*

Table 48: Free-Threshing Land Clearance, ***Average Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	49000	110000	72000	140000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***110000***	***250000***	***160000***	***320000***
land clearance work hours per person per year-100% of population working (total work hours/(100% population))]	49	31	14	18
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	110	72	33	40
land clearance work hours per person per year-75% of population working (total work hours/(75% population))]	65	42	19	23
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*150*	*96*	*44*	*53*
land clearance work hours per person per year-50% of population working (total work hours/(50% population))]	98	63	29	35
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*220*	*140*	*66*	*80*
land clearance work hours per person per year-25% of population working (total work hours/(25% population))]	200	130	58	70
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*460*	*300*	*130*	*160*

Table 49: Free-Threshing Land Clearance, ***High Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	36000	86000	51000	110000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***82000***	***200000***	***120000***	***250000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	36	25	10	14
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	82	56	23	31
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	48	33	14	18
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*110*	*75*	*31*	*42*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	72	49	20	28
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*160*	*110*	*47*	*63*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	140	100	41	55
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*320*	*230*	*93*	*130*

9.7.3 Land Clearance Energy of Emmer, depending on yield scenario.

The tables below present required energy input for land clearance for Emmer, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

*Table 50: Emmer Land Clearance, **Low Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	41000	97000	61000	118000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***94000***	***220000***	***140000***	***270000***
land clearance work hours per person per year-100% of population working (total work hours/(100% population))]	41	28	12	15
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	94	63	28	34
land clearance work hours per person per year-75% of population working (total work hours/(75% population))]	55	37	16	20
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*130*	*85*	*37*	*45*
land clearance work hours per person per year-50% of population working (total work hours/(50% population))]	82	55	24	30
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*190*	*130*	*56*	*68*
land clearance work hours per person per year-25% of population working (total work hours/(25% population))]	164	111	49	59
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*380*	*250*	*110*	*140*

*Table 51: Emmer Land Clearance, **Average Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	34000	79000	51000	97000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***78000***	***180000***	***120000***	***220000***
land clearance work hours per person per year-100% of population working (total work hours/(100% population))]	34	23	10	12

Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	78	52	23	28
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	45	30	14	16
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*100*	*69*	*31*	*37*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	68	45	20	24
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*156*	*103*	*47*	*56*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	140	90	41	49
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*320*	*210*	*93*	*110*

Table 52: Emmer Land Clearance, ***High Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	29000	69000	41000	82000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***66000***	***160000***	***94000***	***190000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	29	20	8	10
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	66	45	19	23
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	39	26	11	14
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*89*	*60*	*25*	*31*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	58	39	16	21

Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*130*	*90*	*38*	*47*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	120	79	33	41
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*270*	*180*	*75*	*94*

9.7.4 Land Clearance Energy of Einkorn, depending on yield scenario.

The tables below present required energy input for land clearance for Einkorn, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 53: Einkorn Land Clearance, ***Low Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	47000	110000	66000	140000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***110000***	***250000***	***150000***	***320000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	47	31	13	18
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	110	72	30	40
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	63	42	18	23
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*140*	*96*	*40*	*53*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	94	63	26	35

Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*220*	*140*	*60*	*80*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	190	130	53	70
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*440*	*300*	*120*	*160*

Table 54: Einkorn Land Clearance, ***Average Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	40000	93000	56000	117600
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***92000***	***210000***	***128000***	***270000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	40	27	11	15
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	92	61	26	34
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	53	35	15	20
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*120*	*81*	*34*	*45*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	80	53	22	29
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*180*	*120*	*51*	*67*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	160	110	40	59

Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*370*	*250*	*92*	*130*

Table 55: Einkorn Land Clearance, ***High Yield***

Population	1000	3500	5000	8000
Land Clearance Hours total, per year *(land needed/clearance hectare/hour)*	34000	83000	46000	100000
PAR Land Clearance =	*5.7*			
BMR MJ/hour	*0.40*			
Energy of land clearance in Megajoules per year *((land clearance work hours)x(PAR of land clearance)x(BMR)*	***78000***	***190000***	***110000***	***230000***
land clearance work hours per person per year- 100% of population working (total work hours/(100% population))]	34	24	9	13
Energy of land clearance in Megajoules per person per year 100% population working *(land clearance work hours 100% population working)x(PAR of land clearance)x(BMR)*	78	54	21	29
land clearance work hours per person per year- 75% of population working (total work hours/(75% population))]	45	32	12	17
Energy of land clearance in Megajoules per person per year 75% population working. *(land clearance work hours 75% population working)x(PAR of land clearance)x(BMR)*	*100*	*72*	*28*	*38*
land clearance work hours per person per year- 50% of population working (total work hours/(50% population))]	68	47	18	25
Energy of land clearance in Megajoules per person per year 50% population working. *(land clearance work hours 50% population working)x(PAR of land clearance)x(BMR)*	*160*	*110*	*42*	*57*
land clearance work hours per person per year- 25% of population working (total work hours/(25% population))]	140	95	37	50
Energy of land clearance in Megajoules per person per year 25% population working. *(land clearance work hours 25% population working)x(PAR of land clearance)x(BMR)*	*320*	*220*	*80*	*110*

9.8 TILLAGE

9.8.1 Tillage Energy of Barley, depending on yield scenario

The tables below present required energy input of tillage for Barley, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 56: Barley Tillage, ***Low yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	82000	280000	390000	660000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***170000***	***570000***	***800000***	***1400000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	82	80	78	83
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	170	160	160	170
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	110	110	100	110
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*230*	*230*	*200*	*230*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	160	160	160	170
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*330*	*330*	*330*	*350*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	330	320	310	330
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*680*	*660*	*630*	*680*

*Table 57 Barley Tillage, **Average Yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	33000	110000	160000	260000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***68000***	***230000***	***330000***	***530000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	33	31	32	33
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	68	64	66	67
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	44	42	43	43
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*90*	*86*	*87*	*89*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	66	63	64	65
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*140*	*130*	*130*	*130*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	130	130	130	130
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*270*	*270*	*270*	*270*

*Table 58 Barley Tillage, **High Yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	21000	69000	99000	160000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			

Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***43000***	***140000***	***200000***	***330000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	21	20	20	20
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	43	40	41	41
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	28	26	26	27
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*57*	*54*	*54*	*55*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	42	39	40	40
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*86*	*81*	*81*	*82*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	84	79	79	80
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*170*	*160*	*160*	*160*

9.8.2 Tillage Energy of Free-Threshing Wheat, depending on yield scenario

The tables below present required energy input of tillage for Free-Threshing Wheat, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 59 Free-Threshing Wheat Tillage, ***Low Yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	49000	160000	230000	360000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***100000***	***330000***	***470000***	***740000***

tillage hours per person per year- 100% of population working (total work hours)/(100% population)	49	46	46	45
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	100	94	94	92
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	65	61	61	60
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*130*	*120*	*130*	*120*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	98	91	92	90
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*200*	*190*	*190*	*180*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	200	180	180	180
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*410*	*370*	*370*	*370*

Table 60 Free-Threshing Wheat Tillage, ***Average Yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	32000	110000	150000	240000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***66000***	***230000***	***310000***	***490000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	32	31	30	30
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	66	64	61	61

tillage hours per person per year- 75% of population working (total work hours)/(75% population)	43	42	40	40
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*87*	*86*	*82*	*82*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	64	63	60	60
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*130*	*130*	*120*	*120*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	130	130	120	120
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*270*	*270*	*250*	*250*

Table 61 Free-Threshing Wheat Tillage, ***High Yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	23000	79000	110000	180000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***47000***	***160000***	***230000***	***370000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	23	23	22	23
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	47	46	45	46
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	31	30	29	30
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*63*	*62*	*60*	*61*

tillage hours per person per year- 50% of population working (total work hours)/(50% population)	46	45	44	45
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*94*	*92*	*90*	*92*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	92	90	88	90
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*190*	*180*	*180*	*180*

9.8.3 Tillage Energy of Emmer, depending on yield scenario

The tables below present required energy input of tillage for Emmer, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 62: Emmer Tillage, ***Low yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	26000	89000	130000	200000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***53000***	***180000***	***270000***	***410000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	26	25	26	25
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	53	52	53	51
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	35	34	35	33
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*71*	*69*	*71*	*68*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	52	51	52	50
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*110*	*100*	*110*	*100*

tillage hours per person per year- 25% of population working (total work hours)/(25% population)	100	100	100	100
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*200*	*200*	*200*	*200*

*Table 63: Emmer Tillage, **Average yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	22000	72000	110000	170000
PAR tillage =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***45000***	***150000***	***230000***	***350000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	22	21	22	21
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	45	42	45	44
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	29	27	29	28
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*60*	*56*	*60*	*58*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	44	41	44	43
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*90*	*84*	*90*	*87*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	88	82	88	85
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*180*	*170*	*180*	*170*

*Table 64: Emmer Tillage, **High yield***

Population	1000	3500	5000	8000
Tillage Hours total per year *land needed/(tillage hectare/hour)*	18000	62000	89000	141000
PAR tillage =	*5.1*			

BMR MJ/hour	*0.40*			
Energy of tillage in Megajoules per year *(tillage work hours)x(PAR of tillage)x(BMR)*	***37000***	***130000***	***180000***	***290000***
tillage hours per person per year- 100% of population working (total work hours)/(100% population)	18	18	18	18
Energy of tillage in Megajoules per person per year, 100% population working *(tillage work hours 100% population)x(PAR of tillage)x(BMR)*	37	36	36	36
tillage hours per person per year- 75% of population working (total work hours)/(75% population)	24	24	24	24
Energy of tillage in Megajoules per person per year, 75% population working *(tillage work hours 75% population)x(PAR of tillage)x(BMR)*	*49*	*48*	*49*	*48*
tillage hours per person per year- 50% of population working (total work hours)/(50% population)	36	35	36	35
Energy of tillage in Megajoules per person per year, 50% population working *(tillage work hours 50% population)x(PAR of tillage)x(BMR)*	*74*	*73*	*73*	*72*
tillage hours per person per year- 25% of population working (total work hours)/(25% population)	72	71	71	71
Energy of tillage in Megajoules per person per year, 25% population working *(tillage work hours 25% population)x(PAR of tillage)x(BMR)*	*150*	*150*	*150*	*140*

9.9 PLANTING

9.9.1 Planting Energy of Barley, depending on yield scenario

The tables below present required energy input of planting for Barley, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 65 Barley Planting, ***Low Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	61000	200000	290000	480000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***92000***	***300000***	***440000***	***720000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	61	57	58	60

Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	92	86	87	90
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	81	76	77	80
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*120*	*110*	*120*	*120*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	120	110	120	120
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*180*	*170*	*180*	*180*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	240	230	230	240
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*360*	*350*	*350*	*360*

*Table 66 Barley Planting, **Average Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	24000	82000	120000	190000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***36000***	***120000***	***180000***	***290000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	24	23	24	24
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	36	35	36	36
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	32	31	32	32

Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*48*	*47*	*48*	*48*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	48	47	48	48
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*72*	*71*	*72*	*71*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	96	94	96	95
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*140*	*140*	*140*	*140*

Table 67 Barley Planting, ***High Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	15000	51000	73000	120000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***23000***	***77000***	***110000***	***180000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	15	15	15	15
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	23	22	22	23
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	20	19	19	20
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*30*	*29*	*29*	*30*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	30	29	29	30

Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*45*	*44*	*44*	*45*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	60	58	58	60
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*90*	*88*	*88*	*90*

9.9.2 Planting Energy of Free-Threshing Wheat, depending on yield scenario

The tables below present required energy input of planting for Free-Threshing Wheat, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 68 Free-Threshing Wheat Planting Energy, ***Low Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	36000	120000	170000	270000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***54000***	***180000***	***260000***	***410000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	36	34	34	34
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	54	52	51	51
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	48	46	45	45
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*72*	*69*	*68*	*68*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	72	69	68	68

Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*110*	*100*	*100*	*100*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	140	140	140	140
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*210*	*210*	*210*	*210*

Table 69 Free-Threshing Wheat Planting Energy, ***Average Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	23000	78000	110000	180000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***35000***	***120000***	***170000***	***270000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	23	22	22	23
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	35	34	33	34
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	31	30	29	30
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*46*	*45*	*44*	*45*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	46	45	44	45
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*69*	*67*	*66*	*68*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	92	89	88	90

Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*140*	*130*	*130*	*140*

Table 70 Free-Threshing Wheat Planting Energy, ***High Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year (*land needed)/(planting hectare/hour)*	17000	58000	82424	133333
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***26000***	***90000***	***120000***	***200000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	17	17	16	17
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	26	25	25	25
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	23	22	22	22
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*34*	*33*	*33*	*33*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	34	33	33	33
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*51*	*50*	*50*	*50*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	68	66	66	67
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*102*	*100*	*99*	*100*

9.9.3 Planting Energy of Emmer, depending on yield scenario

The tables below present required energy input of planting for Emmer, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

*Table 71 Emmer Planting Energy, **Low Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	20000	65000	95000	150000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***30000***	***98000***	***140000***	***230000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	20	19	19	19
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	30	28	29	28
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	27	25	25	25
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*40*	*37*	*38*	*38*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	40	37	38	38
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*60*	*56*	*57*	*56*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	80	74	76	75
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*120*	*110*	*110*	*110*

*Table 72 Emmer Planting Energy, **Average Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	16000	53000	78000	120000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***24000***	***80000***	***120000***	***180000***
planting work hours per person per year- 100% of population working	16	15	16	15

(total work hours)/(100% population)				
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	24	23	23	23
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	21	20	21	20
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*32*	*30*	*31*	*30*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	32	30	31	30
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*48*	*46*	*47*	*45*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	64	61	62	60
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*96*	*91*	*94*	*90*

Table 73 Emmer Planting Energy, ***High Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year (*land needed)/(planting hectare/hour)*	14000	46000	65000	100000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***21000***	***70000***	***100000***	***150000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	14	13	13	13
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	21	20	20	19
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	19	18	17	17
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*28*	*26*	*26*	*25*
planting work hours per person per year- 50% of population working	28	26	26	25

(total work hours)/(50% population)				
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*42*	*40*	*39*	*38*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	56	53	52	50
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*84*	*79*	*78*	*75*

9.9.4 Planting Energy of Einkorn, depending on yield scenario

The tables below present required energy input of planting for Einkorn, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 74 Einkorn Planting Energy, ***Low Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year (*land needed)/(planting hectare/hour)*	22000	75000	110000	170000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***33000***	***110000***	***170000***	***260000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	22	21	22	21
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	33	32	33	32
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	29	29	29	28
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*44*	*43*	*44*	*43*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	44	43	44	43

Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*66*	*64*	*66*	*64*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	88	86	88	85
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*130*	*130*	*130*	*130*

Table 75 Einkorn Planting Energy, ***Average Yield***

Population	1000	3500	5000	8000
Planting Hours total, per year (*land needed)/(planting hectare/hour)*	19000	63000	90000	150000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***29000***	***95000***	***140000***	***230000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	19	18	18	19
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	29	27	27	28
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	25	24	24	25
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*38*	*36*	*36*	*38*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	38	36	36	38
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*57*	*54*	*54*	*56*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	76	72	72	75

Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*110*	*110*	*110*	*110*

Table 76 Einkorn Planting Energy, high yield

Population	1000	3500	5000	8000
Planting Hours total, per year *(land needed)/(planting hectare/hour)*	16000	56000	77000	130000
PAR Planting =	*3.7*			
BMR MJ/hour	*0.40*			
Energy of planting in Megajoules per year *(planting work hours)x(PAR of planting)x(BMR)*	***24000***	***84000***	***120000***	***200000***
planting work hours per person per year- 100% of population working (total work hours)/(100% population)	16	16	15	16
Energy of planting in Megajoules per person per year 100% population working *(planting hours 100% population working)x(PAR of planting)x(BMR)*	24	24	23	24
planting work hours per person per year- 75% of population working (total work hours)/(75% population)	21	21	21	22
Energy of planting in Megajoules per person per year 75% population working *(planting hours 75% population working)x(PAR of planting)x(BMR)*	*32*	*32*	*31*	*33*
planting work hours per person per year- 50% of population working (total work hours)/(50% population)	32	32	31	33
Energy of planting in Megajoules per person per year 50% population working *(planting hours 50% population working)x(PAR of planting)x(BMR)*	*48*	*48*	*46*	*49*
planting work hours per person per year- 25% of population working (total work hours)/(25% population)	64	64	62	65
Energy of planting in Megajoules per person per year 25% population working *(planting hours 25% population working)x(PAR of planting)x(BMR)*	*96*	*96*	*93*	*98*

9.10 AGRICULTURAL ENERGY OF HARVESTING, THRESHING, WINNOWING, AND SIEVING BASED ON CEREAL AND POPULATION (CHAPTER 6)

The sections within this appendix chapter focus on the energy input requirements of harvesting, threshing, winnowing, dehusking, and sieving, depending on crop, crop yield, and population. The data within this appendix was used for calculations throughout Chapter 6.

9.10.1 Harvesting

9.10.1.1 Harvesting Energy of Barley, depending on yield scenario

The tables below present required energy input of harvesting Barley, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

*Table 77 Barley Harvesting Energy, **Low Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(barley harvest with sickle hectare/hour)*	56000	190000	270000	440000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***94000***	***320000***	***460000***	***740000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	56	54	54	55
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	94	92	91	93
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	75	72	72	73
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*130*	*120*	*120*	*120*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	110	110	110	110
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*190*	*190*	*190*	*190*

Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	220	220	220	220
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*370*	*370*	*370*	*370*

Table 78 Barley Harvesting Energy, ***Average Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year (*land needed)/(barley harvest with sickle hectare/hour)*	22000	75000	110000	170000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***37000***	***130000***	***190000***	***290000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	22	21	22	21
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	37	36	37	36
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	29	29	29	28
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*49*	*48*	*49*	*48*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	44	43	44	43
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*74*	*72*	*74*	*72*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	88	86	88	85

Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*150*	*140*	*150*	*140*

Table 79 Barley Harvesting Energy, ***High Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year (*land needed)/(barley harvest with sickle hectare/hour)*	14000	47000	67000	110000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***24000***	***79000***	***110000***	***190000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	14	13	13	14
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	24	23	23	23
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	19	18	18	18
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*31*	*30*	*30*	*31*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	28	27	27	28
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*47*	*45*	*45*	*46*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	56	54	54	55
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*94*	*91*	*90*	*93*

9.10.1.2 Harvesting Energy of Free-threshing Wheat, depending on yield scenario

The tables below present required energy input of harvesting Free-Threshing Wheat, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 80 Free-Threshing Wheat Harvesting Energy, ***Low Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year (*land needed)/(harvesting free-threshing wheat with a sickle hectare/hour)*	52000	170000	240000	380000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***88000***	***290000***	***400000***	***640000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	52	49	48	48
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	88	82	81	80
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	69	65	64	63
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*120*	*110*	*110*	*110*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	100	97	96	95
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*170*	*160*	*160*	*160*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	210	190	190	190
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*350*	*320*	*320*	*320*

Table 81 Free-Threshing Wheat Harvesting Energy, ***Average Yield***

Population	1000	3500	5000	8000

Harvesting Hours total, per year (*land needed)/(harvesting free-threshing wheat with a sickle hectare/hour)*	33000	110000	160000	250000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***56000***	***190000***	***270000***	***420000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	33	31	32	31
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	56	53	54	53
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	44	42	43	42
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*74*	*71*	*72*	*70*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	66	63	64	63
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*110*	*110*	*110*	*110*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	130	130	130	130
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*220*	*220*	*220*	*220*

Table 82 Free-Threshing Wheat Harvesting Energy, ***High Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year (*land needed)/(harvesting free-threshing wheat with a sickle hectare/hour)*	24000	82000	120000	190000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			

Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***40000***	***140000***	***200000***	***320000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	24	23	24	24
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	40	40	40	40
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	32	31	32	32
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*50*	*50*	*50*	*50*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	48	47	48	48
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*81*	*79*	*81*	*80*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	96	94	96	95
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*160*	*160*	*160*	*160*

9.10.1.3 Harvesting Energy of Emmer, depending on yield scenario

The tables below present required energy input of harvesting Emmer, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 83 Emmer Harvesting Energy, ***Low Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Emmer with a sickle hectare/hour)*	28000	95000	140000	220000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***47000***	***160000***	***240000***	***370000***

Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	28	27	28	28
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	47	46	47	46
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	37	36	37	37
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*63*	*61*	*63*	*62*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	56	54	56	55
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*94*	*92*	*94*	*93*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	110	110	110	110
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*190*	*190*	*190*	*190*

Table 84 Emmer Harvesting Energy, ***Average Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Emmer with a sickle hectare/hour)*	23000	78000	113000	180000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***39000***	***130000***	***190000***	***300000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	23	22	23	23
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	39	38	38	38
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	31	30	30	30
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*52*	*50*	*51*	*51*

Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	46	45	45	45
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*78*	*75*	*76*	*76*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	92	89	90	90
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*160*	*150*	*150*	*150*

Table 85 Emmer Harvesting Energy, ***High Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Emmer with a sickle hectare/hour)*	20000	67000	95000	150000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***34000***	***110000***	***160000***	***250000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	20	19	19	19
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	34	32	32	32
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	27	26	25	25
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*45*	*43*	*43*	*42*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	40	38	38	38
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*67*	*65*	*64*	*63*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	80	77	76	75
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*130*	*130*	*130*	*130*

9.10.1.4 Harvesting Energy of Einkorn, depending on yield scenario

The tables below present required energy input of harvesting Einkorn, according to population and yield. Extra calculations include megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Table 86 Einkorn Harvesting Energy, ***Low Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Einkorn with a sickle hectare/hour)*	29000	96000	140000	220000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***49000***	***160000***	***240000***	***370000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	29	27	28	28
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	49	46	47	46
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	39	37	37	37
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*65*	*62*	*63*	*62*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	58	55	56	55
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*98*	*93*	*94*	*93*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	120	110	110	110
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*200*	*190*	*190*	*190*

*Table 87 Einkorn Harvesting Energy, **Average Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Einkorn with a sickle hectare/hour)*	24000	81000	120000	190000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			
Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***40000***	***140000***	***200000***	***320000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	24	23	24	24
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	40	39	40	40
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	32	31	32	32
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*54*	*52*	*54*	*53*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	48	46	48	48
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*81*	*78*	*81*	*80*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	96	93	96	95
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*160*	*160*	*160*	*160*

*Table 88 Einkorn Harvesting Energy, **High Yield***

Population	1000	3500	5000	8000
Harvesting Hours total, per year *(land needed)/(harvesting Einkorn with a sickle hectare/hour)*	21000	72000	99000	160000
PAR harvesting =	*4.2*			
BMR MJ/hour	*0.40*			

Energy of harvesting in Megajoules per year *(harvesting work hours)x(PAR of harvesting)x(BMR)*	***35000***	***120000***	***170000***	***270000***
Harvesting work hours per person per year- 100% of population working (total work hours)/(100% population)	21	21	20	20
Energy of harvesting in Megajoules per person per year 100% population working *(harvesting hours 100% population working)x(PAR of harvesting)x(BMR)*	35	35	33	34
Harvesting work hours per person per year- 75% of population working (total work hours)/(75% population)	28	27	26	27
Energy of harvesting in Megajoules per person per year 75% population working *(harvesting hours 75% population working)x(PAR of harvesting)x(BMR)*	*47*	*46*	*45*	*45*
Harvesting work hours per person per year- 50% of population working (total work hours)/(50% population)	42	41	40	40
Energy of harvesting in Megajoules per person per year 50% population working *(harvesting hours 50% population working)x(PAR of harvesting)x(BMR)*	*71*	*69*	*67*	*67*
Harvesting work hours per person per year- 25% of population working (total work hours)/(25% population)	84	82	79	80
Energy of harvesting in Megajoules per person per year 25% population working *(harvesting hours 25% population working)x(PAR of harvesting)x(BMR)*	*140*	*140*	*130*	*130*

9.11 THRESHING

For this analysis, it is assumed that harvesting is successful, no matter yield. Thus, threshing depends upon *amount of cereals* rather than crop yield.

9.11.1 Barley Threshing

Table 89 Barley Threshing, 2 rounds total. The table below presents the required energy input of threshing Barley, according to population. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Threshing Hours total, per year (kilograms needed)/(threshing kilogram per hour)	*8000*	*26000*	*38000*	*62000*
PAR threshing =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of threshing in Megajoules per year *(threshing work hours)x(PAR of threshing)x(BMR)*	***16000***	***54000***	***78000***	***130000***

Threshing work hours per person per year- 100% of population working (total work hours)/(100% population)	8.0	7.4	7.6	7.8
Energy of threshing in Megajoules per person per year 100% population working *(threshing work hours 100% population working)x(PAR of threshing)x(BMR)*	16	15	16	16
Threshing work hours per person per year- 75% of population working (total work hours)/(75% population)	11	10	10	10
Energy of threshing in Megajoules per person per year 75% population working *(threshing work hours 75% population working)x(PAR of threshing)x(BMR)*	*22*	*20*	*21*	*21*
Threshing work hours per person per year- 50% of population working (total work hours)/(50% population)	16	15	15	16
Energy of threshing in Megajoules per person per year 50% population working *(threshing work hours 50% population working)x(PAR of threshing)x(BMR)*	*33*	*31*	*31*	*32*
Threshing work hours per person per year- 25% of population working (total work hours)/(25% population)	32	30	30	31
Energy of threshing in Megajoules per person per year 25% population working *(threshing work hours 25% population working)x(PAR of threshing)x(BMR)*	*66*	*61*	*63*	*64*

9.11.2 Free-Threshing Wheat Threshing

Table 90 Threshing of Free-Threshing Wheat, 1 round. The table below presents the required energy input of threshing Free-threshing wheat, according to population. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Threshing Hours total, per year (kilograms needed)/(threshing kilogram per hour)	*4500*	*15000*	*22000*	*35000*
PAR threshing =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of threshing in Megajoules per year *(threshing work hours)x(PAR of threshing)x(BMR)*	***9300***	***31000***	***45000***	***72000***
Threshing work hours per person per year- 100% of population working (total work hours)/(100% population)	4.5	4.3	4.4	4.4

Energy of threshing in Megajoules per person per year 100% population working *(threshing work hours 100% population working)x(PAR of threshing)x(BMR)*	9.3	8.8	9.1	9.0
Threshing work hours per person per year- 75% of population working (total work hours)/(75% population)	6	6	6	6
Energy of threshing in Megajoules per person per year 75% population working *(threshing work hours 75% population working)x(PAR of threshing)x(BMR)*	*12*	*12*	*12*	*12*
Threshing work hours per person per year- 50% of population working (total work hours)/(50% population)	9	9	9	9
Energy of threshing in Megajoules per person per year 50% population working *(threshing work hours 50% population working)x(PAR of threshing)x(BMR)*	*19*	*18*	*18*	*18*
Threshing work hours per person per year- 25% of population working (total work hours)/(25% population)	18	17	18	18
Energy of threshing in Megajoules per person per year 25% population working *(threshing work hours 25% population working)x(PAR of threshing)x(BMR)*	*37*	*35*	*36*	*36*

9.11.3 Emmer Threshing

Table 91 Threshing Emmer, Two rounds. The table below presents the required energy input of threshing Emmer, according to population. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Threshing Hours total, per year (kilograms needed)/(threshing kilogram per hour)	*8800*	*30000*	*42000*	*68000*
PAR threshing =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of threshing in Megajoules per year *(threshing work hours)x(PAR of threshing)x(BMR)*	***18000***	***62000***	***87000***	***140000***
Threshing work hours per person per year- 100% of population working (total work hours)/(100% population)	8.8	8.6	8.4	8.5
Energy of threshing in Megajoules per person per year 100% population working *(threshing work hours 100% population working)x(PAR of threshing)x(BMR)*	18	18	17	18
Threshing work hours per person per year- 75% of population working (total work hours)/(75% population)	12	11	11	11

Energy of threshing in Megajoules per person per year 75% population working *(threshing work hours 75% population working)x(PAR of threshing)x(BMR)*	*24*	*24*	*23*	*23*
Threshing work hours per person per year- 50% of population working (total work hours)/(50% population)	18	17	17	17
Energy of threshing in Megajoules per person per year 50% population working *(threshing work hours 50% population working)x(PAR of threshing)x(BMR)*	*36*	*35*	*35*	*35*
Threshing work hours per person per year- 25% of population working (total work hours)/(25% population)	35	34	34	34
Energy of threshing in Megajoules per person per year 25% population working *(threshing work hours 25% population working)x(PAR of threshing)x(BMR)*	*73*	*71*	*69*	*70*

9.11.4 Einkorn Threshing

Table 92 Threshing Einkorn, Two rounds. The table below presents the required energy input of threshing Einkorn, according to population. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Threshing Hours total, per year (kilograms needed)/(threshing kilogram per hour)	8200	28000	40000	64000
PAR threshing =	*5.1*			
BMR MJ/hour	*0.40*			
Energy of threshing in Megajoules per year *(threshing work hours)x(PAR of threshing)x(BMR)*	***17000***	***58000***	***82000***	***130000***
Threshing work hours per person per year- 100% of population working (total work hours)/(100% population)	8.2	8.0	8.0	8.0
Energy of threshing in Megajoules per person per year 100% population working *(threshing work hours 100% population working)x(PAR of threshing)x(BMR)*	17	16	16	16
Threshing work hours per person per year- 75% of population working (total work hours)/(75% population)	11	11	11	11
Energy of threshing in Megajoules per person per year 75% population working *(threshing work hours 75% population working)x(PAR of threshing)x(BMR)*	*23*	*22*	*22*	*22*
Threshing work hours per person per year- 50% of population working (total work hours)/(50% population)	16	16	16	16

Energy of threshing in Megajoules per person per year 50% population working *(threshing work hours 50% population working)x(PAR of threshing)x(BMR)*	*34*	*33*	*33*	*33*
Threshing work hours per person per year- 25% of population working (total work hours)/(25% population)	33	32	32	32
Energy of threshing in Megajoules per person per year 25% population working *(threshing work hours 25% population working)x(PAR of threshing)x(BMR)*	*68*	*66*	*66*	*66*

9.12 WINNOWING

For this analysis, it is assumed that harvesting is successful, no matter yield. Thus, winnowing depends upon *amount of cereals* rather than crop yield.

9.12.1 Barley Winnowing Energy

Table 93 Barley Winnowing, first round. The table below presents the required energy input of winnowing Barley, according to population. All cereals are winnowed in this first round, regardless of if they are used for storage. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*1300*	*4200*	*6000*	*9800*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1400***	***4600***	***6600***	***11000***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1.3	1.2	1.2	1.2
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.4	1.3	1.3	1.4
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1.7	1.6	1.6	1.6
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.9*	*1.8*	*1.8*	*1.8*

Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	2.6	2.4	2.4	2.5
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.9*	*2.6*	*2.6*	*2.7*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	5.2	4.8	4.8	4.9
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*5.7*	*5.3*	*5.3*	*5.4*

Table 94 Barley Winnowing, second round. The table below presents the required energy input of winnowing Barley, according to population. The second round does not include cereals used in storage (see chapter 6 for more details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*1100*	*3700*	*5300*	*8600*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1200***	***4100***	***5800***	***9500***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1.1	1.1	1.1	1.1
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.2	1.2	1.2	1.2
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1.5	1.4	1.4	1.4
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.6*	*1.6*	*1.6*	*1.6*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	2.2	2.1	2.1	2.2

Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.4*	*2.3*	*2.3*	*2.4*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	4.4	4.2	4.2	4.3
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*4.9*	*4.7*	*4.7*	*4.7*

9.12.2 Free-Threshing Wheat Winnowing Energy

Table 95 Winnowing of Free-Threshing Wheat, one round. The table below presents the required energy input of winnowing Free-Threshing Wheat, according to population. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*1800*	*6000*	*8500*	*14000*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***2000***	***6600***	***9400***	***15000***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1.8	1.7	1.7	1.8
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	2.0	1.9	1.9	1.9
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	2.4	2.3	2.3	2.3
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*2.6*	*2.5*	*2.5*	*2.6*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	3.6	3.4	3.4	3.5
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*4.0*	*3.8*	*3.7*	*3.9*

Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	7.2	6.9	6.8	7.0
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*7.9*	*7.6*	*7.5*	*7.7*

9.12.3 Emmer Winnowing Energy

Table 96 Emmer Winnowing, first round. The table below presents the required energy input of winnowing Emmer, according to population. All cereals are winnowed in this first round, regardless of if they are used for storage. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*1100*	*3700*	*5300*	*8400*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1200***	***4100***	***5800***	***9300***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1.1	1.1	1.1	1.1
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.2	1.2	1.2	1.2
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1.5	1.4	1.4	1.4
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.6*	*1.6*	*1.6*	*1.5*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	2.2	2.1	2.1	2.1
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.4*	*2.3*	*2.3*	*2.3*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	4.4	4.2	4.2	4.2
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*4.9*	*4.7*	*4.7*	*4.6*

Table 97 Emmer Winnowing, second round. The table below presents the required energy input of winnowing Emmer, according to population. The second round of winnowing does not include cereals used in storage (see chapter 6 for more details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*970*	*3200*	*4600*	*7400*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1100***	***3500***	***5100***	***8200***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1	1	1	1
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.1	1.0	1.0	1.0
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1	1	1	1
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.4*	*1.3*	*1.4*	*1.4*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	2	2	2	2
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.1*	*2.0*	*2.0*	*2.0*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	4	4	4	4
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*4.3*	*4.0*	*4.1*	*4.1*

9.12.4 Einkorn Winnowing Energy

Table 98 Einkorn Winnowing, first round. The table below presents the required energy input of winnowing Einkorn, according to population. All cereals are winnowed in this first round, regardless of if they are used for storage. Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	1000	3500	4900	8000
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			

Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1100***	***3900***	***5400***	***8800***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	1.0	1.0	1.0	1.0
Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.1	1.1	1.1	1.1
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1.3	1.3	1.3	1.3
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.5*	*1.5*	*1.4*	*1.5*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	2.0	2.0	2.0	2.0
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.2*	*2.2*	*2.2*	*2.2*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	4.0	4.0	3.9	4.0
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*4.4*	*4.4*	*4.3*	*4.4*

Table 99 Einkorn Winnowing, second round. The table below presents the required energy input of winnowing Einkorn, according to population. The second round of winnowing does not include cereals used in storage (see chapter 6 for more details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Winnowing hours total, per year (kilograms needed)/(winnowing kilogram per hour)	*910*	*3100*	*4400*	*7000*
PAR winnowing =	*2.7*			
BMR MJ/hour	*0.40*			
Energy of winnowing in Megajoules per year *(winnowing work hours)x(PAR of winnowing)x(BMR)*	***1000***	***3400***	***4900***	***7700***
Winnowing work hours per person per year- 100% of population working (total work hours)/(100% population)	0.91	0.89	0.88	0.88

Energy of winnowing in Megajoules per person per year 100% population working *(winnowing work hours 100% population working)x(PAR of winnowing)x(BMR)*	1.0	1.0	1.0	1.0
Winnowing work hours per person per year- 75% of population working (total work hours)/(75% population)	1.2	1.2	1.2	1.2
Energy of winnowing in Megajoules per person per year 75% population working *(winnowing work hours 75% population working)x(PAR of winnowing)x(BMR)*	*1.3*	*1.3*	*1.3*	*1.3*
Winnowing work hours per person per year- 50% of population working (total work hours)/(50% population)	1.8	1.8	1.8	1.8
Energy of winnowing in Megajoules per person per year 50% population working *(winnowing work hours 50% population working)x(PAR of winnowing)x(BMR)*	*2.0*	*2.0*	*1.9*	*1.9*
Winnowing work hours per person per year- 25% of population working (total work hours)/(25% population)	3.6	3.5	3.5	3.5
Energy of winnowing in Megajoules per person per year 25% population working *(winnowing work hours 25% population working)x(PAR of winnowing)x(BMR)*	*4.0*	*3.9*	*3.9*	*3.9*

9.13 DEHUSKING- EMMER AND EINKORN

For this analysis, it is assumed that harvesting is successful, no matter yield. Thus, dehusking depends upon *amount of cereals* rather than crop yield. For this analysis, only Emmer and Einkorn are dehusked.

9.13.1 Dehusking Emmer

Table 100 Dehusking Emmer The table below presents the required energy input of dehusking Emmer, according to population. Dehusking does not include the cereals used in storage, and, dehusking rate is based on the average rate of emmer dehusking described in chapter 6 (see chapter 6 for more details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Dehusking Hours total, per year (kilograms needed)/(dehusking emmer kilogram per hour)	25000	83000	120000	190000
PAR Dehusking =	*5.4*			
BMR MJ/hour	*0.40*			
Energy of dehusking in Megajoules per year *(dehusking work hours)x(PAR of dehusking)x(BMR)*	***54000***	***180000***	***260000***	***410000***
Dehusking work hours per person per year- 100% of population working (total work hours)/(100% population)	25	24	24	24

Energy of dehusking in Megajoules per person per year 100% population working *(Dehusking work hours 100% population working)x(PAR of Dehusking)x(BMR)*	54	52	52	52
Dehusking work hours per person per year- 75% of population working (total work hours)/(75% population)	33	32	32	32
Energy of dehusking in Megajoules per person per year 75% population working *(Dehusking work hours 75% population working)x(PAR of Dehusking)x(BMR)*	*73*	*69*	*70*	*69*
Dehusking work hours per person per year- 50% of population working (total work hours)/(50% population)	50	47	48	48
Energy of dehusking in Megajoules per person per year 50% population working *(Dehusking work hours 50% population working)x(PAR of Dehusking)x(BMR)*	*110*	*100*	*100*	*100*
Dehusking work hours per person per year- 25% of population working (total work hours)/(25% population)	100	95	96	95
Energy of dehusking in Megajoules per person per year 25% population working *(Dehusking work hours 25% population working)x(PAR of Dehusking)x(BMR)*	*220*	*210*	*210*	*210*

9.13.2 Dehusking Einkorn

Table 101 Dehusking Einkorn. The table below presents the required energy input of dehusking Einkorn, according to population. Dehusking does not include the cereals used in storage, and dehusking rate is based on the average rate of einkorn dehusking described in chapter 6 (see chapter 6 for more details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Dehusking Hours total, per year (kilograms needed)/(dehusking emmer kilogram per hour)	***32000***	***110000***	***150000***	***240000***
PAR Dehusking =	*5.4*			
BMR MJ/hour	*0.40*			
Energy of dehusking in Megajoules per year *(dehusking work hours)x(PAR of dehusking)x(BMR)*	***70000***	***240000***	***330000***	***520000***
Dehusking work hours per person per year- 100% of population working (total work hours)/(100% population)	32	31	30	30
Energy of dehusking in Megajoules per person per year 100% population working *(Dehusking work hours 100% population working)x(PAR of Dehusking)x(BMR)*	70	68	65	65

Dehusking work hours per person per year- 75% of population working (total work hours)/(75% population)	43	42	40	40
Energy of dehusking in Megajoules per person per year 75% population working *(Dehusking work hours 75% population working)x(PAR of Dehusking)x(BMR)*	*93*	*91*	*87*	*87*
Dehusking work hours per person per year- 50% of population working (total work hours)/(50% population)	64	63	60	60
Energy of dehusking in Megajoules per person per year 50% population working *(Dehusking work hours 50% population working)x(PAR of Dehusking)x(BMR)*	*140*	*140*	*130*	*130*
Dehusking work hours per person per year- 25% of population working (total work hours)/(25% population)	130	130	120	120
Energy of dehusking in Megajoules per person per year 25% population working *(Dehusking work hours 25% population working)x(PAR of Dehusking)x(BMR)*	*280*	*280*	*260*	*260*

9.14 SIEVING

For this analysis, it is assumed that harvesting is successful, no matter yield. Thus, sieving depends upon *amount of cereals* rather than crop yield.

9.14.1 Energy of Sieving Barley

Table 102 Barley Sieving energy. The table below presents the required energy input of sieving Barley, according to population. Barley cereals except for those in storage are sieved thrice (see chapter 6 for details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Sieving hours total, per year (kilograms needed)/(sieving kilogram per hour)	*960*	*3300*	*4500*	*7500*
PAR sieving =	*4.3*			
BMR MJ/hour	*0.40*			
Energy of sieving in Megajoules per year *(sieving work hours)x(PAR of sieving)x(BMR)*	***1600***	***5700***	***7700***	***13000***
Sieving work hours per person per year- 100% of population working (total work hours)/(100% population)	0.96	0.94	0.90	0.94
Energy of sieving in Megajoules per person per year 100% population working *(sieving work hours 100% population working)x(PAR of sieving)x(BMR)*	1.6	1.6	1.5	1.6

Sieving work hours per person per year- 75% of population working (total work hours)/(75% population)	1.3	1.3	1.2	1.3
Energy of sieving in Megajoules per person per year 75% population working *(sieving work hours 75% population working)x(PAR of sieving)x(BMR)*	*2.2*	*2.2*	*2.1*	*2.1*
Sieving work hours per person per year- 50% of population working (total work hours)/(50% population)	1.9	1.9	1.8	1.9
Energy of sieving in Megajoules per person per year 50% population working *(sieving work hours 50% population working)x(PAR of sieving)x(BMR)*	*3.3*	*3.2*	*3.1*	*3.2*
Sieving work hours per person per year- 25% of population working (total work hours)/(25% population)	3.8	3.8	3.6	3.8
Energy of sieving in Megajoules per person per year 25% population working *(sieving work hours 25% population working)x(PAR of sieving)x(BMR)*	*6.6*	*6.5*	*6.2*	*6.4*

9.14.2 Energy of Sieving Free-Threshing Wheat

Table 103 Free-Threshing Wheat Sieving energy. The table below presents the required energy input of sieving Free-Threshing Wheat, according to population. All free-threshing wheat is sieved twice (see chapter 6 for details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Sieving hours total, per year (kilograms needed)/(sieving kilogram per hour)	800	2800	3800	6200
PAR sieving =	*4.3*			
BMR MJ/hour	*0.40*			
Energy of sieving in Megajoules per year *(sieving work hours)x(PAR of sieving)x(BMR)*	***1400***	***4800***	***6500***	***11000***
Sieving work hours per person per year- 100% of population working (total work hours)/(100% population)	0.80	0.80	0.76	0.78
Energy of sieving in Megajoules per person per year 100% population working *(sieving work hours 100% population working)x(PAR of sieving)x(BMR)*	1.4	1.4	1.3	1.3
Sieving work hours per person per year- 75% of population working (total work hours)/(75% population)	1.1	1.1	1.0	1.0

Energy of sieving in Megajoules per person per year 75% population working *(sieving work hours 75% population working)x(PAR of sieving)x(BMR)*	*1.9*	*1.8*	*1.7*	*1.8*
Sieving work hours per person per year- 50% of population working (total work hours)/(50% population)	1.6	1.6	1.5	1.6
Energy of sieving in Megajoules per person per year 50% population working *(sieving work hours 50% population working)x(PAR of sieving)x(BMR)*	*2.8*	*2.8*	*2.6*	*2.7*
Sieving work hours per person per year- 25% of population working (total work hours)/(25% population)	3.3	3.2	3.0	3.1
Energy of sieving in Megajoules per person per year 25% population working *(sieving work hours 25% population working)x(PAR of sieving)x(BMR)*	*5.6*	*5.5*	*5.2*	*5.3*

9.14.3 Energy of Sieving Emmer

Table 104 Emmer Sieving Energy. The table below presents the required energy input of sieving Emmer, according to population. Emmer cereals except for those in storage are sieved thrice (see chapter 6 for details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Sieving hours total, per year (kilograms needed)/(sieving kilogram per hour)	1100	3600	5100	8100
PAR sieving =	*4.3*			
BMR MJ/hour	*0.40*			
Energy of sieving in Megajoules per year *(sieving work hours)x(PAR of sieving)x(BMR)*	***1900***	***6200***	***8800***	***14000***
Sieving work hours per person per year- 100% of population working (total work hours)/(100% population)	1.1	1.0	1.0	1.0
Energy of sieving in Megajoules per person per year 100% population working *(sieving work hours 100% population working)x(PAR of sieving)x(BMR)*	1.9	1.8	1.8	1.7
Sieving work hours per person per year- 75% of population working (total work hours)/(75% population)	1.5	1.4	1.4	1.4
Energy of sieving in Megajoules per person per year 75% population working *(sieving work hours 75% population working)x(PAR of sieving)x(BMR)*	*2.5*	*2.4*	*2.3*	*2.3*
Sieving work hours per person per year- 50% of population working (total work hours)/(50% population)	2.2	2.1	2.0	2.0
Energy of sieving in Megajoules per person per year 50% population working	*3.8*	*3.5*	*3.5*	*3.5*

(sieving work hours 50% population working)x(PAR of sieving)x(BMR)				
Sieving work hours per person per year- 25% of population working (total work hours)/(25% population)	4.4	4.1	4.1	4.1
Energy of sieving in Megajoules per person per year 25% population working *(sieving work hours 25% population working)x(PAR of sieving)x(BMR)*	*7.6*	*7.1*	*7.0*	*7.0*

9.14.4 Energy of Sieving Einkorn

Table 105 Einkorn Sieving Energy. The table below presents the required energy input of sieving Einkorn, according to population. Einkorn cereals except for those in storage are sieved thrice (see chapter 6 for details). Extra calculations include Megajoules per person per year for those completing agricultural work, depending on if 100%, 75%, 50%, and 25% of the population were working.

Population	1000	3500	5000	8000
Sieving hours total, per year (kilograms needed)/(sieving kilogram per hour)	*1000*	*3300*	*4800*	*7500*
PAR sieving =	*4.3*			
BMR MJ/hour	*0.40*			
Energy of sieving in Megajoules per year *(sieving work hours)x(PAR of sieving)x(BMR)*	***1700***	***5700***	***8300***	***13000***
Sieving work hours per person per year- 100% of population working (total work hours)/(100% population)	1.0	0.9	1.0	0.9
Energy of sieving in Megajoules per person per year 100% population working *(sieving work hours 100% population working)x(PAR of sieving)x(BMR)*	1.7	1.6	1.7	1.6
Sieving work hours per person per year- 75% of population working (total work hours)/(75% population)	1.3	1.3	1.3	1.3
Energy of sieving in Megajoules per person per year 75% population working *(sieving work hours 75% population working)x(PAR of sieving)x(BMR)*	*2.3*	*2.2*	*2.2*	*2.2*
Sieving work hours per person per year- 50% of population working (total work hours)/(50% population)	2.0	1.9	1.9	1.9
Energy of sieving in Megajoules per person per year 50% population working *(sieving work hours 50% population working)x(PAR of sieving)x(BMR)*	*3.4*	*3.2*	*3.3*	*3.2*
Sieving work hours per person per year- 25% of population working (total work hours)/(25% population)	4.0	3.8	3.8	3.8

Energy of sieving in Megajoules per person per year 25% population working *(sieving work hours 25% population working)x(PAR of sieving)x(BMR)*	*6.9*	*6.5*	*6.6*	*6.5*

9.15 COMBINED DATA: VARIOUS YIELD SCENARIOS

The sections within this appendix chapter focus on the combined energy inputs presented throughout this thesis (the data presented throughout chapters 5 and 6). The data within this appendix chapter was used for calculations throughout Chapter 7.

9.15.1 Low Yield Data, Amalgamated

Table 106: High Yield Crop Yield Data, Combined. All values in Megajoules per year.

Process	1000	3500	5000	8000	Note
Total Final Energy Consumption (Total Output)	2600000	8800000	12000000	20000000	
Land Clearance Energy	684000	1600000	950000	2000000	
Tillage (1)	384000	1280000	1830000	3020000	tillage once
Tillage (2)	384000	1280000	1830000	3020000	tillage once
Tillage (3)	384000	1280000	1830000	3020000	tillage once
Tillage total (3x)	1200000	3800000	5500000	9100000	tillage total, thrice
Planting Energy	210000	690000	1010000	1600000	average of 5:1 planting ratio (broadcast) and 10:1 ratio dibbiling/sowing
Energy of Harvesting Barley	94000	320000	460000	740000	
Energy of Harvesting Emmer	47000	160000	240000	370000	
Energy of Harvesting Einkorn	49000	160000	240000	370000	
Energy of Harvesting Free-Threshing Wheat	88000	290000	400000	640000	
Total Harvesting Energy	280000	930000	1300000	2120000	
Crop loss	440000	1500000	2100000	3300000	
Energy of Threshing Barley	16000	54000	78000	130000	Threshing: Barley x2
Energy of Threshing Emmer	18000	62000	87000	140000	Threshing Emmer x2
Energy of Threshing Einkorn	17000	58000	82000	130000	Threshing Einkorn x2
Energy of Threshing Free-Threshing Wheat	9300	31000	45000	72000	Threshing Free-Threshing Wheat x1

Total Threshing Energy	60000	210000	290000	470000	Threshing Total: Emmer 2x, Einkorn 2x, Barley 2x, Free-Threshing Wheat 1x
Energy of Winnowing Barley	2600	8700	12000	21000	Winnow 2 times each-- about the average
Energy of Winnowing Emmer	2300	7600	11000	18000	Winnow 2 times each-- about the average
Energy of Winnowing Einkorn	2100	7300	10000	17000	Winnow 2 times each-- about the average
Energy of Winnowing Free-Threshing Wheat	2000	6600	9400	15000	Winnow 1 time
Total Winnowing Energy	9000	30000	42000	71000	
Energy of Dehusking Emmer	54000	180000	260000	410000	all emmer dehusked (excluding 2nd round seed for next year)
Energy of Dehusking Einkorn	70000	240000	330000	520000	all einkorn dehusked (excluding 2nd round seed for next year)
Total Dehusking Energy	120000	420000	590000	930000	
Storage loss	220000	740000	1000000	1700000	
Dehusking loss	440000	1500000	2100000	3300000	
Energy of Sieving Barley	1600	5700	7700	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Emmer	1900	6200	8800	14000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Einkorn	1700	5700	8400	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Free-threshing Wheat	1400	4800	6500	11000	coarse sieved 1, fine sieved 1
Total Sieving Energy	6600	22000	31000	51000	
Seed for Planting	410000	1400000	1900000	3100000	
Total input	2600000	7700000	9700000	16000000	
Total loss	1100000	3700000	5200000	8300000	

9.15.2 Average Yield Data, Amalgamated

Table 107: Average Yield Crop Yield Data, Combined. All values in Megajoules per year.

Process	1000	3500	5000	8000	Note
Total Final Energy Consumption (Total Output)	2500000	8600000	12000000	20000000	
Land Clearance Energy	380000	950000	570000	1100000	
Tillage (1)	217000	760000	1090000	1740000	tillage once
Tillage (2)	217000	760000	1090000	1740000	tillage once
Tillage (3)	217000	760000	1090000	1740000	tillage once
Tillage total (3x)	650000	2300000	3300000	5200000	tillage total, thrice
Planting Energy	130000	460000	640000	1000000	average of 5:1 planting ratio (broadcast) and 10:1 ratio dibbiling/sowing
Energy of Harvesting Barley	36000	130000	180000	290000	
Energy of Harvesting Emmer	37000	130000	190000	300000	
Energy of Harvesting Einkorn	39000	140000	190000	310000	
Energy of Harvesting Free-Threshing Wheat	53000	190000	260000	420000	
Total Harvesting Energy	170000	590000	820000	1300000	
Crop loss	410000	1400000	2100000	3300000	
Energy of Threshing Barley	16000	54000	78000	130000	Threshing: Barley x2
Energy of Threshing Emmer	18000	62000	87000	140000	Threshing Emmer x2
Energy of Threshing Einkorn	17000	58000	82000	130000	Threshing Einkorn x2
Energy of Threshing Free-Threshing Wheat	9300	31000	45000	72000	Threshing Free-Threshing Wheat x1
Total Threshing Energy	60000	210000	290000	470000	Threshing (2x emmer, 2x einkorn, 2x barley,1x wheat)
Energy of Winnowing Barley	2600	8700	12000	21000	Winnow 2 times each-- about the average

Energy of Winnowing Emmer	2300	7600	11000	18000	Winnow 2 times each-- about the average
Energy of Winnowing Einkorn	2100	7300	10000	17000	Winnow 2 times each-- about the average
Energy of Winnowing Free-Threshing Wheat	2000	6600	9400	15000	Winnow 1 time
Total Winnowing Energy	9000	30000	42000	71000	
Energy of Dehusking Emmer	54000	180000	260000	410000	all emmer dehusked (excluding 2nd round seed for next year)
Energy of Dehusking Einkorn	70000	240000	330000	520000	all einkorn dehusked (excluding 2nd round seed for next year)
Total Dehusking Energy	120000	420000	590000	930000	
Storage loss	210000	720000	1000000	1600000	
Dehusking loss	410000	1400000	2100000	3300000	
Energy of Sieving Barley	1600	5700	7700	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Emmer	1900	6200	8800	14000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Einkorn	1700	5700	8400	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Free-threshing Wheat	1400	4800	6500	11000	coarse sieved 1, fine sieved 1
Total Sieving Energy	6600	22000	31000	51000	
Seed for Planting	390000	1400000	1900000	3100000	
Total input	1600000	4900000	6300000	11000000	
Total loss	1100000	3700000	5200000	8300000	

9.15.3 High Yield Data, Amalgamated

Table 108: High Yield Crop Yield Data, Combined. All values in Megajoules per year.

Process	1000	3500	5000	8000	Note
Total Final Energy Consumption (Total Output)	2500000	8600000	12000000	20000000	
Land Clearance Energy	290000	730000	430000	860000	
Land Clearance Energy	164000	570000	820000	1310000	tillage once
Tillage (1)	164000	570000	820000	1310000	tillage once
Tillage (2)	164000	570000	820000	1310000	tillage once
Tillage (3)	490000	1700000	2500000	3900000	tillage total, thrice
Planting Energy	89000	320000	450000	850000	average of 5:1 planting ratio (broadcast) and 10:1 ratio dibbiling/sowing
Energy of Harvesting Barley	22000	78000	110000	180000	
Energy of Harvesting Emmer	32000	110000	160000	250000	
Energy of Harvesting Einkorn	33000	120000	170000	270000	
Energy of Harvesting Free-Threshing Wheat	39000	140000	200000	310000	
Total Harvesting Energy	130000.0	450000.0	640000.0	1000000.0	
Crop loss	410000	1400000	2100000	3300000	
Energy of Threshing Barley	16000	54000	78000	130000	Threshing: Barley x2
Energy of Threshing Emmer	18000	62000	87000	140000	Threshing Emmer x2
Energy of Threshing Einkorn	17000	58000	82000	130000	Threshing Einkorn x2
Energy of Threshing Free-Threshing Wheat	9300	31000	45000	72000	Threshing Free-Threshing Wheat x1
Total Threshing Energy	60000	210000	290000	470000	Threshing (2x emmer, 2x einkorn, 2x barley,1x wheat)
Energy of Winnowing Barley	2600	8700	12000	21000	Winnow 2 times each-- about the average

Energy of Winnowing Emmer	2300	7600	11000	18000	Winnow 2 times each-- about the average
Energy of Winnowing Einkorn	2100	7300	10000	17000	Winnow 2 times each-- about the average
Energy of Winnowing Free-Threshing Wheat	2000	6600	9400	15000	Winnow 1 time
Total Winnowing Energy	9000	30000	42000	71000	
Energy of Dehusking Emmer	54000	180000	260000	410000	all emmer dehusked (excluding 2nd round seed for next year)
Energy of Dehusking Einkorn	70000	240000	330000	520000	all einkorn dehusked (excluding 2nd round seed for next year)
Total Dehusking Energy	120000	420000	590000	930000	
Storage loss	210000	720000	1000000	1600000	
Dehusking loss	410000	1400000	2100000	3300000	
Energy of Sieving Barley	1600	5700	7700	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Emmer	1900	6200	8800	14000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Einkorn	1700	5700	8400	13000	coarse sieved 2 times, fine sieved 1
Energy of Sieving Free-threshing Wheat	1400	4800	6500	11000	coarse sieved 1, fine sieved 1
Total Sieving Energy	6600	22000	31000	51000	
Seed to planting	390000	1400000	1900000	3100000	
Total input	1200000	4000000	4900000	8300000	
Total loss	1100000	3700000	5200000	8300000	

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