Assessing the potential of no-tillage farming across contrasting European soils

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Abstract

This interdisciplinary thesis explored no-tillage adoption and its impacts on soils. In no-tillage farming, seeding is performed directly into the soil, causing minimal disturbance and representing an alternative to conventional tillage in which seedbeds are prepared with various field operations.

The analytical approach was based on Actor-Network Theory, understanding adoption as a negotiated outcome of interconnected human and non-human actors. Their interaction co-created their multiple roles and knowledges. The assemblage of actor-networks was informed by semi-structured interviews with conventional and no-tillage neighbours from Spain and the UK. Results showed the multiplicity of no-tillage as a tool, technological package and system. Moreover, adoption to reduce production costs linked to meteorological risks and financial sustainability, and was changing the role of yield as a symbol of good farming. Environmental paths driving or constraining adoption connected farmers' land stewardship with soils' and herbicides' roles. Furthermore, farmers' innovative roles and their bonds with global farming communities supported the long-term adoption of no-tillage.

The assessment of no-tillage impact on soils considered soils' multiplicity. First, soils' multiple roles in farming were described from interviews' data. According to those roles, farmers assed their management positively, whether it was through enacting soils as natural entities to be tamed using the right tool after analysing field conditions, by applying a technological package based on conservation agriculture principles or by enhancing soils life and self-organising capabilities. Second, soil structure and compaction were assessed scientifically with on-farm tests and laboratory analysis. Results showed that tillage management had a lower influence on soil structure than other soil properties. Nonetheless, on comparable soils, no-tillage presented similar or better structure but also similar or higher compaction. Finally, it is argued that soil science should engage with the different actor-networks that enact soils to enrich the understanding of soils' multiplicity.

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Declaration

I, Jennifer Lidia Veenstra, confirm that the thesis is my own work, except where work that has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. I am aware of the University's Guidance on the Use of Unfair Means (*www.sheffield.ac.uk/ssid/unfair-means*). This work has not been presented for an award at this, or any other, university.

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I, Jennifer Lidia Veenstra, planned and wrote the manuscript; co-authors reviewed and provided comments on the manuscript.

Table of contents

List of figures

List of tables

Chapter 1.
Introduction

Figure 1. Chapter 1 cover photo: sunset during fieldwork at a no-tillage field in East of England

1.1. Soils and tillage management: an introduction to why they matter

Global agriculture is facing the challenges of growing enough food to feed a growing population with more calorie demanding diets, doing this under a changing climate while reducing the environmental impacts. Indeed, the global population is predicted to reach 9.1 billion in 2050, which requires a 70 % increase in food production (FAO, 2009). Furthermore, the effects of climate change on crop production are already evident in many regions (Porter *et al.*, 2014), particularly because they are affecting already degraded soils (Kassam, Friedrich & Derpsch, 2019). These challenges urgently demand sustainable approaches to farming, considering not only yield and productivity but also environmental and social welfare.

About 10,000 years ago, settled farming civilisations started developing tools to place and cover seeds in the soil (Lal, Reicosky & Hanson, 2007). Similar developments leading to the plough occurred around the globe (Lal, Reicosky & Hanson, 2007). At the beginning of the 20th century, technological advances on tractors and the mechanisation of agriculture fostered the spread of cast iron ploughs (Olmstead & Rhode, 2001; Lal, Reicosky & Hanson, 2007). This way, tillage had become the 'conventional' practice.

Conventional agriculture uses tillage to prepare soils for seeding, which has been effective in producing high yields. Arguments for ploughing the soils are based on the reduction of weeds and on obtaining a uniform and smooth bed for root growth and plant development (Hobbs, Sayre & Gupta, 2008). Specifically, conventional tillage loosens topsoil, ensuring a good seed-soil contact that improves crop establishment. Additionally, it mixes fertilisers and manures to ensure they are homogeneously distributed. Furthermore, it mechanically tears weeds and buries weed seeds in deeper layers allowing crops to grow without competition in the early stages (Hobbs, Sayre & Gupta, 2008). It also incorporates crop residues increasing soil organic matter throughout the ploughed depth. Moreover, it aerates soils, leading to the decomposition of organic matter, and in doing so, it releases nutrients (Hobbs, Sayre & Gupta, 2008). Aeration can also be used to control moisture for optimum seeding conditions. Besides these benefits, crops easily develop a deep root system without mechanical resistances and have so diverted more energy into yield production. In that sense, modern cultivars have been developed and are adapted to conventional tillage soil preparation conditions. Thus, in farms where conventional tillage is applied, soils require seedbed preparation to achieve optimal conditions for farming.

However, physical disturbance of the soil generates many environmental problems. Indeed, it has negative impacts on biodiversity, oxidises organic matter and destroys soil structure (Holland, 2004; Hobbs, Sayre & Gupta, 2008). Those processes lead to erosion, compaction and the reduction in water infiltration, and water retention (Holland, 2004; Hobbs, Sayre & Gupta, 2008) and gaseous exchange (Holland, 2004). Furthermore, these processes have far-reaching consequences such as increasing water pollution, flooding and greenhouse gas concentrations (Holland, 2004). These problems are not only ecological, but they also affect the economy and society because they affect ecosystem services provided by nature (Kassam, Friedrich & Derpsch, 2019). A classic example is the catastrophic soil erosion event known as the 'Dust Bowl' in the USA in the 1930s, which was a result of the combination of years of drought and the expansion of tillage in the Great Plains. There, the loss of fertile soil caused important migratory movements. After that catastrophe, former USA president F. D. Roosevelt stated, 'a nation that destroys its soil destroys itself', and the concern about soil conservation begun.

Conservation agriculture develops this target on soil conservation and offers alternatives to conventional tillage. Conservation agriculture is a family of practices that combine any soil cover (cover crops, mulching, etc.), crop diversification (growing different species in the same field at the same time or consecutively) and the reduction of soil disturbance (Kassam, Friedrich & Derpsch, 2019). This last is achieved by reducing the depth of the plough, associating tillage to only one crop within a rotational system, ploughing in rows or switching to no-tillage (also known as no-till, zero tillage, direct drilling or direct seeding). In no-tillage farming, 'crops are sown without any prior loosening of the soil by cultivation other than the very shallow disturbance (<5 cm) which may arise by the passage of the drill coulters and after which usually 30-100 % of the surface remains covered with plant residues' (Soane et al. 2012, p. 66). No-tillage is the most extreme alternative to conventional tillage and aims to solve its environmental problems through the development of soil structure and protection of soil biota and soil surface while not compromising yields.

Despite its claimed environmental benefits, the spread of no-tillage in the world is geographically uneven. In the USA, no-tillage has been adopted in 25.5 % of its arable land (Derpsch *et al.*, 2010), while in Europe, the percentage was only 3 % in 2010 (EUROSTAT, 2010) and increased to 3.7 % in 2016 (EUROSTAT, 2016). In Europe, conventional tillage was used in 66.83 % of the arable land, and other conservation tillage practices in 19.53 % (EUROSTAT, 2016). Figure 2 shows no-tillage adoption rates in 2013, by sub-national level (data from 2020 agricultural census will be available in 2022). Here, it can be seen that there was no clear geographical pattern for no-tillage adoption. Despite the need to adapt practices to local agro-environmental conditions, the different adoption rates in countries located at the same latitudes (where similar climatological conditions are expected) suggest the need to study no-tillage adoption, including other factors than the agro-environmental. These kinds of studies about the adoption of conservation agriculture, taking into account socio-cultural and economic influences, have been conducted mainly in the USA or in the developing countries, identifying factors as diverse as farmers' age, education level, gross income, land ownership, farm size, management scale, cropping system, erosion rates and soil characteristics (Wauters *et al.*, 2010).

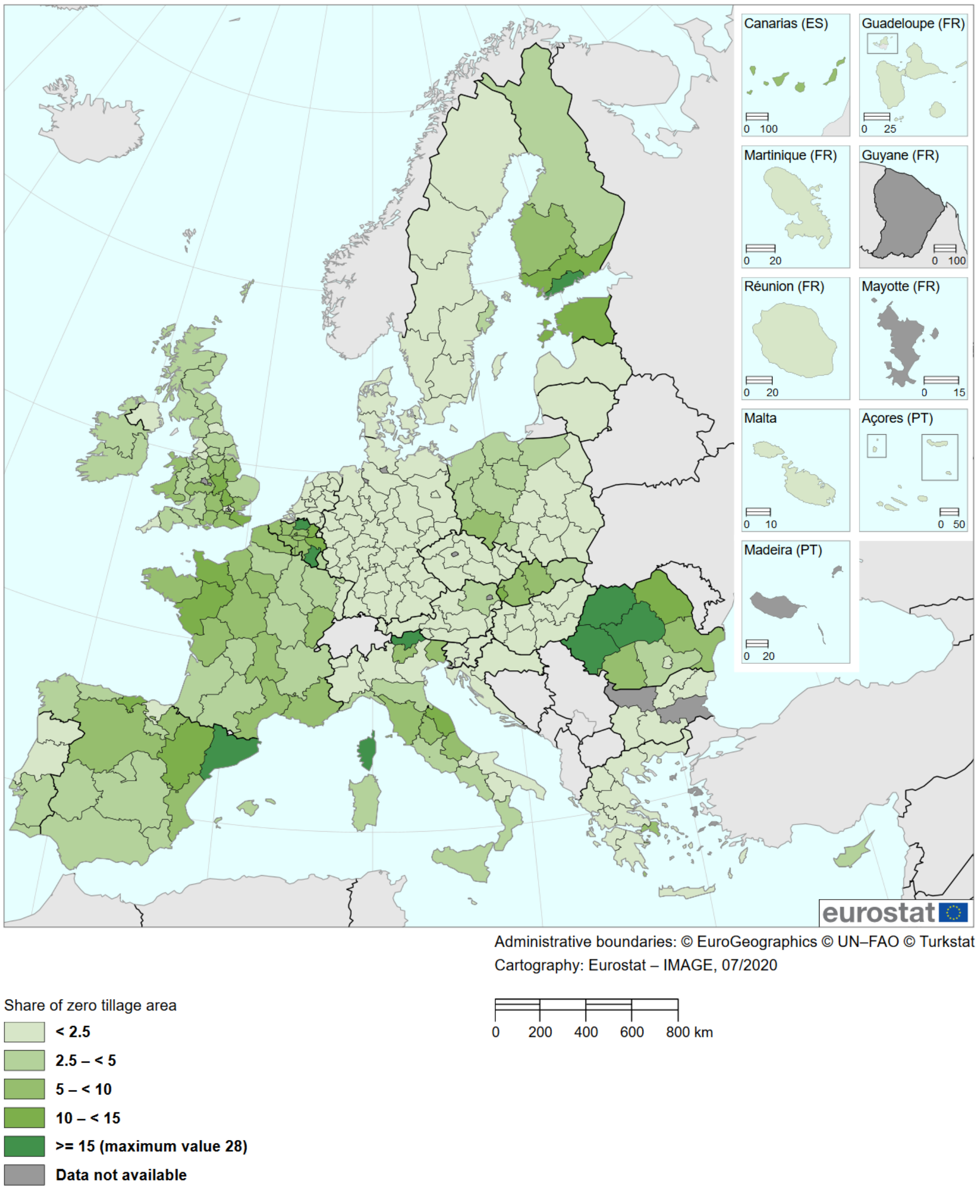


Figure 2. No-tillage share of arable land in Europe. Source EUROSTAT, data from 2013

1.2. Tillage management adoption and soils

This PhD project assessed the potential of no-tillage adoption in Europe, taking an interdisciplinary and Actor-Network Theory (ANT) approach to identify which socio-environmental actors drove and constrained adoption across different regions. Additionally, it assessed the impact of conventional and no-tillage on soil quality according to farmers' and scientific criteria. Thus, this PhD project contributes to understanding the no-tillage potential in Spain and the UK.

1.2.1. Research questions

- Which are the drivers and constraints of no-tillage adoption?
- How does no-tillage impact soil quality?

These research questions continued to be shaped in the following two chapters, in which I discuss in detail the current understanding of the topics, the chosen overarching approach and the available methods.

1.3. Thesis structure

In this section, I explain the structure of the remaining chapters of the thesis. The rationale behind the structure is to present the thesis as a whole, as an interdisciplinary work. Therefore, the literature review and the methodology, despite presenting detailed disciplinary theoretical and methodological information, cover both research questions (adoption of tillage management practice and impact on soils' physical quality). The empirical chapters are divided into disciplinary fields (human and physical geography), although they are interconnected. These chapters proceed from the broader understanding of the many actors (and their relations) involved in farming and tillage management to the detailed investigation of the relationships between farmers and soils. This, in turn, informs farmers' assessment of tillage management impact on soils and the agency of soils influencing farmers' practice. In addition, the thesis presents the soil scientific assessment of no-tillage impacts on soil physical quality. These three chapters are brought together in the concluding discussion and remarks. In more detail:

Chapter 2 is the literature review in which I provide the current understanding of no-tillage adoption and impact on soils, the theoretical approaches to study these topics and how these frame my research questions. First, I present the identified drivers and constraints of no-tillage adoption and tillage management impact on soil properties. Additionally, I discuss the various approaches to study the adoption of innovations and why I decided to use Actor-Network Theory (ANT). Basically, due to acknowledging farmers' and soils' active roles in social change and co-creation of innovation, which is the first step to study these roles. Further, I deepen into the literature about ANT principles that are the foundation for the interdisciplinary task of this project, and I discuss how I understand them. Then, I come back to soils and their importance in food production. Particularly in relation to soil quality, I am focusing on soil structure and introducing the problem of soil compaction.

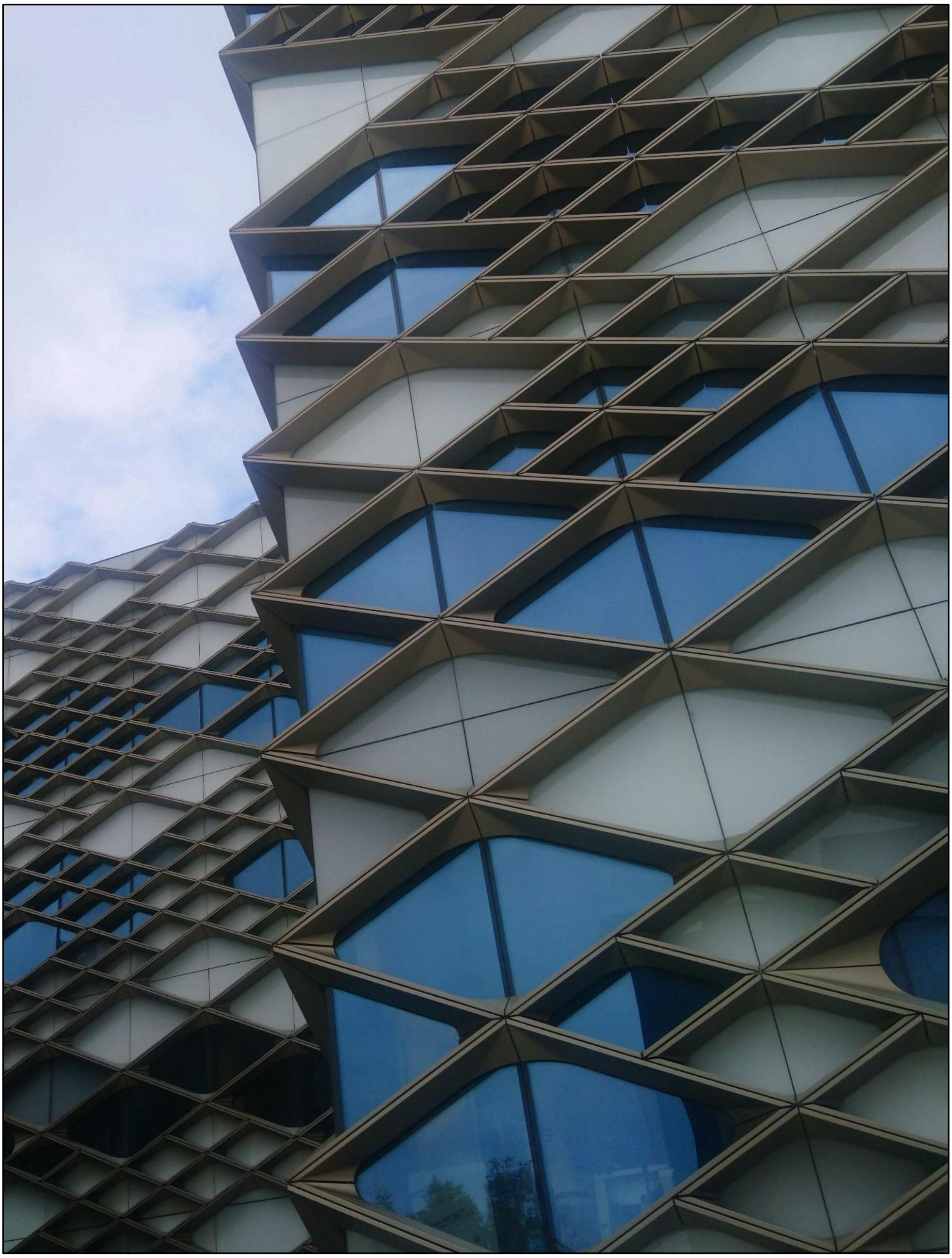
Chapter 3 is the methodology, in which I explain how empirical data informing the findings of this study is produced and analysed, discussing methods' usefulness, bias and limitations. I do this from the overarching approach of ANT to the details of semi-structured interviews with farmers and on-farm and laboratory tests and how these were analysed through thematic coding and statistics. To further frame the research, I discuss my positionality, the local character of the research and the need to conduct on-farm research despite its difficulties.

Chapter 4 addresses the research question about no-tillage adoption drivers and constraints. Following ANT, the analytical approach understands adoption as a negotiated outcome of actor-networks. As these actor-networks were limited and described by farmers, I called them farming actor-networks. Indeed, the configurations of the actors and the relations that constitute the farming actor-networks were informed by the semi-structured interviews with farmers and their analysis. I follow the paths or chains of actors that lead to decisions regarding tillage management in Spain and the UK, and in doing so, I present the relevant actors and the multiple roles they might take, triggering change. Particularly, I focus on farmers, the values and roles that motivate their negotiations, and how multiple roles of no-tillage derive from different configurations of farming actor-networks.

Chapter 5 addresses soils in farming actor-networks. This includes farmers' assessment of the impact of no-tillage on soils and soils' influence on tillage management decisions or the 'soil path' to no-tillage adoption. Following ANT, first, I analyse what soils are in farming actor-networks, what they do and which properties are relevant in farmers' terms. Then, I follow the connections between actors to tillage management outcomes. Results show multiple and sometimes conflicting roles of soils, which differ between no-tillage and conventional tillage more than geographically.

Chapter 6 addresses the question of no-tillage impact on soil physical properties through the scientific assessment. These results stem from the analysis of the on-farm and laboratory tests determining soil structure parameters and soil compaction at fields of neighbour no-tillage and conventional tillage farmers in Spain and the UK. I situate this analysis in the real world by assessing the importance of no-tillage between other aggregation and disaggregation agents. However, I encountered difficulties related to the on-farm nature of the research, namely the differences in soil properties that hindered comparisons between pairs of neighbours, isolating management as the major explanatory agent. After overcoming these by regrouping soils according to their properties, where possible, I assess the impact of no-tillage on physical soil quality compared with conventional tillage. Results show that in some cases, practices have a similar impact, but when significant differences appear, these are an increase in structural quality but, at the same time, an increase in compaction with no-tillage.

Chapter 7 is the conclusion chapter. I briefly discuss the main findings of chapters 4, 5 and 6 and their implications for farming and science. I discuss methodological limitations but also opportunities from acknowledging farmers' and soils' active roles in social change and innovation co-creation. In such a messy world, I come back to the definition of soils as multiple, and I conclude my work with a reflection on the role of soil science in the future.



Chapter 2.
Literature review

Figure 3. Chapter 2 cover photo: detail from the Diamond building, holds part of UoS library collection

2.1. Introduction to the literature review

In this chapter, I provide an overview of the research topic, the coexisting theoretical approaches and a justification for my choice.

In the previous chapter, I discussed that besides potential environmental benefits, the adoption of no-tillage in Europe is low. Moreover, tillage is considered the conventional practice and no-tillage an innovation. From there, I start this chapter by reviewing the identified factors that act as barriers or drivers for no-tillage adoption as an innovation.

However, I move away from linear models of innovation diffusion. The reasons were the need to acknowledge farmers' active roles in the creation of innovations, as well as the participation of agro-environmental non-human actors. These reasons led me to Actor-Network Theory (ANT), whose relevant properties I review in-depth as they constitute the overall approach for this interdisciplinary research and inform my methodology.

I continue by highlighting the importance of soils, as I have already in the introduction, particularly in food production and how it is threatened by increasing intensification demands. Between the different soil properties, I choose to focus on soil physical quality. Therefore, I provide background of soil structure, aggregation and disaggregation processes and the agents that influence these processes, including tillage management and highlighting geographical variability. Moreover, I introduce the problem of soil compaction and how it relates to soil structure.

I finish the chapter by summarising the literature review in key messages, research gaps and existing debates, which lead to the research questions that this project aims to fulfil or add a contribution.

2.2. No-tillage spread across ploughed land: drivers and constraints in Europe

This section summarises how different agro-environmental, socio-cultural and economic factors have influenced the spread of no-tillage across Europe and which are the current interests in no-tillage research.

No-tillage existed since ancient times, although in modern agriculture, farmers have led its spread worldwide. Indeed, no-tillage was developed by the indigenous cultures from Central and South America (Derpsch, 1998). However, the development of the modern technology was strongly linked to the concern about soil conservation after the USA's dust bowl in the 1930s (Kassam *et al.*, 2015; Kassam, Friedrich & Derpsch, 2019), which lead to the invention of no-tillage seeding machines and herbicides (1940s-1950s) (Derpsch, 1998). Conservation agriculture spread is considered a farmers led process, that eventually gathered public, private and civil support (Coughenour, 2003; Kassam *et al.*, 2015). The scientific publications of the 1960s and 1970s contributed to the evaluation and certification of the technology, which was transferred by agricultural extension workers. During the 1990s, conservation agriculture caught international organisations' attention (FAO, World Bank, CIRAD, GIZ and CGIAR), who contributed to its worldwide spread (Giller *et al.*, 2009; Kassam *et al.*, 2015; Kassam, Friedrich & Derpsch, 2019).

In Europe, due to relatively stable weather, soil conservation was not a major concern (Basch *et al.*, 2009), and the adoption of conservation practices was not promoted by governments until recently. The spread of no-tillage in Europe was voluntary, farmer-driven and Lahmar (2010) claims that it was because of economic benefits due to fuel and labour savings. Farmers' attitudes and values towards soils and their awareness of degradation due to farming also influence adoption (Camboni & Napier, 1993). However, adoption should not be oversimplified along a dualistic profit-seeking or stewardship divide (Marr & Howley, 2019). Regarding the influence of policies and subsidies, there is no consensus about how the Common Agricultural Policy (CAP) affected conservation practices' adoption. For Basch et al. (2009), it may have influenced negatively in need for innovation to achieve competitive market prices and reduce production costs with alternative practices, as indicates the comparison with higher no-tillage adoption rates in South America. By contrast, Kassam et al. (2015) mention a positive effect of the CAP's subsidies for farmers who adopt Good Agricultural and Environmental Conditions. With a different focus, the constraints of global markets to farmers' production choices (deciding inputs and outputs: seeds, breeds, livestock and grains etc.), drive them to make unethical choices regarding the environmental or social impacts of their industry (Hendrickson & James, 2005; James & Hendrickson, 2008).

Research has exposed the environmental impacts of conventional agriculture and looks into conservation practices as sustainable alternatives. Accordingly, research has shown that erosion rates for tilled land are 3 to 40 times greater than the upper limit for tolerable soil erosion (Verheijen *et al.*, 2009), which is the one that does not compromise any of the soils' functions and is set as equal to soil formation, 1.4 Mg ha^{-1} yr^{-1} (Verheijen *et al.*, 2009). By contrast, minimum-tillage and no-tillage represent a decrease of 75% of erosion compared to conventional tillage (Panagos *et al.*, 2015). Research has also focused on the potential of no-tillage to reduce greenhouse gas (GHG) emissions of agriculture. Indeed, agriculture accounts globally for 15% of the GHG emissions (Pisante *et al.*, 2010). In this sense, tillage is intensive in energy use based on fossil fuels; thus, ploughing consumes 80 $L{\cdot}ha^{-1}$, whereas no-tillage uses 10 L ha^{-1} (Pisante *et al.*, 2010). Fuel consumption should be added to oxidative soil organic matter breakdown through mechanical tillage (Pisante *et al.*, 2010). However, GHG emissions, including CO_2 and N_2O, depend on the synergic effect of different soil properties and management practices that still need research to be completely understood (Soane *et al.*, 2012). However, environmental benefits and the sustainability narrative of no-tillage are starting to be contested due to high herbicide dependency (Müller, 2021).

Additionally, research has compared yield production, which varies due to local conditions and the combination of management practices. Considering global data, no-tillage decreases yields by 5.7 % compared to conventional tillage (Pittelkow *et al.*, 2014), being the crop type the most important factor for performance (Pittelkow *et al.*, 2015). In Europe, in general, on poor and medium fertile soils, yield does not change dramatically, but it slightly decreases on very fertile soils (Lahmar, 2010). In particular conditions, yields can be higher under no-tillage (Lahmar, 2010), and its suitability is highlighted in rainfed fields in dry climates, also increasing climate change adaptation (Pittelkow *et al.*, 2014; Kassam *et al.*, 2012; Kuhn *et al.*, 2016). By contrast, no-tillage struggles in temperate areas when spring is wet and cold (Lal, Reicosky & Hanson, 2007). Nonetheless, changes in yields do not seem to be critical factors for farmers when deciding about conservation agriculture adoption (Lahmar, 2010), and Soane et al. (2012) argue that yield reduction is acceptable if minimisation in production costs is achieved.

Adoption of no-tillage requires a fundamental change in production system thinking (Kassam *et al.*, 2015) which finds different barriers in established agricultural practices. First, the difficulty of disassociating fertility and tillage (Basch *et al.*, 2009). Second, ploughing is seen as a good practice to control agronomic problems such as weeds, pests and diseases. UK's experience with no-tillage highlights the particular constraint of weed control. Despite the UK being a pioneer country adopting no-tillage at the beginnings of its expansion (Lahmar, 2010), restrictions on straw burning forced farmers to return to plough for weed control (Derpsch, 1998; Basch *et al.*, 2009; Alskaf *et al.*, 2020). This experience led to the current scepticism around weed control without ploughing. This scepticism becomes even stronger when considering higher herbicide use with no-tillage practice and the increasing restrictions on herbicide use coming from environmental regulations, pushed by strong environmental lobbies (Basch *et al.*, 2009). Indeed, in general, the spread of no-tillage has been linked to herbicide efficiency, availability and price fluctuations (Coughenour, 2003; Lahmar, 2010) and even nowadays, herbicides are not efficient for all climatic conditions and all crops (Soane *et al.*, 2012). The lack of knowledge about alternative biological control methods can be an additional constraint for wider no-tillage adoption (Lahmar, 2010). Third, residue retention is considered bad practice because crop residues are seen as a setting for pests and disease proliferation. This is accentuated under European conditions, which produce abundant residues (Basch *et al.*, 2009; Powlson *et al.*, 2012). Fourth, changing to rotation systems that include legumes and other broadleaved crops is challenging in many agricultural areas in Europe that focus on cereals and maize (Basch *et al.*, 2009). These changes in production system thinking are complex and involve many actors, namely: there is a lack of manufacturers who build suitable no-tillage machinery for temperate climate; financial support is needed to conduct research about adaptation to local conditions; and how to combat pests and diseases with alternative practices (Basch *et al.*, 2009; Lahmar, 2010; Soane *et al.*, 2012). Accordingly, the spread of no-tillage requires the active involvement of stakeholders, including administrative authorities, political agencies and food and agricultural engineering industries, amongst others (Basch *et al.*, 2009).

Farmers' life circumstances and identities also influence their decision about soil management practices. Korsching et al. (1983) found that younger farmers, owning large farms with higher gross income, hiring more labour, having more complex farm organisations and having greater involvement with knowledge exchange organisations adopted minimum tillage earlier than other farmers in the USA. Farmers' social networks, including agricultural extension workers and the wider farming community, also have a great influence on the generation and spread of innovations (Coughenour, 2003; Prokopy *et al.*, 2008; Dolinska & D'Aquino, 2016; Skaalsveen, Ingram & Urquhart, 2020). Furthermore, under the hypothesis of the capability to exploit long-term benefits, land ownership (Boardman, Poesen & Evans, 2003; Sklenicka *et al.*, 2015) and generational replacement (Marzban, Allahyari & Damalas, 2016; Marr & Howley, 2019) can drive conservation practices adoption. By contrast, poverty makes farmers concentrate on immediate benefits (Boardman, Poesen & Evans, 2003; Giller *et al.*, 2009). Boardman et al. (2003) claim that power and social status are not relevant factors in Europe, although these can be discussed through the reaffirmation of farmers' identity. For example, how farmers see themselves as natural and cultural heritage keepers as presented by Marzban et al. (2016) or Burgess et al. (2000).There is a large diversity of situations resulting from driving forces and constraints, which are different from country to country and cannot be applied globally (Knowler & Bradshaw, 2007; Lahmar, 2010; Bijttebier *et al.*, 2018). Indeed, several meta-analysis have shown inconsistencies in the importance of particular factors, which could be explained not only by the diversity of methods used to study adoption but also due to the importance of geographical variability (see: Knowler & Bradshaw, 2007; Prokopy *et al.*, 2008; Wauters & Mathijs, 2014). It is the objective of this PhD to obtain a comprehensive understanding of how multiple factors interact and lead to no-tillage adoption in the UK and in Spain.

2.3. Theories of adoption of agricultural innovations

In this section, an overview of different adoption theories is presented, as well as a justification of the selected approach.

2.3.1. Linear models of innovation diffusion

Traditionally, linear models of innovation diffusion dominated the adoption theories (Giller *et al.*, 2008).

In innovation diffusion models, a successful technology or management innovation is developed by scientists, transferred by intermediaries such as agricultural extension workers and then adopted by farmers. Early models followed an epidemic dynamic for diffusion; the key factor for adoption was access to information (Adesina, 1993; Dijk, Kemp & Valkering, 2013). In other words, the farmer had to be informed and trained about the best available practice in order to be able to implement it on the farm; if the farmer did not implement the so-called best available practice, it was due to a knowledge gap. Innovation was fostered by social contacts and marketing (Dijk, Kemp & Valkering, 2013). Although some of the epidemic innovation diffusion models included the need to adapt technologies to local agro-environmental conditions, the valuable knowledge producers and so-called experts in these models were the scientists and the agronomists, who educated the farmers. However, inconsistencies in the long term adoption of best available practices promoted by rural development projects and extension programmes based on epidemic innovation diffusion suggested the need to include social constraints in innovation models.

This led to the inclusion of socio-economic factors in the economic constraint models (Adesina, 1993), which dominated in the 1950s (Burton, 2004a). Those models were based on the hypothesis that farmers' decisions would be made to achieve the optimal economic result (Burton, 2004a). Those models are also referred to as the rational choice models or threshold models, meaning that users would adopt an innovation as soon as it became an economic advantage compared to the existing practices (Dijk, Kemp & Valkering, 2013). Those models were sensitive to economic inequalities, which were responsible for uneven access to resources (Adesina, 1993) and so explained inconsistent uptake of the innovation. Nonetheless, these models still did not explain well enough long term adoption.

Gradually farmers' cultural context and personal factors gained relevance during the 1970s (Burton, 2004a; Wauters *et al.*, 2010), and the adopter perception paradigm arose (Adesina, 1993). In these models, acceptance of the proposed practice is acknowledged in order to achieve sustainable adoption (Prager & Posthumus, 2010). Farmers' attitudes, values and norms are assessed through behavioural economics, which takes into account the subjective characteristics of the goods or actions as perceived by the decision-maker (Wossink *et al.*, 1997), namely, the farmer. Several studies in the USA extended the focus from psychological and personal characteristics of the farmer to their perception of social structures, such as national farm structure (Camboni & Napier, 1993), economic pressures and complexity and compatibility of the farming innovations (Smit & Smithers, 1992). In the 'cultural turn', during the 1980s and 1990s, language, meaning, representation, identity, and difference gained importance (Burton, 2004a). But still, in these studies, 'a range of agricultural technologies has been developed and now 'sit on the shelf' awaiting adoption (Wossink *et al.*, 1997:p.410), highlighting a passive role of farmers in agricultural innovation as mere adopters of science-based policy solutions and not participating in the design process of an innovation.

A more dynamic framework was proposed by the evolutionary or non-equilibrium models. Those models included feedback processes from the users to the innovation designers as well as users' learning processes, although the economic focus remained (Dijk, Kemp & Valkering, 2013). Windrum and Birchenhall (2005) used a multiagent model of firms and users in which firms had heterogeneous knowledge. They introduced the "technological shock" as offering a new feature to the existing set of service characteristics which in turn originated a new consumer class. According to Dijk, Kemp and Valkering (2013), the merit of Windrum and Brirchenhall's approach was that they identified a technology as a set of characteristics, which made it a variable multi-faceted, mediating device between evolving consumers and firms. However, the approach lacked an understanding of the social meanings of a technology and imitation of adoption (Dijk, Kemp & Valkering, 2013).

2.3.2. Co-creation of innovation

Two main arguments can be followed towards the increasing relevance of other than technoscientific knowledge in agricultural innovation. The first supports the notion that conservation practices have more complex nature than other innovations and advocates for local participation to adapt the innovations to different geographies (Coughenour, 2003). In these cases, the linear model of innovation diffusion still applies and participation is a tool for greater acceptance of an external innovation (Pretty, 1995). Alternatively, the research focus might be on the diffusion aspect of the external innovation, and how it is transmitted inside farmer communities, once it has been adopted by early adopters. The second argument questions the linearity of innovation diffusion and supports a new paradigm of knowledge co-production.

Both of these trends are based on the notion of collective learning and value local, experiential and traditional knowledges. Participatory models, farmer-to-farmer interactions, Agricultural Innovation

Systems, farmers' social networks and Communities of Practice have been studied and developed to understand and enhance social or collective learning and foster innovation.

Accordingly, participatory models included stakeholders participation in innovation design in order to ensure contextual knowledge, values and perspectives (Giller *et al.*, 2008). Those participatory models arose from the realisation of the necessity to deal with multiple realities in societal problem-solving efforts (Chambers, 1997; Giller *et al.*, 2008), contrasting with the previously dominant positivist paradigm of research (Bruges & Smith, 2008). Consequently, farmers' and locals' passive roles as innovation adopters changed into first a collaborative and then participative role. Indeed, first, the involvement was to collaboratively negotiate the methods to achieve pre-defined goals and then to negotiate the project goals in participatory sessions (Bruges & Smith, 2008). Another consequence was the changing role of the scientists, from objective experts to facilitators (Bruges & Smith, 2008) encouraged to take a side on the less powerful and resourceful locals' (Giller *et al.*, 2008). Still, a range of different typologies of participation developed in directions as opposite as those based on the ethical assumption that participation is a fundamental right leading to collective action, empowerment and institution building; and those approaches utilising people's involvement to increase acceptance of external solutions (Pretty, 1995).

The Agricultural Innovation System model acknowledges farmers' social learning processes in networks formed by the farming community and other human actors (Klerkx, Aarts & Leeuwis, 2010; Dolinska & D'Aquino, 2016). Additionally, this frame highlights systems' continuous need to re-assess their context to develop the innovation, which is accomplished by forming effective connections with this context by particular actors (Klerkx, Aarts & Leeuwis, 2010). Within this frame farmers' social networks characteristics and spatial and temporal dynamics have been studied to improve the understanding of implementation of no-tillage (see: Skaalsveen, Ingram & Urquhart, 2020). Similarly some researchers linked Agricultural Innovation Systems with Communities of Practice. In relation to knowledge production, research focusing on Communities of Practice looks into the ways that knowledge emerges from within groups of farmers that share a practice and social norms, meanings, vocabulary, tools, etc. (see: Wenger, 2000; Goulet, 2013). Some studies also look into how Communities of Practice interact with technoscientific knowledge (see: Dolinska & D'Aquino, 2016; Krzywoszynska, 2019). All of these approaches integrate a relational aspect of knowledge production.

The co-creation of innovation approach assumes that knowledge is co-produced in social interaction, not transferred. This is a shift in knowledge production paradigms which claims that knowledge is not universal but emerges from interaction within social and natural contexts (Gibbons *et al.*, 2012; Mauser *et al.*, 2013). This claim implies that science and technology is also socially shaped or constructed (more on this in the next section: Science and interdisciplinary research). Which, in turn, reduces technoscientific knowledge authority compared with other knowledges. The distributed power relations in terms of which knowledge is valuable, indicates the need to include stakeholders in the innovation process. Mausers et al. (2013) model of co-creation of innovation includes stakeholders in all stages of the innovation (design, knowledge production and diffusion). The concept of co-creation of innovation has been used in a variety of ways, Elkjaer et al. systematically reviewed the use of the concept in relation to wind energy transitions and found three different meanings: 'A way of understanding the sociotechnical world where knowledge, values, and material things are intertwined. A(n analytical) tool to understand how changes in sociotechnical systems (can) happen. An approach to organizing social relations in concrete project development.' (Gjørtler Elkjaer, Horst & Nyborg, 2021:p.6). Only the first meaning acknowledges material agency as capable to induce change.

Co-creation of innovation integrating material agency understands reality as co-constructed by humans and non-humans. Materiality is conceptualised as active and relational, having an influence in social life rather than being the background where social life occurs. Several researchers have recurred to Actor-Network Theory (ANT) to include materiality in social constructivism and used this frame to understand innovation. Indeed, ANT does not only allow to break-down the nature/society and the expert/lay knowledge but also other dualisms of local/global and individual/structure. In the section Actor-Network Theory as a research ontology I review ANT principles, to then translate them into application in the section Actor-Network Theory as a methodology to study co-creation of innovation in agro-environmental studies.

2.4. Science and interdisciplinary research

Science, as producing scientific knowledge, has a different value in the different adoption theories. As seen in the previous section, linear models stress knowledge origin in science, and participatory approaches highlight local knowledge and leave scientists as facilitators. This chapter is to discuss further the shifting role of science in society and how scientific disciplinary boundaries are being overcome.

Natural sciences study nature. This is a simple statement, but underpinning, there are two assumptions about what nature is and how it can be known. Although in different scientific disciplines, it might change, most of the natural scientists are realist positivists, believing in a real-world, and a real and universal truth. Furthermore, the truth can be accessed through empirical observation and experience. Therefore, for scientists, it is taken for granted that they produce representations of how the world really is (Pickering, 1993). Karl Popper (2002) demarcated science from other types of knowledge through the use of falsifiable hypothesis: truth claims that can be tested. Scientists frame their hypothesis by means of defining the details of the situation they are studying in order to reduce ambiguity (Turnhout, Tuinstra & Halfmann, 2019). Those delimitations and simplification of real-world situations lead to controlled environments to carry out experiments that test the hypothesis. The reproducibility of research conditions conveys into protocols and standards under which it is possible to reproduce knowledge claims. Thus, scientific knowledge is said to be universal, objective and reproducible.

However, science's universality can be questioned from a historical analysis. Thomas Kuhn (2012) argued that science is produced in dominant scientific paradigms, which represent a consensus among scientists. Kuhn sustained those paradigms change in time with scientific revolutions instead of understanding science as an accumulation of knowledge. Thus, science universality is something that is achieved by consensus in a specific moment in time, rather than something inherent in natural sciences (Clark & Murdoch, 1997). Accordingly, the validity of methods and interpretations of scientific claims are assessed within each paradigms' own theoretical assumptions.

Moreover, norms of moral, scientific knowledge production regulating that it should not follow any personal interests, be independent of the researchers' characteristics, and the products of research made openly available and subjected to organised scepticism (Merton & Storer, 1973) are rather idyllic than realistic. Funding resources, competing schools of thought, researchers' backgrounds, etc., greatly affect the choice of the research topic, the framing of questions, use of methods and materials, etc. Furthermore, publishing and peer review processes, even if improving research outputs, are no guarantee that the shared assumptions are universally true or just in line with the prevailing paradigm. On the contrary, agreeing on science following moral standards implies that scientists are subjected to social norms. Those norms rule how science is produced, legitimated and diffused and, therefore, what counts as significant problems to pursue, who is allowed to practice science and what constitutes good science (Gibbons *et al.*, 2012). This does not mean that science is purely a human construction and that there is no interaction between scientists and the natural world. However, it means that the norms are not dictated by the real world that is under investigation, rather by the scientific communities. Then, scientists are not machines that read the truth objectively from the real world; there is always a certain degree of subjectivity in scientific work. The scientific community has to acknowledge that decisions about the research undertaken and the methods used are a distinctly political move (Watson, 2007). In other words, what constitutes good and bad science is not a matter of truth but a matter of power.

Seeing science as a social practice does not deny the value of scientific knowledge, but it helps to situate it as one from form of social activity amongst others. Furthermore, it helps to understand the post-truth era we are going through, in which scientific facts are questioned, and science status in society has been diminished. This requires understanding that more research or better communication to fulfil a knowledge gap is not always best to only way to address a problem. The challenges can arise from the controversies around different ways of knowing that exist in society. Scientific claims are not always trusted because trust is not granted through scientific authority. Trust also depends on 'the behaviour of scientific experts and their institutions, and on the way science addresses and resonates with the concerns of citizens' (Turnhout, Tuinstra and Halfmann, 2019, p. 77). Finally, instead of interpreting this as a setback, it can be seen as an opportunity to improve links between different ways of producing knowledge in an interaction that lead to new framings, meanings, methods, and in general to new ideas on knowledge production and new knowledge being produced.

Those interactions between different ways of producing knowledge are not only between scientific and lay knowledge but also across the boundaries of different scientific disciplines. The interest in interdisciplinarity does not only come from a sociological interest about how knowledge is produced but also from the natural sciences perspective when focusing on complex real-world issues that can not be solved from one discipline alone (MacMynowski, 2007). Such problems have been called wicked problems, and examples are climate change, loss in biodiversity or, indeed, sustainable food production. In those scenarios, we find controversies among sometimes competing for knowledge claims from heterogeneous sources (Lahsen & Beck, 2005). The difficulty is in finding common ground between disciplines that have different ontological and epistemic assumptions, use different vocabulary and value different data sources and analysis methods.

The definition of common norms and distribution of roles for interdisciplinary research is done by the scientist from different disciplines working together under the existing power dynamics in science. Power can manifest in many ways: the definition of what constitutes a valid environmental problem to research, inclusion or exclusion of researchers in teams, distribution of resources, or highlighting perceived relevance of conclusions for policymakers (MacMynowski, 2007). Too often, natural scientists have dominated research whilst social scientists have been left to a science communication role to close the knowledge gap with society, aligned to the already criticised linear knowledge production and innovation diffusion models. However, disciplines in the social sciences and the humanities provide information about environmental meanings, values and ethics or how different cultures make sense of the environment they inhabit (O'Gorman *et al.*, 2019). Those approaches are essential not only to situate natural scientists knowledge in society or to understand the relationship between society and the natural world but also if questions of sustainability have to be translated into action.

Finding common ground in interdisciplinarity is then to set new norms about how knowledge should be produced. Besides the possibility of a conflict scenario that would prevent the successful development of the project, MacMynowski (2007) identifies three ways of doing interdisciplinary research on environmental issues. The first one is a cooperation in which each discipline works inside their own boundaries, and results are shared. The second way is between disciplines that share philosophical foundations, and the project then approaches different issues within the same analytical framework. The last one is a reorganisation of different conceptual, philosophical, and methodological standpoints to address a common problem. This last scenario is the one adopted by this research project, in which the overarching approach has been selected to articulate a symmetry between soil science and social science, acknowledging lay knowledge production and valuing quantitative and qualitative data in the nexus of farming.

2.5. Actor-Network Theory as a research ontology

Actor-Network Theory (ANT) was selected as the overarching approach for this research. This section describes and discusses the relevant principles of ANT for this interdisciplinary study. This section is mainly based on 'Reassembling the social', in which Latour explains the journey of the analyst using ANT as a methodology by first deploying the many controversies (disciplinary assumptions) in order to incorporate new participants of the social. Second, follow the actors as they themselves stabilise the uncertainties by building formats and standards. Third, make a configuration by seeing how these assemblages give new values of collectiveness. Accordingly, in the subsections that follow, I discuss those steps through the redefinition of agency, the traceability of social relations and searching for patterns in the outcomes of networks' operations.

2.5.1. Actors in actor-networks

This project uses ANT to describe the actors involved in the tillage management network. ANT guideline for describing the networks is to *follow the actors*, which brings us to the question: What counts as an actor?

For ANT, actors are identified because they make an impact in social life which can be traced back to them (Latour, 2005). Thus, any change is a consequence of the action of agents. Additionally, the other way around applies as well; anything that causes an impact exists, whereas what does not have an impact does not exist in actor-networks. This way, ANT's epistemology becomes deterministic in the sense that analysts have to make explicit the causes of empirically noticed, observable and even tested changes in the state of affairs or social order (Latour, 2005).

Accordingly, an actor's existence becomes a relational matter. Indeed, actors are never isolated; they only exist in a network (Sayes, 2014). Then, while Mol states that an association is made or it is not, and an element is either inside or outside a network (Mol 2002, cited in Watson, 2007), in this project, an actors' existence is a negotiation. This is based on the notion of dynamism. A group – or network or actor-network - exists while it is in motion, changing, reassembling, performing and disappears when it stops (Latour, 2005). ANT is not interested in the 'out there' until a relationship is established, and then, that bond is always negotiated by the heterogeneous network. Indeed, Latour (2005) called *plasma* not what is 'out there' but what is in between, not made of social stuff, not hidden but unknown. ANT is to account what it is for an actor to come into existence (Latour, 1999, cited in Watson, 2007). Existence is not binary either; an actor-network, and therefore existence, is always negotiated, dynamic, unstable and can vanish. Actors depend on other entities allowing them to exist, which makes them traceable (Latour, 2005). It requires work to maintain the relations that maintain an actor-network, and the maintenance is its existence.

For ANT, actors act and are enacted at the same time. Law and Mol (2008) situate the origins of these concepts of an actor being anything that makes a difference in other actors and the idea of entities bringing meaning to each other in the field of material semiotics. In any case, that leads to the conclusion that what an actor is, is particular to a network – and also specific in time and space -. If leaving the network, the actor is in danger of losing its integrity (Watson, 2007).

Additionally, Law and Mol (2008) discuss the idea of an actor being *multiple*. They analyse four practices in which a sheep from Cumbria in March 2001 is involved, showing not only the sheep's actions and enactments but also its multiplicity. An actor is multiple because what it is depends on the network in which it is part of, and actors are part of many networks. Multiple is different from single and coherent, as in any network, the actor's version is different; moreover, it is different from plural, as it is still the same actor and the versions of itself are related (Law & Mol, 2008). Latour (2005) states that being a fully competent actor comes in patches; for the analyst to obtain them requires a composition of successive empirically distinct layers. However, Law and Mol (2008) conclude that anything can be an actor, and therefore what is interesting is not what an actor is, but what it is doing, what is happening and how the networks' actors interact to create or destroy.

In conclusion, eliminating preconceptions about actors' identities (Nimmo, 2011) and their world-building capacities (Latour, 1999) is necessary to identify unknown (for the analyst) actors and the relations that bind them to other members of the network so that the network configurations and operations can be described. Forgetting what an actor should look like might be confusing, but it gains importance because it is the core to let the networks self-explain. For ANT, actors know about their networks, whereas the analysts are new to them and are always one 'reflexive loop behind' (Latour, 2005). This notion, in addition to networks being the ones enacting the actors and bringing them into existence, leads to the methodological rule of actors being the ones who decide what counts as an actor in the network: anything that makes them act, a change in their behaviour.

For me, that can be challenging in two ways: incorporating material agency and expanding the body to other figurations.

2.5.1.1. Incorporating material agency

Non-humans possessing agency and the principle of symmetry are the most disputed principles of ANT. The critiques have their origin in the dualism nature/society and the drive for *human exceptionalism*.

The dualism nature/society is the distinction between a natural world that obeys natural laws and a society, which does not. The difference is not made between nature and the human body but with the human mind (McGregor, 2014) and the social construction of the world. Goldblatt (Goldblatt 1996 in: Murdoch, 2001) argues that the divide has its origins in a historical context in which social theorists were experiencing a liberation from natural constraints and not yet the challenges of environmental degradation. On another note, the strong argument in favour of *'*human distinctiveness or human exemptionalism*'* that searches distance from material forces can also be interpreted as a consequence of the effort to separate *'the social'* as an independent sphere to justify a dedicated scientific discipline (Macnaghten and Urry, 1998; cited in Murdoch, 2001). In any case, the two realms distinction was followed by a disciplinary divide that also lacks tools to integrate the other.

Traditional approaches in Social Science grant agency solely to humans, as agency is considered to be related to intentionality. Intentionality is something that natural entities do not have, as they are constrained by natural laws. Accordingly, relations among, for example, social animals are linked to the satisfaction of basic needs and their behaviour is imprinted in their DNA. However, this project uses ANT's redefinition of the concept and uses agency as generating an impact, a change on another actor or, by extension, to the network. Therefore, in this project, regardless of the existence of these differences between humans' and non-humans' agencies, non-humans have a role in social life.

This redefinition of agency constitutes a tool to integrate materiality in social studies, granting the non-human an active role in social co-construction. ANT treats materialism as a continuity rather than a dualism (Law, 1992). It is opposite to nature being the passive context of human action or victim of human endeavour (Murdoch, 2001). ANTs objective is still to describe the social. ANT does not engage in questions about what nature does alone – as natural sciences would question. Indeed, the human is always the focus of the networks of associations, and ANT does not examine what is outside (Watson, 2007). However, with ANT, the social becomes heterogeneous, including both humans (classically only studied by social sciences) and non-humans (classically studied by natural sciences). Latour's primary motivation was to account for the material agency that co-constructs scientific knowledge and enables scientists to operate effectively (Murdoch, 2001). Thus, how networks operate is an analytical focus of ANT. To be able to do this, ANT does not deny differences, but refuses to separate elements according to the ontological categories (Murdoch, 2001) and therefore does not engage in the endless and frustrating dualism (Gray & Gibson, 2013) – not in this one, nor in the micro/macro, local/global, etc. In fact, dualisms and preconceptions are treated as analytical barriers to let the networks self-explain. Indeed, Rachel (1994) identifies ANTs productiveness in looking between dichotomies and examining how things come to be.

2.5.1.2. Expanding the body to other figurations

The challenge of incorporating material agency is discussed and criticised extensively in the existing literature. However, for me as a natural scientist, forgetting the need for a body for an actor to exist – in the Euclidean version of reality in which objects are things that take up space and can be touched (Watson, 2007) – was a greater task to overcome.

It might even be a controversy among ANT theorists. For example, Law (1992) writes that actors, among other things, possess a body and Sayes (2014) excludes not only humans but also the supernatural and entities composed of humans and non-humans from the concept of non-human. However, with the notion of hybridity, humans stop being seen as purely humans and non-humans purely objects; they are networks (Jackson, 2014). So, even the boundary between humans and non-humans is negotiated and empirical (Prout 2000, cited in Jackson, 2014). A closer analysis of Law's *'body'* reveals that the set of elements that an actor inhabits stretches out into the network, and thus, an agent actually is that patterned network (Law, 1992). Furthermore, in '*Reassembling the Social*', Latour (2005) himself provides the example of God as an actor because someone acknowledges God making her do things (causing an impact). However, at the same time, he states that agencies have figurations: 'flesh and features that make them have some form or shape, no matter how vague' (Latour, 2005, p. 53).

In the case of this project, the inclusion of ideas, past experiences, etc., into the concept of 'actor-network' goes back to the empirical evidence. The analysis started considering only tangible actors, but after drafting the first networks, there were impacts that were not explained by anyone in the network but could clearly be related to some event or idea by the informant. Thus, there was a need to include *'abstract figurations'*, a term used by Latour in '*Reassembling the Social*' (2005) to include ideo-, techno- and bio-morphisms. Indeed, what an actor is, is an empirical matter (Doolin & Lowe, 2002) explained by the network itself.

2.5.2. Relations in actor-networks

ANT analyses relations between actors to respond to questions about how the networks are formed or how they are held together. For the analyst, to answer those questions, it is equally important to establish what counts as an actor than what counts as an interaction. So, what is a social tie?

Similarly to actors, relations can take many forms, but the action is their empirical proof of existence. Any kind of interaction between actors is a relation. This can be an exchange of information, material flow, energy, or any other kind of negotiation. Analytically, this translates into every time a bond is traced, something has to happen. No bond exists without a flow. Every time a connection is established, a conduit is laid down, and some type of entity is transported through it (Latour, 2005).

To hold the network, attachments are first, and actors are second (Latour, 2005). Therefore, it is important to pay attention to the flows, the circulation and what is circulating. In the next subsection, translation is going to be discussed and how it relates to power. Translation is the action in which an actor modifies what is circulating so that it obeys its own interests when it continues to flow. The second subsection is about *punctualisation*, which is how networks become stabilised in a way that their action is recognised as from a single actor.

Networks are stabilised, but that does not mean that they are static. Networks are dynamic, meaning that actors fly in and out and relations fluctuate. Sometimes social ties are ephemeral, difficult to grasp, and any new analysis would reveal a different set of actors and relations (Latour, 2005). Methodologically this means that networks are not only spatially but also time-wise unique; this is furthermore discussed in the last subsection.

Sometimes, it is easier to discuss what relations are not, rather than what they are. So, Latour (2005, pp. 199-204) identifies five properties that do not define relations:

- Interactions are not '*homogeneous'*: they are between heterogeneous actors.

- Interactions are not *'isotopic'*: actors are always unique and have unexpected world-building capabilities, resulting from many layers, negotiated in many networks.
- Relations are not *'synchronic'*: time is always folded.
- Bonds are not *'synoptic'*: very few of the participants in a given course of action are simultaneously visible at any given point.
- Interactions are not *'isobaric'*: the pressure to be heard and taken into account by some actors is greater than the pressure that other actors make.

2.5.2.1. Translation and power

Translation is the process of negotiation in which the actors transform the message as it passes through them, introducing their own interests, knowledge, materials, values, etc., changing the original message. This is continuous, from one link to the next in the chain as information flows through the network. A translation is a connection that transports transformation (Latour, 2005). ANT's purpose from a methodological point is to tell empirical stories about processes of translation (Law, 1992); it is to identify strategies of translation that ramify and reproduce themselves through the network (Law, 1992).

Latour makes the difference between mediators and intermediaries, the first translating the information as they carry the message, and the latter not, which grants some predictability for the analyst (Latour, 2005). Furthermore, immutable mobiles are actor-networks that maintain their shape as they pass through different networks (Law, 2002). Nonetheless, in the analysis, it is too easy to overlook an agency (especially from the non-human, non-material, non-synchronic, non-synoptic, non-isobaric actors) and just label it as an intermediary. Indeed, ANT potential and richness is in acknowledging those other agencies, which have been left out in other sociological approaches. Therefore, in this project, all network participants are actors and the artificial categories *'mediators'*, *'intermediaries'* and *'immutable mobiles'* are not used.

Additionally, translations can come from different actor-networks. As seen, actors have multiple layers because they are enrolled in numerous networks. Therefore, actors are influenced by the other networks that they are involved in. Then, they translate flows from one network to the next and into the network the research focuses on. The ephemeral link between the networks can be made durable, with the enrolment of new members or not. For example, no-tillage farmers are also members of a community in a specific village, growing particular crops, etc. If an information exchange does not change the farmers' tillage management (or any other actors' behaviour in the no-tillage network), then the link with the no-tillage network was only temporary.

Translation plays an important role in how power is generated. In ANT, power and domination are not given properties of some kind of agencies, as in other methodological approaches, which include macro- and micro-structures and the direction of the flows (top-down or bottom-up) in the analysis. In ANT, power and domination are also outcomes of the network; they too have to be produced (Latour, 2005). Therefore, as Law (1992, p. 390) states: ANT 'demystifies the power of the powerful', but only to show that 'there are real differences between the powerful and the wretched in the methods and the materials they employ to generate themselves'. For Latour (2005) to say that something is constructed means that it is not a mystery. How an actor, a relation, knowledge, power, etc., has emerged out of inexistence can be explained because it requires the action of the network.

ANT explains network generation in four steps (Callon, 1986):

1. *Problematisation* starts with an identification of the problem and the recruitment of actors who agree to a problem-solution equation;
2. *Interessement* in which the recruiting actor seeks to lock the other actors into the roles defined for them;
3. *Enrolment* when the actors accept their negotiated roles;
4. *Mobilisation* is the final step in which actors commit to the networks endeavour.

Power is central to the negotiations of the actors' roles and networks' endeavours, not as an intrinsic property, but as an outcome of the negotiations and agreements. Enrolment is not an imposition; it is a negotiation (Callon, 1986). Moreover, actors can renegotiate or betray the roles previously negotiated (Jackson, 2014). As translation is the modification of the flows according to the actors' own convenience and interests, in order to convince others to join their own benefit, power is an issue of translation. Power and size are actors' achievements through translations, scaling and contextualising each other (Latour, 2005). Actors are made powerful where they succeed convincing about their interests, enrolling others in their network, sharing particular definitions and roles, or the range of available choices (Burgess, Clark & Harrison, 2000). Thus, power is a relational effect, not an intrinsic characteristics of some actors. Power is an effect, not a cause (Law, 1992). Part of the assumptions an analyst has to forget are the power assumptions regarding size. Rather, through ANT, the analyst should explain how power is generated (Law 1992).

A special note has to be made regarding natural sciences, translation, and power. ANT introduces the concept of calculations, which is a set of social methods and relations imposed on material representations, as a strategy from some actors to speak on behalf of others, but in the action may mask them (Law, 1992) and even silence their own voices. This has been compared to political representation (Law, 1992). It is also related to the critique of ANT as giving too much power to natural sciences as representatives of non-human actors. However, scientists are embedded in a network with their object or subject of study. Therefore they are bound, connected. Scientific networks create a set of identities and values, different from other networks, which define the object/subject of study and the relations with it. Accordingly, scientists are not the only voice that speaks for non-humans, but they have a voice. However, the translations scientists offer regarding non-humans are made meaningful and powerful (or not) by the network in which they flow, as could happen to any other translation. ANT does not privilege natural sciences; rather, it treats them as centres of calculation, whose power is not granted but produced (Law, 1992).

2.5.2.2. Networks' punctualisation

Networks are dynamic because action is constant: new actors enrol, roles are renegotiated, other actors leave, etc. 'Social' then, is only a momentary association characterized by the way it gathers together (Latour, 2005). At the same time, social change or stability is not achieved by people nor objects alone (Law, 1992) but negotiated in heterogeneous networks. Stability is not the same as static; it is not exempt from action. Far-reaching and long-lasting associations require constant investment, work, and effort (Latour, 2005). The investment is in the group delineation by comparison with other competing ties (Latour, 2005). Effort goes not only in overcoming the external threats to networks' existence but also in overcoming internal resistances from each actor's own strategies and translations. Moreover, social ties have to be constantly renegotiated because they have no inertia; they do not spread in space or last in time (Latour, 2005). Thus, ANT is also an account of how networks become stabilised and through those relations how size, power, and organisation are generated (Law, 1992).

A networks stabilisation leads to its punctualisation. It occurs when a network operates as a single block, meaning that the network's patterns are widely performed so that the action in itself becomes the actor-network (Law, 1992), which means that through punctualisation, the network becomes an actor. Thus, all actors are punctualised networks. Network formation, or the process of ordering social life, does not necessarily mean that all actors in a network completely agree to the same endeavour in the mobilization phase. On the contrary, in a network, actors have conflicting interests but still share either the same aim, enough commonalities or some kind of pursuit to maintain negotiations, so that network ties are still in place. It is by untangling the punctualised actor-networks, analysing the many actors and interactions, that the origins of tensions and change become clear.

Moreover, punctualisations are used to simplify actor-networks under the appearance of a unit or when they achieve the status of taken for granted (Law, 1992). In normal life, it would be impossible to operate without punctualisations. In social analysis, whereas some actor-networks are fully deployed or untangled, others are treated as punctualisations or black-boxes, never opened to explore their operations, and only their effect on the network is taken into account. Otherwise, the analysis would be endless as each actor would fall into its many pieces. The choice of which black-boxes to open and which ones to keep close is not the analyst's decision either; it is, again, by following the actors that the networks deploy or not.

One of the duties of ANT is then to search for strategies that stabilise networks. Latour (2005) identifies one of them in the use of durable materials. The explanation comes from seeing form as a circulating entity, something that allows something else to be transported from one site to another. Form, then, becomes a type of translation: a piece of information is put into a form (Latour, 2005). Durable materials, such as texts, might be good strategies to endure relations and stabilise networks (Latour, 2005). However, those materials may as well have an impact on how the information is transmitted.

2.5.2.3. Networks' limits

As has been suggested, networks are limitless. Actors deploy in other actors, interactions branch in numerous coexisting networks, actors are multiple and are enrolled in multiple networks simultaneously, relations are ephemeral and difficult to grasp, etc. Whereas ANT has been criticised as not recognising its own partial perspective (Watson, 2007), actually, as a methodology, it builds on the notion that only a partial perspective is possible. This means that there are vast fields of actions and actants which are not seen. Then, ANT is used to spotlight, to illuminate smaller parts of larger networks. However, to do that, it still requires a methodological decision concerning what is a part of and apart from the studied network. This decision has to be made understanding networks dynamism and time and spatial dimensions.

Networks' dynamism and shifting shapes come from constant action. Even if networks can be stabilised, they continue being dynamic entities, constantly redefined by fluctuating relations that change structures, generate new patterns or enable new voices (Law, 1992). Moreover, stabilisation is never complete; coexisting divergent strategies interact (Law, 1992) and require effort to overcome or bring change. As suggested earlier, a different network configuration would appear to the analyst each time the description task is faced.

Additionally, to the moment in which the analysis is made, network dimensions can reach far away in time and space. What is acting can have been transported from distant places or times, as well as the strategies that those actors are bringing to negotiation (Latour, 2005). They might even have circulated through a chain of agencies. Thus, action, and therefore, the network, is always dislocated, articulated, delegated and translated (Latour, 2005). ANT is a representation of a different spatiality. Place is a product of the network and should be part of the research enquiry (Latour, 2005) and time as well.

This new spatiality is the way ANT faces the dichotomy micro- /macro-. Local and global become irrelevant as sources of action. No assumptions are made, *'global'* only exists in the local while a connection can be traced. This makes it possible to trace connections outside the definition of the research field (Ruming, 2009) and the research scale. However, Latour (2005) integrates scale in the analysis by proposing the terms *oligoptica* and *panorama* to focus on the narrow details or the wider pictures, respectively. Whilst *oligoptica* are the extremely narrow connections necessary to hold the whole together, panoramas are the big pictures of the whole (Latour, 2005). Whereas oligoptica are constantly revealing fragility, lack of control and what is left between what is surveyed, panoramas provide wholeness and centrality (Latour, 2005). Panoramas become relevant as it is from their stories that metaphors for what binds society together arise (Latour, 2005).

2.6. Actor-Network Theory as a methodology to study co-creation of innovation in agro-environmental studies

This section focuses on how ANT has been translated into this project of innovation studies. In short, ANT framework makes it possible to study co-creation of innovation seeing farmers, soils, and scientists as active agents in the process of knowledge generation and diffusion. As seen in the sections above, the adoption of an innovation has been studied as part of a knowledge production and diffusion process, and more recently, as a co-creation between stakeholders. ANT take on knowledge is as an outcome of the network: it is co-created in the interaction between the different actors in a more-than-human social network. As seen, meanings, values, and identities of the involved actors are built in negotiation between the actors themselves and the surrounding network members. This accounts for humans and non-humans. As the networks are dynamic, with changing relations, limits, and members, so are the products of the negotiations (knowledge, identities, roles, etc.). Knowledge, then, is not universal; it is situated in particular social networks. Additionally, knowledge is not static; as networks are in constant evolution, knowledge is constantly translated by the networks' members, modified and contested as it circulates through the network. Then, in ANT, knowledge diffusion entails a translation by the actors, and therefore, it is part of the collective knowledge production.

Moreover, due to ANT's refusal of the dualism nature-society, science-culture, expert-lay knowledge, ANT is a powerful tool for environmental questions (Burgess, Clark & Harrison, 2000) and more generally innovation in fields as disparate as urban planning (see: Farhangi *et al.*, 2020), energy (see: Krzywoszynska *et al.*, 2016; van der Waal, van der Windt & van Oost, 2018), information technology (see: Yoo *et al.*, 2005; Wang *et al.*, 2015) or international relations (see: Barry, 2013).

This potential of ANT has been used previously to study agricultural networks. Gray and Gibson (2013) identified actors in the industrial agriculture actor-network in Kansas, USA. They conclude that financing institutions, crop insurances, equipment and technology, soils, fertilisers, experts, and the Ogallala (from which water for irrigation was provided) were the major actors constraining farmers' choices. An interesting comparison between conservation scientists' and farmers' translations of nature has been done by Burgess (2000) for agro-environmental scheme participation in English wetlands farms. From this study, it is worth noting not only the different knowledge generation, language use and interpretations of nature; but also how farmers' roles in agro-environmental schemes are determined by governmental institutions and not always accepted by farmers (appearance of resistance). Finally, Schneider et al. (2012) applied ANT to study no-tillage adoption in Switzerland, concluding that the spread of no-tillage requires fundamental transformations within the network of conventional tillage, including institutional arrangements, farm equipment, work organisation, concepts of agriculture and personal and professional identities. These authors also stated that the required transformations are too radical for many farmers. This explains why practices that require less transformation because they are more similar to CT networks, such as occasional abandoning of the plough to improve agricultural productivity, achieve broader uptake. In addition, Schneider et al. (2012) claimed that for the success of policy interventions, their role has to be as mediators in complex processes of reciprocal translations between farmers, experts, and scientists, as well as many non-human actors.

In summary, the important distinction that, according to ANT, farmers, non-humans (including soils) and scientists can take active roles in innovation, whereas with other theoretical approaches, it is not even possible.

2.7. Focus on soils

Soils are facing increasing threads as foods demands grow. Indeed, 98.8 % of human caloric intake comes from soil (2849 Kcal per capita) (Kopittke *et al.*, 2019). Therefore, with a growing population (projected to reach 10.9 billion in 2,100) and caloric intake increase due to growing wealth and changing diets, the pressure on soils to match food demands is growing (Kopittke *et al.*, 2019).

Historically, increasing food production has been achieved through *expansionism* and *intensification* (Kopittke *et al.*, 2019). Expansionist strategies implied an expansion of agricultural land; overtaking competing land uses such as forests or moor. While with the Green Revolution, food production increased through an intensification of agricultural land by adding fertilisers and controlling pests and weeds with agro-chemicals. These strategies, in turn, resulted in environmental damages and social costs. The *alternative agriculture* paradigm arose as prioritising the environmental and social aspects, although its potential to feed the growing population is unclear (Mahon *et al.*, 2017). *Sustainable intensification* is conceptualised as the strategy to increase food production within the planetary boundaries delivering more food, better ecosystems and improved livelihoods (Rockström *et al.*, 2017; Mahon *et al.*, 2017).

No-tillage has been enclosed in both, the alternative agriculture and sustainable intensification strategies. Nonetheless, the potential agronomic, environmental and social benefits of no-tillage are being questioned due to its reduction in yields (Pittelkow *et al.*, 2014), reliance on herbicides (Müller, 2021), and its implementation without being adapted to farmers' realities (Giller *et al.*, 2009). This thesis contributes to how farmers' adoption and non-adoption of no-tillage co-construct these different food production narratives and how they relate to soils.

Following the ANT approach, soils are actors co-constructed by the network in which they are enrolled in, actor-networks themselves that can be deployed, and multiple because they pertain to different networks at the same time. Soils' roles and their agencies, do also depend on the actor-networks in which they are enrolled. In other words, what a soil is and what it is able to do does not only depend on the soil, but also on how that soil relates to other actors. From those assumptions that set the overarching frame to study soils, soils are potentially different actors in farming and in soil science.

In the soil science school of thought in which I was trained (my soil science actor-network), soils are natural entities with three-dimensional bodies differentiated into horizons of mineral and organic constituents (Joffe, 1936 cited in Jenny, 1941) result of the evolution of the soil formation factors. These soil formation factors are climate, parental material, landscape position, time and organisms (including humans) (Jenny, 1941). Due to diverse combinations of these factors around the Globe, soils are geographically varied.

Nonetheless, there is a plurality of concepts of soils in science. The notion of soil has shifted according to societies' information demands (Ibáñez, 2011). Moreover, definitions coexist depending on the area of interest that engages with soils (Ibáñez, 2011). Through the ANT lens, this translates into specific soil properties being taken out of the plasma (the unknown), and gaining relevance and power in particular actor-networks while in other actor-networks those properties remain in the plasma or play a less important role in enacting soils (what soils are and what they are able to do). Ibáñez and Boixadera (2002:p.104) summarised the multiple soils in science as:

- Geological entities
- Medium for plant growth
- Natural Bodies
- Structural material
- Water-transmitting mantle
- Ecosystem or ecosystem component
- Holistic entities or geoderma (continuum soil-regolith-landforms)
- Self-organising earth surface system (geoderma + hydrologic system + biological system)

In any case, soils are 'complex', 'multidimensional entities', and as such 'any definition only captures part of its multiple facets, being therefore necessarily incomplete' (Ibáñez, 2011).

Similarly to the variety of soil definitions in science, there are different concepts dealing with soil assessment (how good soils perform what they are supposed to do). Soil *quality* is soils capability to fulfil any of its functions which, in practice, have been related to human well-being and are listed as (Blum, 1998 and 2002, cited in Blum & Swaran, 2006:p.39):

- 'production of biomass through agriculture and forestry;
- protect the groundwater and the food chain against pollution and maintaining biodiversity by filtering, buffering, and transformation activities;
- contribute to the preservation of the gene reserve by enabling the habitat for biota;
- provide the physical basis for infrastructural development, such as housing, industrial production, transport, dumping of refuse, sports, recreation, and others;
- serve as a source of raw materials, furnishing gravel, sand, clay, and other materials;
- preserve the geogenic and cultural heritage by concealing and protecting archaeological and paleontological materials.'

From a multi-functional soil perspective, soils' agency does not only relapse on soil life, the inert matter also has the potential to condition and change the social as relationships develop. This notion is opposed to Ingold (2008) who advocates for a more-than-human agency only in favour of living organisms. Nonetheless, applying ANT in this research, participants decide which other actors have an impact on tillage practice. This agency is neither intentional nor rational but has an impact on the social through their relationships, which establish with other actors when something is exchanged (e.g. material flow, energy, knowledge, etc.).

In the scientific literature, the concept of soil quality, as soils' fulfilment of its functions, is slightly different from soil fertility and soil health. Soil *fertility* focuses on soils' capability to produce food, and historically it has a connotation to refer to chemical characteristics, mainly nutrients (Mizuta *et al.*, 2021). On the contrary, soil *health* distinguishes 'living soils' functionality (Doran & Doran, 2002) and therefore emphasises the importance of soil biological properties (Pankhurst, Doube & Gupta, 1997). Soil *security* is a newer concept and links to soils' key role in providing ecosystem services, from which food production is only one (Bouma *et al.*, 2014). Additionally, soil security is a multi-dimensional and multi-disciplinary concept that 'encompass the social, economic and biophysical sciences and recognise policy and legal frameworks' (McBratney, Field & Koch, 2014). A soil concept less used in scientific publications is soil care (Mizuta *et al.*, 2021). Soil *care* relates to the ethical and practical commitment to the soil which develops in a relational manner through attentiveness to soils (Krzywoszynska, 2019a). Bearing a soil ethics involves personal and collective soil valuing, and cognitive (knowing) and emotional (feeling) empathies towards soils (Grunwald, 2021). Each concept reflects social, cultural, and political needs and events (Mizuta *et al.*, 2021) and the use of them reflect researchers' personal biases.

In this project, I use soil fertility when referring to soils' fulfilment of the biomass production function (but the term includes biological and physical properties); soil quality in a broader sense when assessing soils' functionalities, often linked to environmental cycles or when analysing which soil functions are relevant for farmers; and soil health when referring to soils as alive. However, in all cases, fertile, good quality and healthy soils in agriculture entail a balance in their chemical, biological and physical properties.

Nonetheless, in the scientific assessment, I focus on soil physical properties. First, because soil physical quality is the aim of seedbed preparation, and therefore it is sensitive to tillage management practices. Second, because soil compaction is one of the major threats to soils in European agriculture (Anon, 2015) yet, soil physical quality is closely related to soil biological and chemical properties.

2.8. Background on soil physical quality

In this section, I discuss the theoretical understanding of soil physical quality in soil science. Accordingly, first, I discuss the importance of soil structure and aggregation to understand physical quality. Then, I introduce the different actors that impact soil structure dynamics. These are the main drivers of aggregation and disaggregation processes. Furthermore, I introduce the geographical perspective in the variability of soil aggregation and disaggregation agents. In the end, I relate soil structure to soil compaction and provide an overview of soil compaction, a major problem in agriculture. For the first three sections, I use the materials of the book chapter I co-authored: 'Physical and hydrological processes in soils under conservation tillage in Europe' (Veenstra, Cloy and Menon, in press), in brackets are minor changes to the original text:

2.8.1. "Soil structure, core to soil physical properties

Soils are complex porous media comprised of solid, liquid and gaseous constituents. Soil structure is the aggregation of soil particles (sand, silt, clay and organic matter) into granules, crumbs or blocks. Inorganic and organic constituents are bound together, forming aggregates and leaving voids in between, which constitute the porous system. Soil structure is the shape that the soil takes based on its physical, chemical and biological properties, regulating the soil-water cycle and sustaining a favourable rooting medium for plants (Kibblewhite *et al.*, 2008). Despite the rigidity of the term, soil structure is dynamic, with cyclical aggregate breakdown and new aggregation, depending on many factors. Aggregate stability is an indicator of soil quality, as in well-structured soils with stable aggregates, water and air have no physical impediment to flow. On the contrary, soils with poor structure have unstable aggregates that break easily into smaller particles, reducing the pore space and its connectivity, inducing numerous problems, including waterlogging and oxygen deficits for plant roots and other organisms.

There are many factors influencing aggregate dynamics. These factors are from the soil itself (e.g. organic matter, clay, sand and salts content), the environment in which it develops (e.g. climate or topography) and the land use it is subjected to (e.g. forestry, pasture or cereal cropping). Therefore, soil structure and the physical properties which depend on it are soil- and site-specific. Thus, tillage management practices have different effects on soil physical properties, and in turn, how these influence agricultural production, depending as well on the geographical location. […]

2.8.2. *Soil structure and aggregate dynamics*

Research advances have developed our understanding of soil structure and aggregate dynamics and how they are affected by numerous factors that vary geographically, including tillage practices.

Tisdall and Oades (1982) introduced the importance of soil organic matter (SOM) in the aggregation process. They proposed a hierarchical model in which larger aggregates are formed by smaller aggregates. Moreover, they stated that each aggregate size had its own major binding agent. Indeed, the effectiveness of binding agents depends on their own dimensions in relation to the voids and particles they have to bridge (Kay 1990, cited in Jastrow and Miller, 1997). The nature of the aggregation agents leads to differences in aggregate stability. Thus, roots and fungal hyphae are the major binding agents for macroaggregates (> 250 µm diameter), whose labile characteristics explain why macroaggregates break down into smaller particles easier than microaggregates (< 250 µm diameter), which are bound together by more recalcitrant organic matter or more stable aggregation agents.

Further development of the hierarchical model helped to relate soil structure to the carbon cycle, in a process that follows organic residue decay, successive integration in soil, occlusion in soil aggregates and sorption to clay minerals (Golchin *et al.*, 1994), which represent consecutively increasing carbon sequestration potential. Afterwards, it was shown that microaggregates form inside macroaggregates (Angers, Recous & Aita, 1997). Since the latter provide physical protection from microbial attack of fresh organic matter, giving it time to establish chemical or physicochemical bonds with clay particles or more stable organic compounds (Balabane & Plante, 2004). [Moreover, organic matter increases intra-aggregate cohesion and hydrophobicity (Blanco-Moure *et al*. 2012, cited in Barik *et al.*, 2014), which provides further protection and facilitates binding between mineral and organic compounds.]

Time is precisely what conservation tillage provides, by avoiding mechanical disturbance, allowing, therefore, the development of [presumably] more stable aggregates. On the contrary, macroaggregate turnover rates in cultivated land are only between 5 and 33 days (Plante & McGill, 2002b, 2002a). Even the hierarchical model highlighted the vulnerability of macroaggregates to tillage since their binding agents are labile. Afterwards, the disruptive effects of tillage have been ratified by other researchers, proving that tillage disturbance increases macroaggregate turnover and carbon mineralisation (Six *et al.*, 1998). Notwithstanding the generally accepted slower turnover rates in microaggregates, Virto et al.

(2010) found similar ages of organic matter from within silt-size microaggregates and from outside those silt-size microaggregates, questioning, therefore, the understanding of turnover rates of this aggregate fraction, which would be much quicker than previously thought.

Besides, the major influence of organic matter in aggregate dynamics, aggregate formation and breakdown is a complex process influenced by many other factors. Even the authors of the hierarchical model highlighted that organic matter becomes the major binding agent only in soils where other binding agents are absent. Amézketa (1999) showed there are many intrinsic or extrinsic factors affecting soil aggregate stability in different soils, making it a site- and soil-specific property. Among the binding agents are calcium carbonate, calcium sulfate (gypsum), silica, iron or aluminium oxides, clays and organic matter. In turn, their effects can be influenced by the soil solution electrolyte concentration, clay mineralogy, the nature of the organic compounds, climate, time (or ageing), roots, soil microbes, edaphofauna and agricultural management (i.e. tillage, irrigation, organic matter amendments, crop type and crop rotation, chemical amendments, etc.). Additionally, aggregate stabilization factors have interactions. For example, in an experiment in Argentina investigating the interaction between water regimes and vegetation, the results showed that aggregate stability was higher under wet and dry cycles with vegetation compared to the same moisture conditions in sterile soil (Taboada *et al.*, 2004). Therefore, the importance of the synergies among conservation agriculture practices, including soil surface protection with crop residues or cover crops, and crop rotation and diversification, becomes apparent.

2.8.3. [Aggregation agents and aggregate breakdown factors: the geographical perspective]

Across Europe, different soils and locations have distinct combinations of aggregation agents, which might be dominated by one particular agent. Cementing compounds are major aggregation agents in different soils; for example, Regelink et al. (2015) describe the importance of Fe-(hydr)oxides in Austria, Czech Republic and Greece; and Boix-Fayos et al. (2001) stresses the importance of calcium carbonate in Spain. Furthermore, clay mineralogy has been studied by Norton (2006) through soils of a range of clay types and under a range of land uses, discovering that under cultivation, kaolintic (1:1 clays, less reactive) soils had greater aggregate stability than in illitic or smectitic soils (2:1 clays, more reactive) and that kaolintic clays associated with iron oxides provide a stability that might be resistant even to land-use change. However, the importance of studying the aggregation of distinct clay types stemming from the

> same soil has been emphasised to avoid interference of other aggregation agents. Thus, Virto et al. (2008) and Fernández-Ugalde et al. (2013) showed that microaggregates tend to form between the more reactive 2:1 clays than the kaolinite-type clays (1:1 type) or quartz. [Therefore,] in the same soil, the latter are more abundant in non-aggregated particles.
>
> Aggregate dynamics also depend on aggregate breakdown, which is not exclusively linked to organic matter decay. The disruptive processes that lead to aggregate breakdown include as well physico-chemical dispersion, slaking, differential swelling and the impact of mechanical forces (Le Bissonnais, 1996). Physico-chemical dispersion occurs in soils containing high concentrations of monovalent cations such as sodium from sodium chloride salt deposits. They act as dispersants between clay particles, whereas polyvalent cations, such as calcium, act as flocculants. Physico-chemical dispersion leads to aggregates breaking down into elemental particles. Several researchers observed that soil management history influenced clay dispersibility (Kay and Dexter, 1990; and Watts, 1996, cited in Amézketa, 1999). Furthermore, slaking disrupt aggregates during wetting due to forces generated by trapped air; it occurs at the same time as differential swelling, whose origin is influenced by the diverse expanding behaviours among soil compounds when moist. As a result of slaking and differential swelling, aggregates break into smaller aggregates. Finally, mechanical disruption occurs when external forces impact on soil aggregates, such as the "splash effect" from raindrops or the impact from tillage. According to soils' composition, some soils, for example saline soils rich in sodium, are naturally more vulnerable to any of these aggregate disruptive processes and therefore, they have to be treated with special care in agricultural land use (Rengasamy & Olsson, 1991)."

This thesis focuses on two distinct biogeographical regions: the Mediterranean and the Atlantic. Soils in these biogeographical regions are the product of different soil formation processes and have contrasting characteristics (more detailed reviews in section: Soils in bio-geographical regions). Accordingly, the impact of tillage management on soil structure can not be generalised. Furthermore, soils' spatial variability influence the impact of no-tillage and conservation agriculture on soil structure and physical properties even at a field scale (Skaalsveen & Clarke, 2021). Nonetheless, no-tillage has shown to increase structural stability due to the increase in soil organic matter and the reduction of mechanical disturbance in both, the Mediterranean region (Sidiras, Bilalis & Vavoulidou, 2001; Hernanz *et al.*, 2002; Álvaro-Fuentes *et al.*, 2008; Plaza-Bonilla *et al.*, 2013; Apesteguía *et al.*, 2017; Barut & Celik, 2017) and the Atlantic region (D'Haene *et al.*, 2008; Pulido Moncada *et al.*, 2014b).

2.8.4. Soil compaction

Soil compaction is often identified as one of the major environmental problems of conventional agriculture (McGarry, 2003). Soil compaction decreases pore space affecting gases, water and carbon stocks and flows, inducing runoff and erosion (Holland, 2004). Moreover, soil compaction leading to anaerobic conditions can be toxic for some species, changing biological communities (Holland, 2004). Furthermore, soil compaction also comes with an agricultural cost affecting seed emergence, crop establishment, root growth and might even lead to drought stress due to increased runoff (Lal, 1985).

Anthropogenic soil compaction occurs due to compressive forces derived from wheels, tillage tools and livestock trampling acting on vulnerable soils (Batey, 2009). The main soil factor controlling compaction is soil water content at the moment when the pressure is applied: field capacity or wetter conditions increases soil compaction risk (Batey, 2009). The event produces a compacted layer with greater soil density, which presents higher resistance to penetration resistance. Therefore bulk density and penetration resistance are two common ways of measuring soil compaction along with soil strength and sensors (Sharifi et al., cited by Batey, 2009). However, several authors consider it essential to examine the soil profile to identify compaction (Batey, 2009).

Soil compaction and soil structure are related in several ways. First, soil aggregation increases intra-aggregate density, but the inter-aggregate space also increases. Second, soil aggregation (in a range of aggregate sizes) increases compaction complexity, as compaction depends on the friction points between particles (Rücknagel *et al.*, 2007). Thus, soils with similar bulk densities might present different vulnerabilities to soil compaction depending on structural stability (Baumgartl & Horn, 1991). Third, when compaction forces are applied (such as machinery traffic or livestock trampling), soil aggregates rearrange, and the inter-aggregate pore space decreases with further compaction, macroaggregates breakdown, which in turn decreases inter-aggregate space (Menon *et al.*, 2015).

Root systems also interfere with compaction (Hamza & Anderson, 2005). Indeed, roots can only grow through compacted soil with pores bigger than their limiting diameter or by displacing the soil, which would require a greater force than the mechanical soil strength (Cannell, 1985). Different crop species and cultivars have different ability to penetrate compacted soil; root systems with a deep taproot usually possess the greatest ability to grow through compacted soil and can be used to minimise soil compaction risk by including them in the crop rotation (Hamza & Anderson, 2005). A better understanding of root responses to soil compaction will be possible thanks to research using computed tomography (Tracy *et al.*, 2011). Besides root’s different abilities to grow through compacted layers, a cone penetration resistance of 2 MPa has been used as a threshold limiting root growth in a cereal rotation system (see: da Silva, Kay and Perfect, 1994; Betz *et al.*, 1998; Benjamin, Nielsen and Vigil, 2003).

In relation to tillage management, many research studies have reported an increase in soil compaction under conservation tillage or no-tillage around the globe (e.g. Da Silva, Kay and Perfect, 1997; Schlüter *et al.*, 2018), among others due to a settling effect of the soil structure and the cease of repeated soil loosening by the plough. At the same time, research shows better soil structures under conservation tillage. Even the existence of plough pans (compacted layers beneath the regularly ploughed depth) that appear in conventional tillage might diminish when conservation tillage or no-tillage is adopted (e.g. Riley *et al.*, 2005).

This research aims to contribute to the existing soil ad site-specific literature on soil structure and soil compaction about how they are influenced by tillage management.

2.9. Key messages and research gaps

- Sustainable tillage management is essential to guarantee sustainable food production.
- Conservation tillage practices, particularly no-tillage, have shown to reduce environmental impacts of conventional tillage, especially decreasing erosion. However, not all environmental factors have shown consistent responses, nor the penalty on yield is clearly established because of the complex interaction of factors, including soils.
- "Healthy soils are well structured, with high aggregate stability and continuous porous systems, enabling air and water flows and benefiting crop growth. Therefore, maintaining these soil properties has to be considered an aim for any farming practice." (Veenstra, Cloy and Menon, in press)
- "Conservation tillage effects on soils' physical […] properties vary geographically because the intrinsic and environmental factors that influence aggregate stability, soil structure and consequently, the porous system, vary geographically." (Veenstra, Cloy and Menon, in press)
- "Organic matter plays an important role as an aggregation agent and stabilising soil structure, but in some locations, other agents have this major role. Conservation tillage practices have [previously] shown to increase aggregate stability in the Mediterranean [and] Atlantic […] regions, increasing soil structural stability and soils' bearing capacity for heavy machinery." (Veenstra, Cloy and Menon, in press)
- Conventional tillage is the dominant tillage management practice in Europe.
- Adoption of no-tillage should be analysed as social change. However, for that purpose, research has to go beyond nature/ society divide.

- There is a need to increase the available literature on the co-creation of farming innovation, including generally obviated actors such as farmers and non-humans (particularly soils). This means to leave behind farmers' and non-humans' passive roles and acknowledge them as active agents in innovation and social change.
- ANT is an adequate framework to undertake this kind of interdisciplinary research focused on agro-environmental innovation practices.

Chapter 3.
Methodology

Figure 4. Chapter 3 cover photo: soil sample preparation for laser particle size analysis

3.1. Introduction to the methodology

In this section, I summarise the key elements of the overarching conceptual framework and how they translate into the practicalities of the research, providing an overview of the structure of the chapter.

I start the chapter describing in detail the ANT based analytical framework, which is followed by a reflection of my positionality and the local character of the research to discuss how those might have influenced the research, as science is a social practice and no investigation is exempt from bias. Additionally, the appropriateness of conducting on-farm research is discussed.

Thereafter, I describe in detail the methods to collect and analyse the empirical data. A series of pilot studies helped to select the methods and develop the research design. Semi-structured interviews with farmers were used to collect data from within farming actor-networks to analyse no-tillage adoption and the assessment of its impact on their soils. Additionally, soil science methods were applied to analyse the impact of no-tillage on structural quality and compaction of the case studies' soils. How these data inputs and analysis relate to each other and the overall structure of the thesis chapters is explained in the next section.

3.2. An ANT based analytical framework

From the wider range of co-existing approaches to innovation diffusion and co-creation of innovation (described in the Theories of adoption of agricultural innovations), the approach taken in this project considers long-term or sustainable adoption as a process that actively modifies the innovation, and therefore farmers are part of the knowledge production. Additionally, non-humans are part of the social and can influence social change. ANT allows farmers and non-humans to adopt these roles, as discussed in the literature review.

Using ANT as an overarching framework for understanding innovation adoption means that tillage management practices (no-tillage or conventional tillage) take the form of actor-networks. Those networks are then analysed to identify chains of actors or adoption paths whose relations explain tillage management adoption. By comparing farming actor-networks it is possible to find repeated patterns and changes to those patterns.

To assemble the farming actor-networks, actors and relations were investigated, applying the definitions discussed in the literature review. In summary, actors are any humans or non-humans possessing bodies or abstract figurations that deploy in actor-networks themselves and cause a traceable impact in the investigated actor-network. Furthermore, actors are enacted by the actor-networks, meaning that what they are is co-constructed by themselves and the other actor-network members. Because actors pertain simultaneously to multiple networks, actors are multiple. On another note, relations between actors are dynamic, might extent through time and space, and the heterogeneous nature of the actor-networks results in heterogeneous and diverse relations. Additionally, actors translate messages into their terms introducing their interests as information circulates through the network. Agreement or rejection of those messages determines power relations and the appearance of network tensions. Therefore, I identified actors and relations to compose the farming actor-network configurations and paid special attention to translations to identify paths of tillage management decisions.

The methodology to identify actors and relations was also based on ANT. First, I performed a series of pilot studies to obtain an initial understanding of the topic. Then, I applied the ANT rule of 'following the actors'. To 'follow the actors' means to pursue the understanding of a social issue based on the actors that are involved in it, and not applying pre-established structures. Following the actors is to use a 'infra-language' to become attentive to what actors are saying (Latour, 2005), to then use the actors' language, metaphysics and explanations to re-assemble their realities. It is to follow or investigate the links that connect them with other actors as given by themselves. This process acknowledges that actors know more about their realities than an external researcher (Latour, 2005). In practice, that translates into not having a pre-established structure in which the actors should fit in but build this structure from the explanations of the actors. It is to leave the task of defining and ordering the social to the actors themselves (Latour, 2005). Following the actors is also understood as networks being analysed from within because 'the behaviour, definition, roles, and interests of actors are negotiated within the network' (Murdoch, 1995 p.753).

To decide where to start, this research concentrated on the action of the research question, ploughing or direct seeding, which is carried out or arranged by farmers. Therefore, I focused on farmers to describe their farming actor-networks. Semi-structured interviews were performed to be able to discuss the networks in depth. Because ANT does not limit what counts as an actor and how wide the network can spread, in practice, those limitations were set by farmers' judgement about who and what is part of their farming practice and has impacted their behaviour. Hence, *'farming actor-networks'* are the networks described and limited by the farmers around their farm management.

Semi-structured interviews addressed farmers' tillage management practice, their farm, challenges, and other actors involved in the practice according to previously reviewed literature and pilot studies. During the interview and the analysis I focused on identifying actors and how they relate to each other. Details of the method, interview design, conduct and analysis are explained in section: Semi-structured interviews. Stakeholder interviews have been used extensively in ANT studies. For example, Ruming (2009) used stakeholder interviews, together with textual and discursive document analysis; Van der Waal et al. (2018) used them together with other sources of information such as websites and documents and Devi and Kumar (2018) with ethnographic methods. The benefits of using interviews compared to other methods were that non-human actors were identified through human accounts from within the network, it was possible to collect data from different study cases in a shorter amount of time and combine them with soil sampling, and through interview recording, coding and analysis eased the traceability of the results.

From each interview, I re-assembled a farming actor-network configuration. An analogy I used to visualise ANT were molecules: each actor as an element, hold in position through the links with other actors, together developing an action. For example, proteins can conduct different processes depending on the position of their elements and groups. Therefore, I visualised the changing practices as a change in the actors or the links that hold them together. The goal was to re-assemble individual farming actor-networks from each interview and compare all of them to identify similarities and differences. In practice, from each interview I identified the actors (with names as given by farmers) and described their roles (as given by the farmer but assuming, according to ANT, that those are co-constructed by the actor-network in which they are enrolled).

Figure 5 shows the difference between a list of actors and the farming actor-network configuration. In the list the actors are plain spheres and their roles in the wider network, relations with other actors or power are not defined. On the contrary, in the farming actor-network configurations, actors (spheres) are situated within their actor-networks and their roles (position and layers), power (size) and relations (lines) are defined.

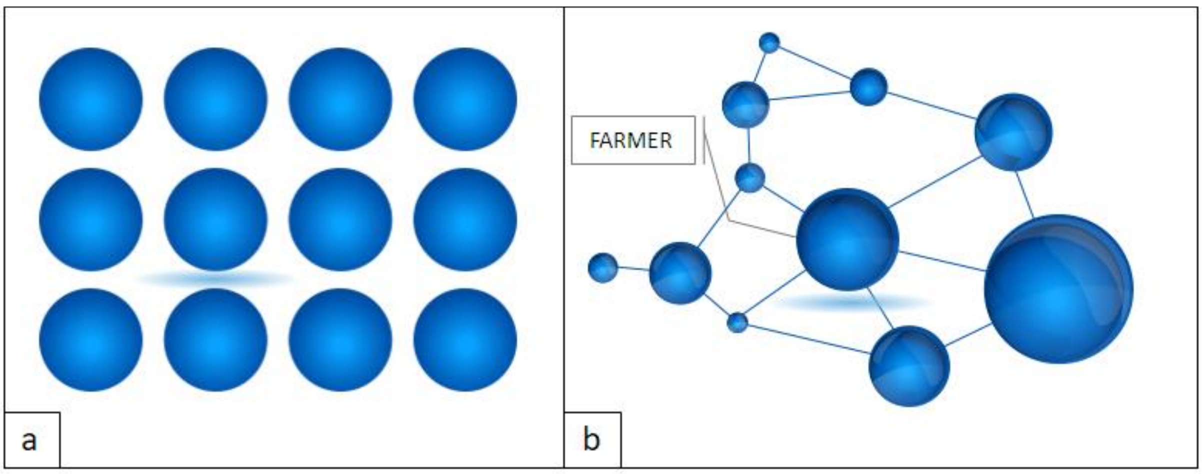


Figure 5. Lists and actor-network configurations. a: list of actors. b: farming actor-network configurations (farmer centered)

Actor-networks are heterogeneous chains of actors bond together through their relations. No actor nor relation exist by its own outside a chain of human and non-human actors (Latour, 1992). Each pair of actors is bond together through a link through which circulates some kind of flow (Latour, 2005). Each actor receives, translates, and pass the flow in a transformed way. What is circulating can be of different nature, and is modified and co-constructed by the chain. The interactions can be material, energetic, informational, economic, etc. Moreover, the interactions are constant negotiations which determine what actors are and what they are able to do, in other words, through these relations actors are enacted by the actor-network. I used chains as a methodological tool to simplify the actor-networks and focus the research on part of the wider and complex actor-network. Because I focused on the relations that co-constructed adoption of no-tillage or sustained the adoption in the long term, I referred to those chains as '*adoption paths*'.

In practice, chains were built by adding to the matrix the links to tillage management practices if mentioned during the interview. This were answers to direct questions about tillage management and the early stages of the adoption of no tillage, and other responses related to tillage management, in the wider sense of the actor-network, which provided details of the shape, roles, and relationships that enabled and sustained adoption or non-adoption. This way, the link between tillage management practice to an actor was established by the farmer. In the thesis, I distinguished different adoption paths by following the links between actors, as specified by the farmers, around a particular theme or flow related to the tillage management. This way, I re-assembled the farming actor-network configurations and I identified patterns in the form of actors' roles and chains of actors (adoption paths) which could be recognised in several actor-networks.

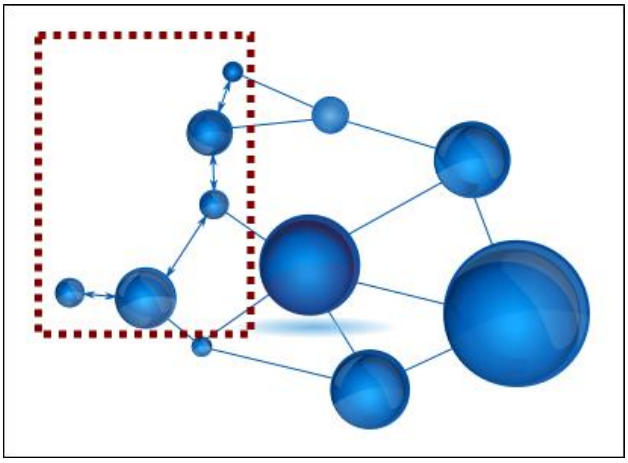


Figure 6. Adoption paths

Figure 6 illustrates the idea of an adoption path within the farming actor-network. The red rectangle highlights the focus of the analysis. The double-headed arrows (relations) symbolise the flows and negotiations between the spheres (actors). Spanish and British no-tillage adoption paths are analysed in detail in chapter 4, except those adoption paths in which soils played a key role which were analysed in chapter 5.

Soils were key actors in the analysis for both research questions. Soils' role in the adoption of tillage management practice was investigated, paying special attention to the relation between farmers and the soils on their farms. The soil path for no-tillage adoption (and non-adoption) was researched in detail in chapter 5. I focused on farmers' account of soils, acknowledging that the farmers were acting as spokespersons of soils but understanding that the language and ideas used by farmers was influenced by the farming actor-networks in which they are enrolled (Hinchliffe, 2007). Additionally, I used the concept of actors' multiplicity (Law & Mol, 2008) to study soils' multiple roles. These multiple roles greatly influenced the soil path for no-tillage adoption and how impact of the tillage management practices on soils is understood within the farming actor-networks. I used the data collected through the semi-structured interviews with farmers and in the analysis I focused on the roles soils had in farming actor-networks, which soil knowledges sustained those roles. Furthermore, I deployed soils as actor-networks themselves, opening the black boxes or punctualised actor-networks in which they had become. I did this by analysing soil classification, assessment and the soil properties that became important in each farming actor-network from the interview data. Only by establishing what soils are and what they are able to do within the farming actor-networks it was possible to understand the farming actor-networks' assessment of the tillage managements impact on soils.

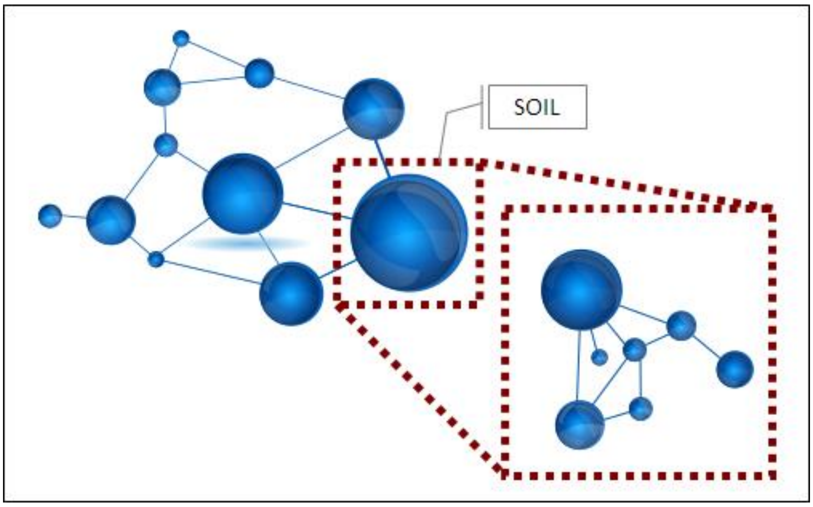


Figure 7. Deploying soils. No-tillage impact on soils assessment from within the farming actor-network

Figure 7 illustrates the exercise of deploying soils within farming actor-networks. The red rectangles represent the focus of the analysis: soil and a zoom into soil as an actor-network. The layering around the spheres represent actors' multiplicity. Chapter 5 provides the analysis of soils' adoption paths, soils' multiplicity, soils' deployment and the impact assessment of no-tillage on soils (and conventional tillage) within farming actor-networks in Spain and the UK.

Furthermore, as a soil scientist I assessed the impact on soil structure and compaction. This assessment was performed to soils as natural entities (see section: Focus on soils) under the theoretical models discussed in the literature review that understand soil structure as being dynamic and influenced by many aggregation agents and break-down factors (see section: Background on soil physical quality). I did the soil assessment independently, without the participation of the farmers. Therefore, it is understood that it constitutes a different soil science actor-network. Details of the methods used for the soil science assessment of impact on soil physical properties are given in the section Soil assessment.

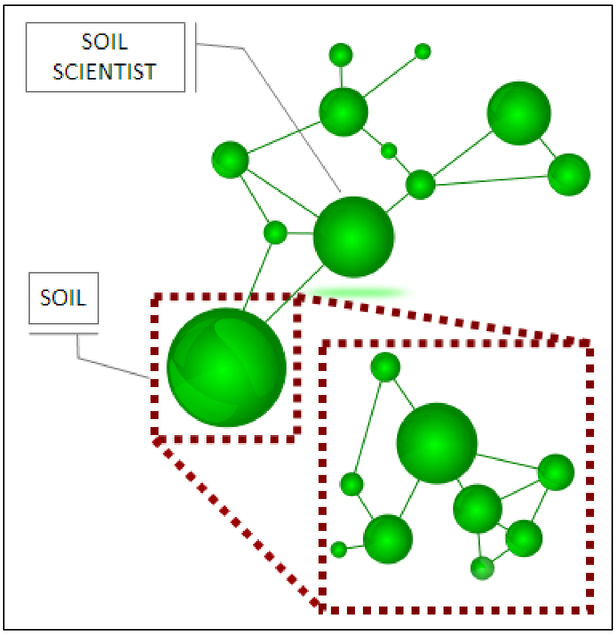


Figure 8 Deploying soils. Scientific assessment of no tillage impact on soils

Figure 8 illustrates the scientific assessment as a different actor-network in which soils are enrolled occupying a different position and role than in the farming actor-networks. The deployment exercise performed in this case focuses on soils' physical properties. I start with the assessment of soil structure because it is fundamental to understand soil functionalities and a better structured soil is more resilient towards compaction. As explained later in the chapter, I used aggregate stability and mean wide diameter to assess soil structure. Chapter 6 is the scientific assessment of no-tillage impact on soil aggregates and compaction.

Throughout the thesis I provide multiple roles of soils in farming actor-networks in addition to soils' understood as natural entities in soil science. In the conclusions chapter (chapter 7) I summarise those roles together with the main findings and I discuss the difficulties of putting into conversation soils' multiple ontologies. Figure 9 illustrates soils' multiplicity in the layering of multiple roles, pertaining to different actor-networks and the different deployments those make of soils.

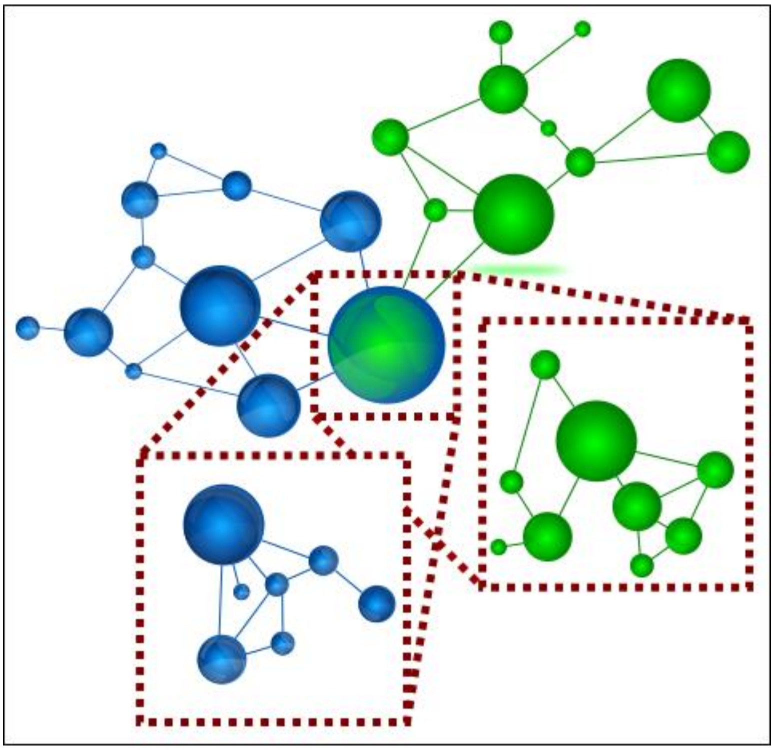


Figure 9. Reassembling the multiple soils

The ANT based analytical framework is summarised in Figure 10. The figure includes data inputs: Preliminary studies, data collection, and data analysis methods used for reassembling farming actor-network configurations, doing the external soil science assessment and reassembling the multiple soils.

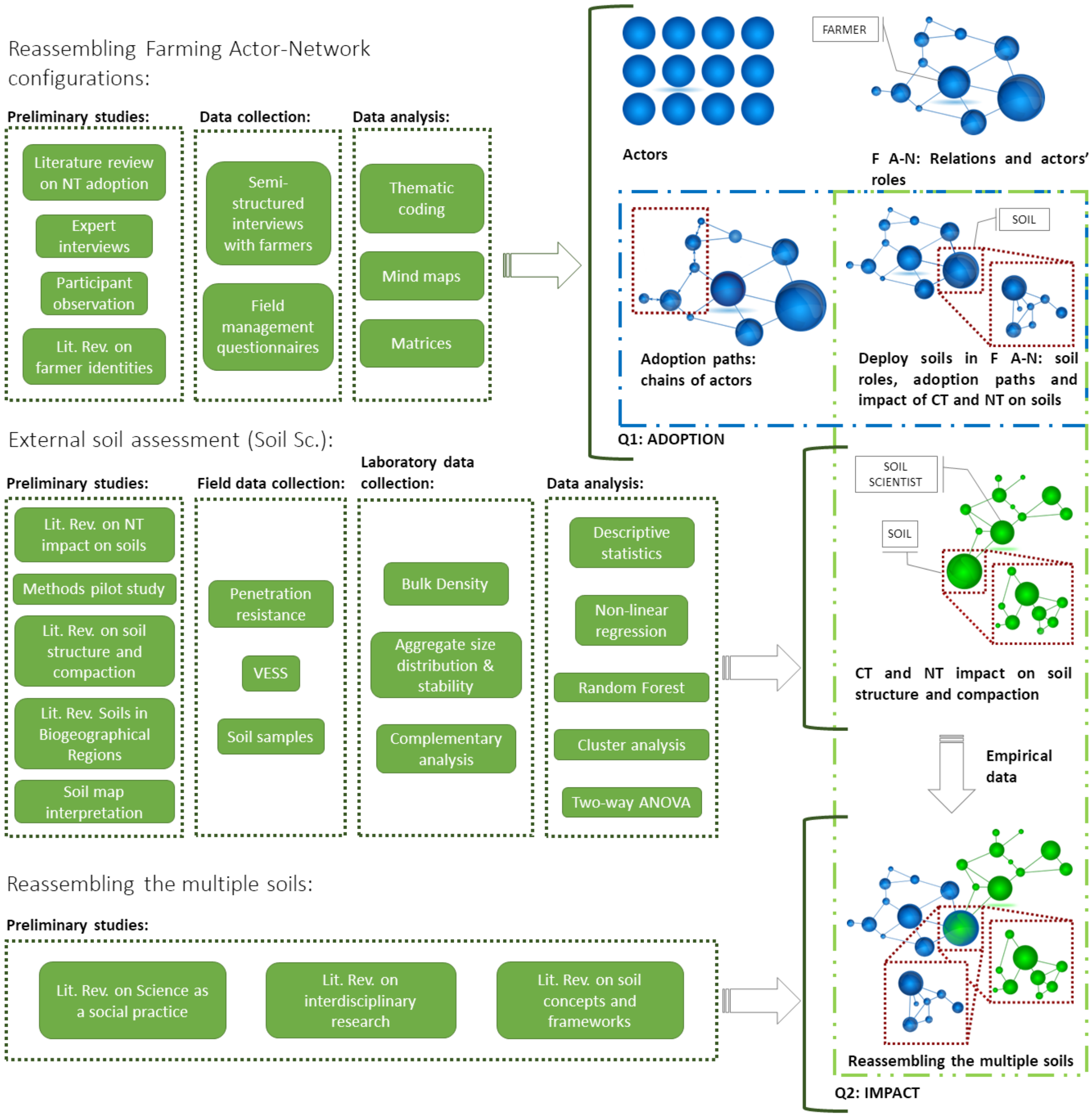


Figure 10. ANT based analytical framework. F a-N: Farming Actor-Network. CT: Conventional Tillage. NT: No-tillage.

3.3. Positionality and local character of research

This section reflects on how my identity, the relation with the farmers during the interviews, and my background have affected the research produced. As commented previously, different disciplines have diverse approaches to subjectivity. However, it has also been pointed out that no scientific practice is detached from social norms that determine the framing of questions, methods, and materials, distribution of resources, etc. Therefore, this section is also to understand in which research community this research has been produced, to understand better not only the local character of the data collected but also the local character of the research produced.

3.3.1. Positionality

During an interview, the interviewer is the main research tool. The interviewer guides and controls the interview. Who the researcher is in terms of race, class, gender, etc., does necessarily influence the interview dynamics (Sharp & Kremer, 2006; Gill & Maclean, 2002). In this section, I discuss how my identity and background (picture in Figure 11) affected the relationship with the interviewees, and thus, the qualitative data collection.

Figure 11. Myself during fieldwork

Age and gender are important aspects of interviewing. Especially if the interviewer is female, considering farming is a male-dominant industry (Chiswell & Wheeler, 2016). In this study, all farmers were male. The age and gender difference often result in the younger female interviewer playing a subordinate role towards the dominant male (Sharp & Kremer, 2006). That power relation can be beneficial for the data collection as the participant does not feel intimidated and talks more openly about his practices with less fear of judgement. This is related to the stereotypical gender discourses, which see women's role in conversations as empathic listeners of men's narratives (Pini, 2005). Moreover, the interviewer being a female, might also encourage farmers to show vulnerability and talk more openly about feelings and attitudes compared to men-men interviews. However, this subordinated role due to the female gender has its limits and cannot lead to male participants taking control over the interview (Sharp & Kremer, 2006) or leading to sexual harassment (Chiswell & Wheeler, 2016; Sharp & Kremer, 2006; Gill & Maclean, 2002).

In this research, interviews and sample collections were performed by myself alone and on-farm. That was decided to increase farmers' comfort at being in a known environment (their homes or farm offices) and not inviting them to a setting in which the power balance would have benefited me (e.g. the university). However, that meant that I was entering environments controlled by male farmers with an added risk of sexual harassment (Chiswell & Wheeler, 2016). Therefore, a protocol was developed to decrease my risk exposure. A detailed list of farm locations and overnight stays with contact numbers was shared with supervisors and family. Additionally, phone contact with supervisors or family members was done during fieldwork after each farm visit. Participants were either recruited through an intermediary or through farming forums. The anonymity of the farming forums covered sexist remarks from other forum members. Consequently, the visit of two neighbour farmers recruited through a farming forum was coordinated with a male co-worker (another PhD student), and the first meeting took place in a public space, even if in a small village that decision compromised the anonymity of participants. Indeed, for one of the participants, showing his participation in a research project probably contributed to his identity building as an innovator. Even if those strategies compromise participant anonymity, they are not uncommon in social science research, and Ethics Committees prioritise researchers' safety (Chiswell & Wheeler, 2016). In the case of this research, even if the male escort was a silent presence on the side, it possibly affected the data collection in two ways: a restrain towards sharing sentiments and a search for validation from an agronomist.

Me being part or not of the farming industry was perceived differently among the farmers. I shared my background in soil science and my intent to collect and analyse soil samples. Additionally, the interviews included questions about the farmers' relation and knowledge about their soils. Even if soil science does not necessarily link to agriculture (e.g. soil biology, soil genesis, soil mapping, contaminated soil remediation, etc.), for the majority of farmers, that field of expertise linked to their practices and generated some expectations. The creation of those expectations was beneficial for the participant recruitment, as a set of soil analysis were promised to be shared with the farmers, and that could be perceived as a benefit for the farmers. During the interviews, I handled the power assumptions regarding scientific epistemic authority (Pini, 2004) between farmer and soil scientist by avoiding any knowledge claim (Ryen, 2001), presenting myself as a student (instead of researcher or professional), showing a genuine interest in farmers knowledge and the reiteration of being an outsider of farming. However, the success of that strategy can be debatable.

My role as an outsider was highlighted by nationality. In the case of Spain, the difference was perceived in physical features (blond, blue eyes, pale). However, the possible cultural barrier due to German-Dutch origin was diluted due to growing up in Spain and sharing some cultural features. That mixture of culturally close but still foreign was an asset to drive interviews in a familiar and relaxed tone to build rapport, while at the same time, farmers showed their willingness to show their locality, not only in the interviews but also in sharing food and beverages or information about their places outside of the interviews. Therefore, in the Spanish cases, my cultural background helped to build rapport and obtain farmers' cooperation (Ryen, 2001). On the contrary, at the beginning of the data collection, the cultural differences with the British farmers were a barrier to the interview process. This was so because interviewing requires the analyst to be able to lead through difficult questions related to personal or economic problems that reflect on farming decisions. Additionally, the interviews require interviewers to reflect on the answers while they are being given, to assess if new valuable topics arise and need to be pursued, changing the pre-defined questions. Those capabilities were compromised in the beginning, when my English domain and exposure to different accents and cultural habits were limited. Indeed, misunderstandings and lack of comprehension can arise from both language and non-verbal communication (Ryen, 2001). Nonetheless, I followed a strategy of 'being a good guest' (Kuehne, 2016) and interviewing improved with increasing understanding of British language and culture and with experience.

3.3.2. The local character of this research

It is important to acknowledge that research institutions, funding bodies, available resources, networks, political situation, etc., influence research. Accordingly, I include further reflections on the project's background.

First, mention the interdisciplinary starting point of this research. The project was proposed by a multidisciplinary supervisory team and funded by a centre with a clear orientation to tackle sustainability issues from an interdisciplinary perspective. This provided access to resources (funding, training, information, supervision, etc.) and the required time to develop a new interdisciplinary research identity. Indeed, the process of performing interdisciplinary research is not only challenging at a technical level but does also require self-reflexivity to develop a new and interdisciplinary academic identity (Knaggård, Ness & Harnesk, 2018). Second, the initial framing of no-tillage as the innovative and sustainable practice was influenced by my institutions and international organisations' narratives (e.g. FAO) that support conservation agriculture. This framing changed into acknowledging farmers' capabilities to assess what is 'sustainable' in their farms and the conflicting facts in the scientific literature about no-tillage. Third, my home department being Geography, shaped the research in terms of highlighting the importance of the geographical and local aspects of farming. Additionally, the department composition of human and physical geography researchers influenced the balance of the soil and social aspects of the project. In this sense, also the availability and limitations of equipment and materials shaped the selection of methods. Finally, mention the European context of the research, which eased my mobility across borders and soil samples transport.

3.4. On-farm research

Traditional agricultural research investigates one or two factors at a time in controlled stations. Despite its importance in increasing food and fibre production, it has shown to be insufficient in addressing complex environmental and economic systems, which require integrated approaches (Wuest *et al.*, 1999) or to account for economic, societal, or environmental changes to the productivist paradigm that has been dominant since the Second World War (Clark, Christie & Weise, 1996).

Alternatively, on-farm research is performed on commercial or working farms. Many times on-farm research has been reduced to validation of crop varieties, agrochemicals, or technological packages in local environments with little involvement of farmers, other than providing labour and maybe sharing a reaction towards the innovation compared with their traditional practices (Sumberg & Okali, 1988). Nonetheless, the potential of on-farm research lies in the realism of the farms in terms of scale, management practices, and constraints faced by the farmers (Drinkwater, 2002). The combination of all of those parameters cannot be reproduced in research stations, even if they are set as commercial farms, just because of social factors. Additionally, on-farm research does not establish management guidelines and includes farmers' experimentations in the analysis, and therefore, it is recommended to study socio-economic interactions and management decisions (Drinkwater, 2002). On-farm research accounts for real farms' complexity and initiates a mutually beneficial dialogue between farmers and researchers (Luschei *et al.*, 2009). This dialogue is even more beneficial in no-tillage research, as farmers have led its spread around the Globe.

Despite its benefits, on-farm research is not extensively performed due to the added difficulties to access farms and to generalise the data produced. In conventional laboratory or field trials, the environmental factors leading to an impact are controlled and manipulated to test hypotheses. The lack of control of influencing factors in the real world leads to difficulty in testing hypotheses (Drinkwater, 2002). Detailed descriptions of sites characteristics are required to improve the hypothesis testing, with its consequent increase in research costs (Drinkwater, 2002). Even then, the same degree of certainty cannot be achieved due to the number of interactions between the factors and the quality of the data collected. Those might be the reasons why there are only a few on-farm examples of soil management impact on soil health (Williams, Colombi & Keller, 2020).

However, in light of the advantages that on-farm research offers to study innovation, this strategy was applied in this project. Additionally, neighbour farms were selected to reduce physical and social variability, focusing on different management practices (Drinkwater, 2002). Nonetheless, this was not always successful as soils are spatially highly variable. Details on research design and issues of generalisability are discussed in upcoming sections.

3.5. Pilot studies

This subsection describes the preliminary work undertaken to understand the farming context in the UK, and particularities related to no-tillage farming, which helped to shape the consequent research.

3.5.1. Participant observation

I attended two on-farm workshops for farmers, organised by Scotland's Rural College (SRUC), in February and March 2017 (Figure 12) and a no-tillage on-farm farming fair (Groundswell) in June 2017. Participant observation is an ethnographic research method that puts the researcher where the action is, taking part in peoples' daily activities or uncommon events as means of learning about their life routines or their culture (DeWalt & DeWalt, 2010). It can be the only method applied for data collection, but it is often used to approach the fieldwork, gain an understanding of fundamental processes and provide context for interview and questionnaire guides (DeWalt & DeWalt, 2010).

Figure 12. On-farm workshop organised by SRUC.

I attended the events to be introduced to farming practices and communities and gain a holistic understanding of farmers' physical environments and social realities in the UK. My field notes focused on farmers' attitudes towards soils and scientific knowledge. Additionally, during the workshops, I handed out short questionnaires about no-tillage drivers and barriers to farmers and extension services workers. I used the preliminary results of the collected data to shape the in-depth interview protocols.

3.5.2. Experts interviews

Context interviews were performed with researchers in the UK. Interviews with experts are considered an efficient method of gathering data at the exploratory phases of the research (Anon, 2009a). Experts in the research area of the project share an understanding of the social relevance of the topic, which motivates them to participate, resulting in useful entry conduits to the investigated field (Anon, 2009a).

The aim was to enrich my knowledge of the UK's physical and social environment and its influence on no-tillage adoption as perceived by agronomic and social researchers. These interviews were performed mainly on the telephone, recorded but not transcribed. Answers were not used as results to build the farming actor-networks but as exploratory data to further design the research, particularly the semi-structured interviews with the farmers and widen the scope of the literature review. Therefore, the disadvantages of telephone interviewing regarding reduced social cues such as body language, was outbalanced by the advantages of accessing a wide geographical area, saving travel cost and being more time-efficient (Opdenakker, 2006).

3.5.3. Soil assessment pilot study

I participated in master and undergraduate projects about no-tillage in the UK, which I used as a pilot experience for the scientific soil quality assessment. The team was integrated by Jo Wilkinson, Sarah Stewart, Jim Heaton, and Pedro Almeida, under the supervision of Manoj Menon and the assistance of laboratory technicians Alan Smalley and Robert Ashurst. Results of the pilot study influenced the sampling design and soil properties included in this research project. The changes emerged from the results of the assessment combined with the work loads. Particularly, the soil assessment pilot study validated the research design comparing neighbour fields and the focus on soil structure and compaction. However, it rejected a focus on nutrients and soil organic carbon fractions and a depth of analysis up to 60 cm.

For the soil assessment pilot study soil samples were collected during October and November 2016 in three cereal farms in the UK, with soils classified as freely draining slightly acid sandy soils, freely draining slightly acid loamy soils and freely draining lime-rich loamy soils. In each location, five pits were opened in no-tillage fields and three in tillage fields. In each pit, soil samples were taken in layers of 10 cm depth until 60 cm. Additional cylinder samples to measure bulk density were taken in the same 10 cm layers until 30 cm depth. Visual Evaluation of Soil Structure analysis was performed at each pit. Nitrates, Ammonium, orthophosphates and potassium were analysed for the first 50 cm with an Ion Chromatography analyser. Wet aggregate stability was analysed using wet sieving for samples until 40 cm depth, with sieve sizes 5.6 mm, 2 mm, 1 mm, 0.250 mm and 0.065 mm. Loss on ignition was used to measure soil organic matter. Soil organic carbon was calculated for all aggregate sizes, and total organic carbon was measured in samples until 60 cm depth.

3.6. Research design

This section provides the rationale behind the selection of researched farms in Spain and the UK and the participant recruitment process.

First, I assumed farming actor-network configurations between no-tillage and conventional tillage were different and that those differences explained tillage management decisions. Accordingly, farmers were identified as no-tillage and conventional tillage farmers. Second, agro-environmental and socio-economic actors and their relations were assumed to vary geographically; therefore, biogeographical regions were selected. Third, participants were recruited as neighbours to reduce the factorial variability and focus on tillage management to assess the impact on soil properties. In total, 20 farms were distributed in pairs of neighbours (referred to as research locations) in two countries from different biogeographical regions: the UK and Spain.

3.6.1. Biogeographical regions

Research locations were selected from different biogeographical regions based on the assumption that they would present diverse agro-environmental and socio-economic conditions. This way, it was possible to study two different contexts in which no-tillage and conventional tillage are practised. Ideally, a range of biogeographical regions would have been sampled, but in the scope of the project, it was only possible to visit Spain and the UK.

Biogeographical regions integrate vegetation, climatic, geologic, geomorphologic, edaphic and land cover information. European biogeographical regions were delimited for Natura 2000 network by the European Environment Agency. The biogeographical regions were based on interpretation and generalisation of the Map ‘Natural Vegetation of the member countries of the European Community and the Council of Europe’ from Noirfalise A., 1987 (Roekaerts, 2002) and resulted in the map shown in Figure 13. Because of the integration of various soil formation factors in the delimitation of biogeographical regions, they are adequate frameworks for the analysis of soil geography at a European scale, better than administrative boundaries or drainage basins (Ibáñez, Zinck and Dazzi, 2013).

Participant farms were not selected to represent typical Atlantic and Mediterranean conditions, but a variety of conditions found in each region. Furthermore, local administrative units (LAU) for territorial statistic at the European Union were used to provide local context for farms. LAU level 1 are territorial units that join several municipalities with similar socio-economic conditions. In Spain, LAU 1 units are referred to as agricultural regions (‘*comarcas agrícolas’*).

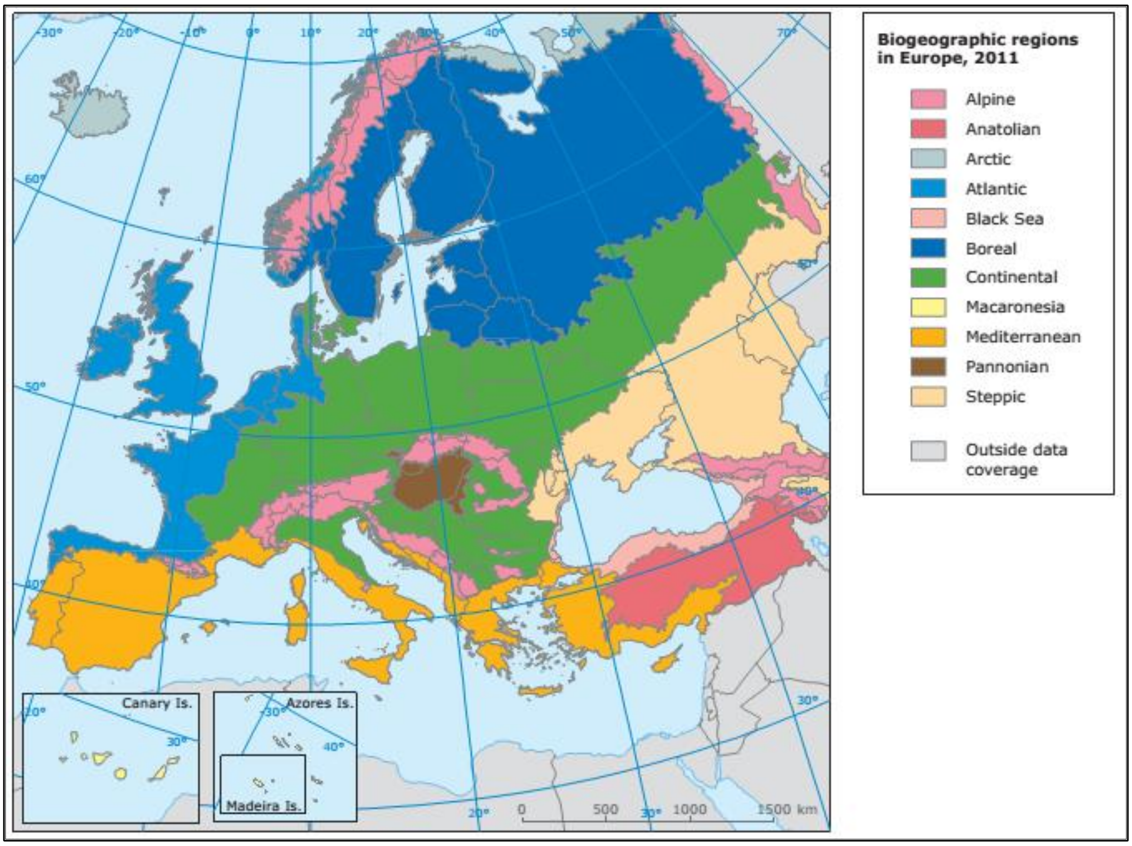


Figure 13. Biogeographical regions in Europe. Source: European Environmental Agency.

To account for different tillage management impact on soil physical, further reduction of the internal heterogeneity of agro-environmental conditions was made, assuming that neighbour farms shared major agro-environmental and socio-cultural conditions. Therefore, research locations encompassed a pair of no-tillage and conventional tillage farmers to compare the effect of tillage management between neighbour fields. However, after analysing collected data, these did not always support those assumptions and led to re-grouping soils to allow the assessment on similar soils.

Soil sampling and field measurements were conducted in one field from each farm, which was selected by the corresponding farmer. VESS was performed at three random sites within the field, where soil samples were collected at 0 – 5 cm and 5 – 10 cm depth for aggregate stability, aggregate size distributions and other soil properties’ analyses. Furthermore, in a 1 m radius of the extracted soil block, at each site, two (initially three) bulk density samples were taken from 0 – 5 cm and from 5 – 10 cm and three penetration resistance measurements were taken.

3.6.2. Participant recruitment and data management

The participant recruitment process followed a mixture of clustered and snowball sampling strategies. The aim was to recruit five pairs of no-tillage and conventional tillage neighbours in the UK and five pairs in Spain (twenty farmers in total). All cases were cereal farms and no-tillage sampling fields were at least one year under no-tillage. No other criteria regarding farms nor farmers were applied resulting in a variety of farm sizes, land tenures, crop rotations, business models etc. and a variety of farmers regarding age, education etc. even their main source of income was not always farming. To achieve the recruitment of no-tillage and conventional tillage neighbours, the focus was on recruiting no-tillage farmers first because this practice is less extended than conventional tillage. Requests searching for participants were posted on two farming forums, The Farming Forum (Anon, n.d.) in the UK and Foros Agroterra (Anon, n.d.) in Spain, noting that internet-based recruitment leads to a bias towards farmers familiar with the internet and social media. Additionally, in Navarra, some participants were recruited through an agricultural extension service worker who acted as a gatekeeper. The use of the gatekeeper speeded up the recruitment process, but it introduced a bias in the selection process as those farmers had a link with the extension service. Further recruitment was done through snowballing or respondent-driven access by recruiting neighbours whose details were provided by the no-tillage farmers. Moreover, clustered recruitment was followed to complete pairs of farmers, based on the first participant farm location, contacting commercial farms in the neighbourhood through email, phone or in person.

Snowball recruitment is useful when the studied population is not known or difficult to access (Sedgwick, 2013). However, as it is not a random selection, a bias regarding the probability of being selected from the population is introduced (Sedgwick, 2013), and therefore does not lend to statistical inference (Maertens & Barrett, 2013). However, it is a common practice to recruit commercial farmers for interviewing purposes in innovation studies and farming social network analysis (see: Carolan, 2006; Díaz-José *et al.*, 2016). Additionally, in this research, it was not the only recruiting method, and in the resulting sample of farmers, participants were not all interconnected. On another note, clustered recruitment does also introduce a bias regarding the categorical variable the subjects/objects are clustered around. Nonetheless, in this case, the sampling was geographically clustered on purpose to compare no-tillage and conventional tillage neighbour farms.

All participants were emailed or handed in an information sheet. Those contained details about the research, what participation entailed, the possibility to withdraw at any moment, and contact details of the researchers and supervisors if questions or complaints arose during the project. Additionally, farmers were asked to sign a consent form to give written proof of understanding the extent of the confidentiality and anonymity, and written consent to be interviewed, recorded, and their answers shared among the research group. Those consent forms and other data collected during the research was stored in secure lockers and computers with passwords.

It is a common practice among studies involving human subjects to protect participants from possible damages caused by their participation or their opinions. An opposite alternative, particularly in the frame of co-production of knowledge, is co-authoring research outputs, but that requires the involvement of farmers in output production. In the case of this research, no names are provided, but complete anonymity cannot be granted. This is because of the recruitment processes, the geographical character of the research, which requires details of farms and their context and the fact that it was performed in farming communities in which those details might stand out or be known.

3.7. Semi-structured interviews

In this section, I justify the use of semi-structured, in-depth, qualitative interviews as a methodology to collect farmers' accounts of no tillage and conventional tillage adoption, their farming actor-networks and their relations with soils. Furthermore, I provide details about how I designed, conducted and analysed the interviews. I finish the section by acknowledging the limitations to the generalisation of the findings.

3.7.1. Semi-structured interviews as a research method

Semi-structured interviews are 'conversations with a purpose' (Mason, 2002). The aim is to gather in-depth information of informants' accounts on themselves, their lived experiences, values, ideology, cultural knowledge, decisions and perspectives (Johnson, 2001). In qualitative interviews, participants are seen as meaning makers as opposed to passively providing pre-established answers (Warren, 2001). Semi-structured interviews are appropriate for research questions in which the knowledge sought is often taken for granted or in which different conflicting perspectives on the same topic exist (Johnson, 2001). These reasons justified the use of this method to collect data in this project.

Semi-structured interviews follow thematic topics or a set of pre-defined questions but have a flexible structure to enable new topics emergence (Mason, 2002). Therefore, it requires the interviewer to critically reflect on the conversation that is occurring to assess if it is worth following the paths opened by the interviewees in their responses. Moreover, it is the interviewer's responsibility to build the required rapport for the interviewees to feel comfortable sharing information. Mainly by using a relatively informal style (Mason, 2002) and a relaxed tone in verbal and non-verbal communication.

In-depth interviews were opportunities for participants to construct their worlds and their self-identities. Interviews are occasions in which interviewees can describe themselves and their world in their own words and stress what they find important (Kvale and Brinkmann, 2009 cited in Kuehne, 2016). However, by doing so, participants shape the world in which they live and how they are according to their truth, at best. Participants can also manipulate, lie or just decide which information is shared, to portraying themselves in a certain manner. In the case of farmers, this is often related to portrait themselves as *'good farmers'*, *'innovators'*, but can also be in any other way that might be important for them (Kuehne, 2016). Farmers' masculinity might also be displayed by presenting themselves as heterosexual, powerful and knowledgeable men (Pini, 2005). Moreover, the information given is subject to a moment in time and to the interviewees own truth. Therefore, participants' views might change or might not be shared by other 'insiders' of the researched topic.

3.7.2. Semi-structured interviews design

I designed the interview questions around several thematic topics. Those topics were framed by the overall ANT approach and the specificities of tillage management that were highlighted in the literature and during the pilot studies. The selected topics can be clustered around two methodological aspects:

- *Network description:* Farmers are situated in agricultural networks. The overall aim of the interviews was to identify and describe the actors forming these networks, their roles and relations, from the farmers' point of view. This included overall descriptions about the farm and the farming tradition and community and questions addressing soils and no-tillage as actor-networks (what they are, how they are articulated, where and how they act, how the farmers engage with them, etc.). Questions about farmers' values and relations to other actors were included to define farmers' roles in farming actor-networks. Questions were also designed from a list of possible actors (e.g. innovative farmers, media, contractors, policies, etc.), collected from the literature review and pilot study. Farmers were asked regarding their experiences in the interaction with those actors to clarify roles and relations. The flexible structure in the interviewing meant that it was more of a conversation, and questions were not read but constituted a checklist of the scope of the interview. Nonetheless, explicit questions about the potential actors were made when these were not discussed in the course of the conversation.

- *Following adoption in the networks*: Attention was paid to the network configuration differences that could reveal relations that enable or constrain farmers' choice of tillage management practices. As choice is a matter of power and in ANT this is a negotiated outcome, it was important to formulate questions regarding the attitudes or links of different actors towards the different tillage practices, their relations with farmers and their explicit or implicit roles in adoption. Additionally, technological innovation has been framed as providing solutions to existing problems. Therefore, farmers were questioned about problematic or challenging situations on their farms, independently of the nature of those problems. Linked to the 'problem-solution' framing are knowledge production and circulation. For this reason, questions about knowledge generation, the ways it is shared, and processes of learning were made during the interviews.

These were the guidelines for the semi-structured interview design. The application of those guidelines resulted in 28 questions with follow-up questions to search detail and 4 additional questions for conventional tillage farmers regarding no-tillage. The complete list of interview questions can be checked in Appendix A.

3.7.3. Interview conduct

I designed the interview to be a face to face conversation with one farmer. However, the reality of farming is complex, and on two occasions, interviews were done with multiple interviewees. This was considered enriching to the data collection and reflecting on the complex farming networks in which farm responsibilities might be shared among spouses, other family members or business partners.

Where consent was given, interviews were recorded. In total, 21 interviews were conducted, and 20 were recorded. There is no exact number of needed interviews to complete a qualitative research project. By contrast, it is generally accepted that a *'saturation point'* has to be achieved, which means that topics and views presented in new interviews had already been discussed in other interviews and that no new relevant information is generated (Johnson, 2001). In this study, the ANT approach sought to give rich accounts of the networks rather than compare them with a huge amount of other networks. Additionally, the interdisciplinary nature of the research required balancing the workload between social and soil analysis. Therefore, each farm was treated as a case study and effort was put into enriching the descriptions of those actor-networks rather than in increasing the number of participants. Thus, the number of participants was fixed from the beginning at 10 interviews per country.

In the UK, 12 h 7 min and 38 sec of recorded material were produced in 9 interviews. One interview was not recorded, but notes about the responses were taken during the interview, and further reflexive field notes were taken after the day spent on the farm. In Spain, 11 interviews were produced. One of the no-tillage interviewed farmers did minimum-tillage all his fields, and therefore he was not included in the soil assessment. In total, in Spain, 17 h 10 min and 33 sec of recording were produced. Being recorded inhibited farmers relaxed conversation in the first minutes of the interview. The recording quality was generally good, except for a couple of interviews which were done in cafes with occasionally high levels of background noise. Additional field notes were taken about farm visits, describing the interviewing experience in a personal diary style.

3.7.4. Interview analysis

3.7.4.1. Interview transcriptions

To further analyse the data collected in audio format, interviews were transcribed into text formats. Verbatim transcription is used to maintain participants' words and referencing speaker (interviewer or farmer) and time since the beginning of the interview. Transcriptions from the British interviews were done by a transcription service, and Spanish transcriptions were done by myself. In the latter cases, the transcription process was also a reminder of the lived experience and evoked details not recorded, and at the same time, an opportunity to review the answers and continue to make sense of the data as part of the analysis. However, transcriptions are very time-consuming and in the case of this research, the quality of the transcriptions obtained and the time saved reassured the worth of the transcription services' costs.

Besides the practicalities of time and money, a note on the manipulation of the original data has to be made. Through transcription, the audio data is transformed into text. In doing so, several errors might occur. Those errors and problems, as identified by Poland (2001), are in sentence structure, use of quotation marks, omissions, and mistaking words or phrases for others. Additionally, it has been argued that transcriptions are constructs of the audio recordings rather than representations of them (Hammersley, 2010). Taking an ANT approach to the flow of information through a research process, as discussed in previous sections when ANT was presented, the information is always transformed by every step and every actor involved. Therefore, the interview, the audio record and the transcript are different things. However, the transformations that the information undergoes do not necessarily diminish its value. In the case of the transcripts, the value consists in the data that is maintained from the interviews, the possibility of storing, sharing and further manipulating the data by coding and analysing it.

3.7.4.2. Interview coding

Qualitative data from the interviews was inductively analysed. That means that rather than fitting the data into pre-established theoretical frames or searching for evidence that confirms assumptions (deductive analysis), theoretical models arise from the data (Thomas, 2006). This does not mean that the analysis is not influenced by the theoretical framing or the research question, but it means that no prior assumptions about the results are made. Particularly, applying the ANT based analytical frame I contemplated the possibility of non-humans having agency, actors being multiple, and actor-network configurations determining tillage management, and I contrasted these assumptions with the data. Furthermore, from the list of possible actors I developed from the pilot studies and literature review, their enrolment in the farming actor-networks and their roles emerged from the interviews rather than from previous materials. Therefore, this is a suitable approach to data analysis to follow when applying ANT.

Additionally, thematic coding was applied. This is a systematic method in which the analyst reads the interview transcripts and groups data into topics and themes. This is done by assigning codes to segments of text. Those codes refer to the topic discussed. Because this is applied to all interviews, a comparison between codes is possible. In conclusion, thematic coding is a means by which the data is condensed, establishing clear links between the transcripts and the results and enabling the development of a model from the data (Thomas, 2006).

As mentioned, the analysis is influenced by the aims and objectives of the research and the theoretical approach. In the case of this research, the aim was to describe the actor-networks in terms of identifying the actors in each network and their relations. Therefore, the codes correspond to actors and to attitudes towards them from the farmers' side. Normally, in the generation of new categories resulting from grouping topics of preliminary analysis, the descriptive codes (in the interviewee's words) are interpreted by the analyst and transformed into analytical codes. Those analytical codes refer to broader themes, attitudes or meanings. However, organising the actors in the hierarchical manner of coding trees is not a reflection of networks dynamic where actors are inter-linked between different domains. Multiplying the codes for the same actors would also have been confusing. Therefore, the resulting categories and coding trees in this project does not represent the themes arising from the interviews but present a single possibility about how actors could be grouped and maintained throughout the coding phase.

A series of decisions were made about the practicalities of coding the interviews. Spanish interviews were coded and analysed in their original language without translations. Spanish is my native language, and translations would have been time-consuming, required a professional translation to avoid mistakes, and it would have added another layer of transformation to the data from the interviews. Additionally, coding was assisted by the qualitative data analysis software NVivo. This resulted particularly useful because the software allows accessing all text segments assigned to a particular code. Then, it was possible to compare how similar or dissimilar farmers talked about certain actors in their farming actor-networks.

3.7.4.3. Reconstructing the actor-networks: cognitive maps and matrices

Through the coding process, the network actors were identified, and some of the attitudes described farmers' relation with them. However, this resulted in something more like a list of actors rather than in an actor-network configuration. Further analysis had to be made to understand the nature of the actors, their roles in the particular networks and how they relate to the other actors. For this, additional tools were used. Although it could have been understood as part of the grouping exercise in coding, in the analysis of this project, coding and building the networks were understood as two distinct phases.

Initially, it was planned to build the actor-networks from the codes of each interview through building cognitive maps. Cognitive maps are graphic illustrations of people's mental associative representations about how they understand the external world (Gray *et al.*, 2015). Individuals use those mental models to reason and make predictions (Jones *et al.*, 2011). This potential of cognitive maps has been widely used in a range of fields, including system analysis in ecology and agriculture. In those fields, they are used to synthesize expert knowledge in a graphic expression about how key concepts (nodes) are connected through relationships (lines). They organise those concepts in a way that provides hierarchies and inter-connections between different domains (Cañas, 2010). Because of their potential in analysing systems and networks, they were produced from data from initial interviews with MindMap software. Nonetheless, in practice, they were not representing some of the complexities of actor-networks (e.g. actors' multiple ontologies or the nature of the relations between actors) and additionally they rapidly developed into complex and unreadable maps which were not self-explanatory anymore. Therefore, this methodology was dropped as a representation of actor-networks, although simplified cognitive maps were still produced throughout the whole analysis.

Then, matrices were created to be able to compare different actor-networks. Matrices are common tools to assess the environmental impact of project actions on system components and to indicate interdependence among system components (Shopley, Sowman & Fuggle, 1990). In this study, MS Excell sheets were created opposing the list of coded actors to the list of interviewed farmers. In the coinciding cells, a summary of the coded responses was provided. In this arrangement, columns represented individual networks and rows generic actors (e.g. father) or specific actors' (e.g. the rural extension service from a particular region) descriptions and roles in each network. This arrangement loosely followed Latour's (2005) suggestion of writing actors' descriptions in a way that could be shuffled around. Additionally, Latour (2005) also defended the value of actors' own meta-language (with stronger concepts than the analysts' ones) and recommended avoiding the substitution of participants words with social vocabulary. This was possible in the matrix format by including actors' (farmers') own descriptions in the coinciding cells, avoiding problems of assumptions and misrepresentations. In conclusion, the matrix method enabled the comparison between actor-networks configurations in a systematic manner, maintaining farmers' language.

3.7.4.4. The generalisation of qualitative research

The generalisation of qualitative research results is often questioned. In the past, it has been claimed that qualitative research cannot be generalised at all because social phenomena are neither time- nor context-free and that it is not its purpose to be generalizable (Williams, 2000). On the contrary, it was said that the purpose of qualitative research is to deepen into the causal relations of particular instances (Gobo, 2008). Therefore, research projects with qualitative methods direct resources towards detail rather than scope and rely on small sample sizes, compared to quantitative methods. The focus on detail is common to all qualitative research, but many sociological investigations generalise their results to 'similar conditions' (Williams, 2000; Payne & Williams, 2005; Gobo, 2008).

The problem with generalisability is sample representativeness of the target wider population. While some researchers maintain that representativeness can only be assured through statistically meaningful samples or probabilistic samples, others claim that 'theoretical sampling' based on the subjects' status regarding particular research criteria can lead to theoretical development (Gobo, 2008). Then, generalisation is possible to a moderate degree and has been described as 'naturalistic generalisation', 'transferability', 'analytic generalisation', 'extrapolation', 'moderatum generalisation', etc. (Gobo, 2008). Nonetheless, the problem of representativeness persists, as inferences are made for populations of unknown characteristics.

The approach taken in this research is rather conservative regarding the generalisation claims made for both the soil science and the sociological results. This is so because the complexity and uncertainty of the real world (population) applies to both. Thus, each farm is treated as a case study. How soil data is treated is further discussed in the corresponding section. In the case of the farming actor-networks, individual actor-networks are drawn for each farm, understanding there might be individual particularities that are not repeated in other cases. Nonetheless, actor-networks are compared in search of repeated patterns in and differences between each category. By acknowledging heterogeneity, a moderate generalisation to each category is made in the extent, or accuracy level, of the description of those categories regarding the factors regulating the patterns.

Results are discussed in the empirical chapters, arranged by country and structured around network configurations.

3.8. Soil management history questionnaires

This research had an on-farm approach. As explained, this kind of research has to deal with high variability in the factors that affect the measured variables. Accordingly, it is important to account for the range of possible causes of the differences in the measured variable.

In this case, the variables of interest were related to soil physical quality. Thus, how the field was managed in the past had a direct impact on the variable of interest. A questionnaire was developed to account for the possible influences of a variety of field management operations. Those questionnaires were handed to the participants in person on the day of the interview and returned by email or post by 12 of the 20 farmers interviewed. I decided this procedure to provide time to the farmers to collect the information of the last five years of any farm operation performed on the selected field. Data was not investigated further but served to provide examples of farm operations in no-tillage and conventional tillage farms.

3.9. Soil assessment

In this section, I explain and discuss the different methods used to describe and assess soils. Those methods were aimed to assess soil physical quality. Additionally, complementary tests and soil descriptions were produced to enrich the discussion and understand the many interactions of different aggregation agents. Results are presented in the empirical chapters as a soil science actor-network, layered to the farming actor-network and connected to it through the multiplicity of soils and the relations researcher – farmer.

3.9.1. Soil descriptions

Soil maps from the UK and Spain were consulted to obtain information about soils in the research areas according to their classification. For this purpose, the digitalised version of the Spanish national soil map from 1992 in Soil Taxonomy classification at scale 1 : 2,000,000 (CSIC/IRNAS, 2000) for the Spanish locations, whilst for the British locations, the online SoilSape viewer (Cranfield-University, n.d.) was used, which is a simplified version of the 1 : 250,000 scale Digital National soil map for England and Wales and in turn uses a simplified version of the British classification.

3.9.2. Soil structure assessment

In this section, the different methods used to assess soil structure are explained and discussed. Details about soil structure and soil aggregation were provided in the literature review chapter (Background on soil physical quality). The applied methods included field assessment through Visual Evaluation of Soil Structure (VESS) and wet sieving to measure aggregate stability.

3.9.2.1. Visual evaluation of soil structure

Visual Evaluation of Soil Structure (VESS) is a field method to assess topsoil structure. Because soil structure is related to a number of soil properties, this test provides inferable information to assess soil quality and assist management decisions. In general, visual examinations of soil structure are useful to provide information about land use impact on physical soil properties, but different available indexes do not always agree on the results (Pulido Moncada *et al.*, 2014a).

The VESS method consists of breaking down, describing and scoring a spade of topsoil (Figure 14). The description is focused on the size, shape and strength of aggregates, visible porosity, and presence of roots (Ball *et al.*, 2017). Because the method is intended to be used by professionals but also by farmers and land managers, it is designed as simple as possible. First, a block of soil is extracted from the field by cutting three of the sides and subtracting the block as integer as possible. From the less altered side, layers or soil horizons of visibly, different aggregation patterns are identified. Then, those horizons are assessed and scored separately with the assistance of a score chart Appendix B. That chart describes the characteristics of each of the categories, that range from 1 (healthy) to 5 (compacted). Finally, each score is weighted with the thickness of the horizon to provide an overall score for the topsoil. Besides this, the overall score enables comparison between soils, providing information from each horizon identifies possible problems overseen by means as, for example, specific locations of compacted layers in the soil profile causing diverse effects on water infiltration (Ball *et al.*, 2017).

Figure 14. Pedro Leitão performing VESS during pilot studies

Additionally, it is recommended to perform the test when the soils are not too wet nor too dry so that visible porosity can be easily identified, the aggregates do not smear nor are too hard or fragile (Ball *et al.*, 2017). In practice, however, in this research and many other projects involving a high number of locations, it is not possible to re-visit the fields or wait for suitable conditions, which also disrupt farmers' schedules as those are the times when field operations can be performed. In the case of this research, notes about the moisture conditions were made and water content calculated from bulk density samples to be able to frame and discuss VESS scores.

For this project, VESS was performed on three sites in each field, and overall scores were calculated.

3.9.2.2. Aggregate stability as a measure of soil structure quality

Aggregate stability is a measure of the resistance of soil aggregates against disruptive forces and has been widely used to compare land uses' impact on soil structure. In particular, aggregate stability is used to study soil vulnerability to soil erosion (e.g. García-Orenes *et al.*, 2009), surface crusting (e.g. Lipiec *et al.*, 2018), tillage (e.g. Watts and Dexter, 1997) and compaction (e.g. Baumgartl and Horn, 1991). Alternatively, soil aggregation can be used as a key indicator for geo-system resilience to disturbance (Cammeraat & Imeson, 1998). Of interest are the proportion of aggregates in the bulk soil that resists a particular disruption and their size. Besides being used extensively, there is no universal standard protocol used across research, which has been highlighted as a handicap to compare different studies (Obalum, Uteau-Puschmann & Peth, 2019). Nonetheless, it also has been pointed that a standard might be counterproductive as different methods enhance particular aggregate breakdown forces and flexibility to perform diverse tests might allow the detection of impacts caused by soil management that involve diverse forces (Obalum, Uteau-Puschmann & Peth, 2019). Accordingly, soil sample storage, preparation and testing can be adjusted to the specific research objectives.

In sieving methods, the final aggregate stability is given by the proportion of the aggregates that resist the mechanical or water disruption and is calculated through different indexes to compare soil samples. Sieving methods can be classified as dry or wet. Dry sieving is used as a proxy of mechanical disruption in studies simulating tillage or focusing on the proportion of soil aggregates susceptible to wind erosion (e.g. Hevia, Mendez and Buschiazzo, 2007). Wet sieving methods are used to study the disruptive forces caused by water as a proxy to rain, flooding or other water-related scenarios. Wet sieving is also adequate to assess the impacts of land use transformation from rain-fed to irrigated land (Amézketa *et al.*, 2003). In any case, even if the underlying justification of the chosen method is to determine soils behaviour against specific disruptions that could affect their stability in the field, the forces of the experimental methods are always artificial (Nimmo & Perkins, 2002), and therefore, results have to be treated as outcomes of experimental set-ups and not as representative of real circumstances.

There are additional considerations concerning soil sample storage, pre-treatment and the sieving method itself. Storing air-dried aggregates for long time periods also increases aggregate stability due to the increase in contact points between particles and increasing concentrations of cementing agents such as calcium carbonates or silica (Kemper & Rosenau, 1984).

Moisture content affects aggregate stability. Therefore, it is important to equalise moisture content across samples. Options are to dry samples completely, adjust water to a desired content or achieve water saturation. It is necessary to oven-dry samples at 105°C to dry them completely, but this temperature increases aggregate stability in clayey soils and might create artificial stability for some soils. To reach a desired water content (e.g. field capacity) requires tensile plate equipment and more time, therefore it is rarely used. On the contrary, saturating the soil is a time-effective approach and therefore used in this study. There are many ways to saturate the soil samples, quick submersion in water enhances the disruptive process of slaking, whereas capillary rewetting can be done by gently misting with a diffuser or by spraying the sample or quicker, but less precisely, by matching the water level to the level of the sieve with the soil sample on top. Le Bissonnais (1996) proposed comparing quick and slow pre-wetting methods to understand aggregate stability behaviour of different soils under different circumstances. Moreover, Le Bissonnais and other researchers suggest the use of ethanol, instead of water, to reduce the disruption after different pre-wetting methods.

Different wet sieving machine designs serve to account for different processes. For example, rainfall simulation (e.g. Hu *et al.*, 2018) or continuous water flow. However, the most commonly used approach is to study wet aggregate stability by submerging the sieves in water by hand (e.g. Six *et al.*, 2000) or automatically. Even if deionised water can have a greater disruptive effect on the aggregates than tap water, it is preferred to use deionised water to favour the research replicability. Further variations in the method exist in the number and sizes of the sieves, the number of strokes per minute, the height of stroke and sieving duration.

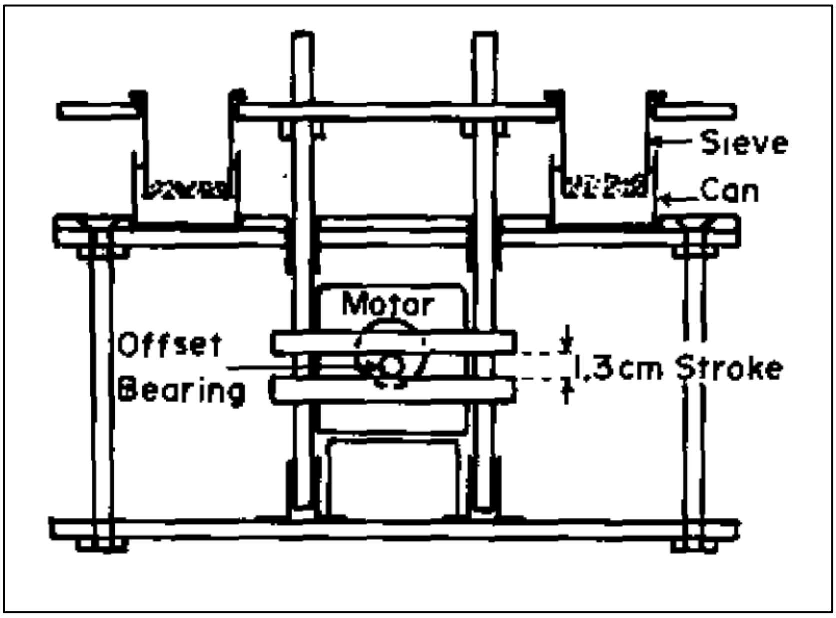


Figure 15. Kemper and Rosenau 1986 diagram of the wet sieving apparatus

Different data can be collected when sieving through a stack of nested sieves of decreasing mesh sizes or a single sieve. Sieving through a tower of nested sieves or consecutive sieving through decreasing mesh sizes is used to measure the size distribution of water stable aggregates. Then, mean wide diameter (MWD) can be calculated following equations **1** (Carmeis Filho *et al.*, 2016). The method of Kemper and Rosenau (1986) to determine aggregate size distribution with a sieving apparatus (Figure 15) is one of the most widely used and modified analysis methods, as described in Nimmo and Perkins (2002). Conversely, single sieves are used to contrast water stable aggregates with a threshold mesh size such as the 250 µm to differentiate micro- and macroaggregates. For calculations, sand correction is performed by dispersing the sample in sodium hexametaphosphate and sieving on the same mesh size to subtract sand and coarse elements from the actual aggregate weight.

$$\mathrm{MWD}w = \sum_{i=1}^{n}(XiWi) \qquad \textbf{\textit{(Eq.}} \textbf{ 1)}$$

Where Xi is the mean diameter of the aggregate fraction calculated as the mean between mesh sizes and Wi the weight of the aggregates retained on the sieve after oven drying and sand correction in proportion to the total sample weight.

Finally, bulk soil or targeted aggregate sizes can be used. In the latter case, samples are first dry sieved, and the selected aggregate fraction subsample is then subjected to the wet sieving process. The wet sieving process is done on the same mesh size or nested sieves, starting with the same mesh size. Thus, results show water stable aggregates in a ratio compared to dry aggregates, and aggregate stability (AS) is calculated following equation **2**. Here, sand correction should also be performed to increase precision

$$AS(\%) = \frac{WSA}{DSA} \times 100 \qquad \textbf{\textit{(Eq.}} \textbf{ 2)}$$

Where WSA is the sand corrected weight of stable aggregates after wet sieving and DSA is the sand corrected weight of aggregates after dry sieving.

This test can be used when investigating soils' responses to different disruptive forces. The Mean Wide Diameter (MWD) of the WSA can be calculated as well. MWD and AS (or WSA) are both widely used also to establish the impact of soil management practices and tillage intensity.

Le Bissonnais (1988, cited in Le Bissonnais, 1996) found that there are no significant differences between using initial aggregate sizes in the range of 2 to 20 mm. However, when using a specific macro aggregate size, only that particular soil fraction is represented, whilst using the bulk soil, the whole of the soil aggregate fractions are included. This is relevant when studying microaggregates because if using only a bigger macroaggregate soil fraction, then smaller WSA such as microaggregates (from 250 - 53 µm) resulting from the test would only represent the WSA microaggregates inside this soil fraction aggregated in large macroaggregates, and not the proportion of microaggregates from the bulk soil.

3.9.2.3. Aggregate stability test

In this research, samples from three locations were collected in each field. Those locations were the same as where VESS was performed. Samples for aggregate stability were collected from the extracted soil block or the surrounding soil from 0 – 5 cm and 5 – 10 cm depth. After fieldwork, samples were stored at 4 ℃ until further analysis to limit biological activity. Samples were air-dried and gently disaggregated into aggregates smaller than 2 cm in diameter. Those samples were subjected to the sieving test.

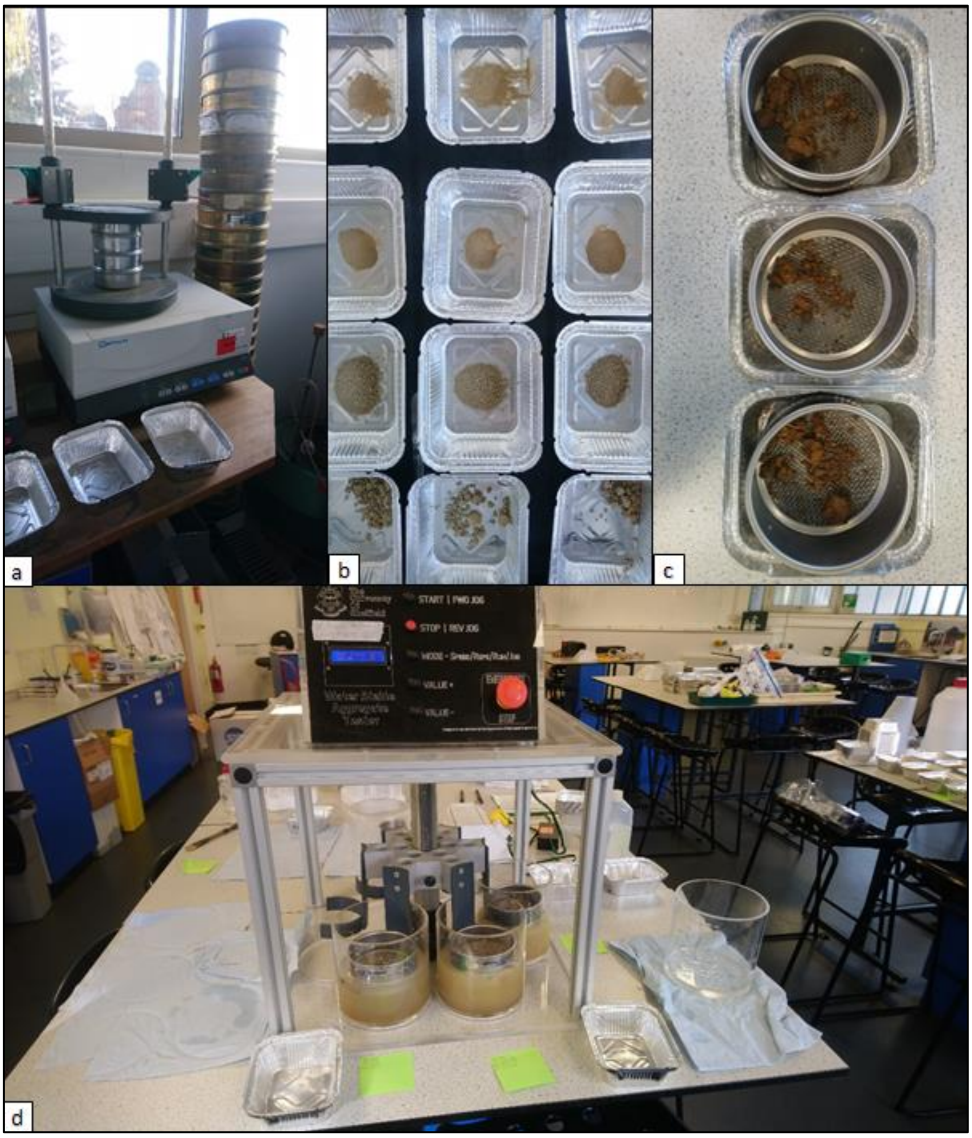


Figure 16. Sieving process. a: dry sieving; b: aggregate fractions after dry sieving; c: macroaggregate re-wetting; d: wet sieving.

A combination of dry and wet sieving analysis was performed (Figure 16). Selected sieves sizes were 2 mm, 250 µm and 53 µm to distinguish four fractions from the bulk soil: large macroaggregates (LMA), small macroaggregates (SMA), microaggregates (MiA) and silt and clay fraction (SC). First, 20 g of bulk air-dried soil samples were dry sieved on a stack of sieves with a Retsch machine at an amplitude of 1 mm, for 5 minutes. The resulting fractions were rewetted using a mist sprayer, except for LMA, which in the initial tests showed they require longer rewetting periods to achieve saturation. In this case, DI water level was matched with the 2 mm sieve, and capillary rewetting was allowed for 3 hours.

Wet sieving was performed using a wet sieving machine, speed was set to 30 cycles per minute, and sieving duration was for 5 minutes. Before wet sieving started, all re-wetted aggregates were submerged in DI water for 3 minutes. The wet sieving machine automatically submerges up to 6 sieves into water tanks. DI water was used for replicability reasons. Water from the tanks of wider mesh sizes containing SMA and MiA were transferred to the next sieve size and sieved again for 5 minutes. Silt and clay fractions in water tanks were discarded, all other fractions were oven-dried at 105°C for 24 h, and weight was recorded. To account for the moisture difference between those aggregate fractions and the initial bulk soil sample, another subsample of 20 g was oven-dried at 105 °C for 24 h. Additionally, sand correction or coarse element correction was performed by adding sodium hexametaphosphate solution 0.1 % (w) to aggregates and allowing them to disperse for 18 h before sieving on the corresponding sieve mesh. This way, coarse elements and debris were also oven-dried, and their weight subtracted from the overall aggregate weight. From these procedures, MWD and AS for different aggregate sizes were calculated.

3.9.2.4. Aggregate stability limitations

On a general account, Young, Crawford and Rappoldt (2001) questioned the use of aggregate stability as an indicator for soil structure, stressing the absence of information about spatial and temporal heterogeneity. Instead, they proposed a focus on topology, which is the three-dimensional soil structure, or where the aggregates and pores locate themselves in the soil continuum. Some of the available technologies to study soil structure and its related properties include in-situ methods such as environmental scanning electron microscopy (ESEM), nuclear magnetic resonance (NMR), ground-penetrating radar (GPR), electromagnetic induction (EMI), proximal or remote sensing and ex-situ methods such as sequenced thin sections, X-ray or gamma-ray Computed Tomography and electrical resistivity tomography (ERT). Developments of these new technologies make it possible to look at the topology in undisturbed soils. Uniting the features that previously were studied from different disciplinary perspectives: the solid matrix (pedology), the pore system (soil hydrology), or the habitats and interfaces (soil biology and biogeochemistry) (Lin, 2012). However, the mentioned technologies are still constricted in terms of detectable soil features, required sample size, penetrating depth, spatial resolution, temporal frequency, cost (Lin, 2012) and sample preparation time, when required.

Nonetheless, visual descriptions of soil profiles and indexes such as VESS can provide qualitative or semi-qualitative information about the mentioned soil architecture, integrating the solid aggregates with the porous system. Therefore, in this research, I used a combination of the two to provide a more comprehensive description of the soil structure.

3.9.3. Soil compaction assessment

In this section, I explain how soil compaction was assessed. Details about what soil compaction is and the impacts it has on farming are provided in the literature review chapter (Soil compaction).

5 pairs of no-tillage – conventional tillage neighbour farms were studied in each country. On their farms, one rainfed field was studied at 3 sites. At each site, 2 - 3 Bulk Density (BD) samples were taken from 0 – 5 cm and 5 – 10 cm; and 3 penetration resistance profiles were recorded. More details on the penetration resistance and bulk density methods and assessment criteria are explained in the following subsections.

3.9.3.1. Penetration resistance

Penetration resistance methods are widely used to measure soil strength. Different methods and indexes exist in a range of applications. The dynamic cone penetrometer is one of the most extensively used methods. The device has a standard weighed hammer incorporated in the equipment, and the penetration achieved is measured against the number of blows required. This method is widely used in engineering in studies related to trafficability and construction (see: Innocent *et al.*, 2015). Another extensively used method is with a pocket penetrometer which contains a small retractable foot that marks maximum strength. This is applied in soil science to assess surface crusting (see: Zobeck *et al.*, 2003) or in smaller soil samples in the laboratory (see: Martínez *et al.*, 2008).

The interest of this research in soil strength is related to compaction with a focus on crop root development, although soil strength is also related to trafficability and plough mechanics. In this case, a handheld MEXE soil assessment cone penetrometer (Figure 17) was used. Although this equipment was developed by the Military Engineering Experimental Establishment (MEXE) to assess soil trafficability, it has been widely used to assess soil compaction for agricultural purposes. The handheld penetrometer is a piece of light equipment suitable for a single person to perform multiple measurements. It enables readings in California Bearing Ratio (CBR), which is a ratio of the strength required for the assessed soil against the strength required to penetrate a reference standard. However, the MEXE penetrometer also enables readings in the form of Cone Index (CI), which was used in this project. The CI is an account of the strength required to penetrate the soil. Each CI unit on the MEXE penetrometer represents 11.12 N. Different cones provide different results due to the base area and the penetration angle. The cone used in this project had a 30° degree angle mounted on a 12.83 mm diameter cone base. Then, readings were converted to MPa.

Conversion to MPa enabled comparisons with thresholds at which root elongation is inhibited, commonly accepted at 2 MPa, although reported values vary between 1.8 and 3 MPa (Chen *et al.*, 2005). Ehlers et al. (1983) even found that oats root elongation was limited on tilled soil at 3.6 MPa and between 4.6 – 5.1 MPa on not tilled soils. These higher values were possible due to the greater amount of biopores that acted as conduits for root elongation on no-tillage fields (Ehlers *et al.*, 1983).

For this research, three penetration resistance profiles were recorded at three locations in each sampled field. Nowadays, modern penetrometers include automatic logging devices, although, with the MEXE penetrometer, hand notes can be made, requiring to stop and resume the pressure exerted. In this case, penetration resistance profiles were made from the maximum CI values recorded for each 5 cm depth increase, which were marked previously on the extension rods. Afterwards, readings in CI were converted to MPa.

Figure 17. MEXE cone penetrometer

3.9.3.2. Bulk density

Soil bulk density is a measurement of the undisturbed dry soil weight contained in a known volume. Therefore, bulk density accounts for the solid phase and the porous media in between soil particles. Thus, bulk density has a direct relation with soil compaction: the more compacted a soil is, the higher the bulk density values.

However, there are many other factors than tillage influencing bulk density. One of them is the density of soil mineral and organic components. For example, clay minerals have a density between 2.00 and 2.60 $Mg \cdot m^{-3}$ whereas minerals rich in metals have a density between 4.90 and 5.30 $Mg \cdot m^{-3}$ (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). Additionally, soil bulk density is related to soil structure and depends on the same aggregation factors. Thus, soil texture also influence bulk density, clay loam and silt loam normal values vary between 1.00 $Mg \cdot m^{-3}$ and 1.60 $Mg \cdot m^{-3}$ whereas sand and sandy loam values vary between 1.20 and 1.80 $Mg \cdot m^{-3}$ (Sarkar, 2005). The lower bulk density in fine-textured soils is attributed to the higher aggregation capacity of clays. Similarly, organic matter decreases soil bulk density because of its lower density and because of the added aggregation capacity. Bulk density critical values in compacted soils, according to soil texture, are listed in Table 1.

Table 1. Critical bulk density values for root development

Soil texture (USDA)	Critical bulk density ($Mg\ m^{-3}$)
Clay loam	1.55
Silty loam	1.65
Fine sandy loam	1.80
Loamy fine sand	1.85

Source: (Bowen, 1981 cited in Porta, López-Acevedo and Roquero, 1999)

The most common method to measure bulk density is the core method, in which a cylinder of known volume is used to sample soils. Then, the soil is dried at 105 ℃ and weighed, and then equation **3** is applied. This method is widely applied in agricultural and ecological studies. However, for ecological and forestry purposes, it has a limit related to the stoniness of the soil, as the core does not perforate the stone. In case stone or gravel content prevent core insertion, a soil pit is excavated, and the volume of the extracted soil is calculated by layering an impermeable material to the pit and adding a known amount of water. In comparison, the core method is quicker and simpler, although it might be less representative of spatial variability (Throop *et al.*, 2012). In this research, I took three repetitions of core samples around each of the three field locations at 0 – 5 cm and at 5 – 10 cm with a marked cylinder (Figure 18).

$$BD = \frac{m_d}{V} \qquad \textbf{\textit{(Eq. 3)}}$$

$$V_c = \pi r^2 h \qquad \textbf{\textit{(Eq. 4)}}$$

Where m_d is the dry weight of the soil sample and V_c the volume of the cylinder, calculated from equation **4** where r is the cylinder's radius and h its height.

Figure 18. Bulk density sampling equipment. a: marked cylinder, hammer and wood slat; b: handle; c: sampling bags and wood stick to extract sample from cylinder.

Bulk density is used to infer compaction and soil hydrological and aeration properties, but it is also used to calculate SOC stocks and nutrient application rates. In this case, it is important to distinguish global bulk density and fine particles bulk density (< 2mm). Coarse elements such as gravel and pebbles (> 2 mm) increase bulk density values but have little or no capacity to store carbon or nutrients (Throop *et al.*, 2012). When coarse elements represent over 15 % (in volume) of the soil, it is considered to affect soil functioning and has to be considered as a texture modifier (Arias *et al.*, 2017). Depending on the method used to calculate bulk density, organic carbon stocks can be overestimated up to 20 % (Arias *et al.*, 2017). Methods that account for both the fine particles capacity to bind with SOC and nutrients and the volume of coarse elements occupy either dilute the density of the fine particles in the total core volume or correct the calculations that account only for the fine particles weight and volume (Throop *et al.*, 2012). In this research, focusing on soil structure and soil compaction, I used a simple account of fine particles bulk density together with the volume of coarse elements understood as not compressible.

It is necessary to know the weight and volume of the coarse elements and coarse organic matter to calculate the fine particles bulk density. In this research, the separation of fine soil and coarse elements was done on air-dried samples before drying both fine soil and coarse elements at 105 ℃ in the oven for 48 h. The physical separation was done by sieving the air-dried field cores through a 2 mm mesh. As most of the samples required disaggregation, I crushed these samples in a mortar or with a rolling pin on paper. Additionally, I measured the coarse elements' volume by submerging them in water in a measuring cylinder and recording the displacement in the water level. Then, to calculate fine particles bulk density, I applied equation **5**:

$$BD_f = \frac{m_{fd}}{V_c - V_{CE}} \qquad \textit{(Eq. 5)}$$

Where m_{fd} is the weight of the dry fine soil, V_c the volume of the cylinder and V_{CE} the volume of the coarse elements. Additionally, sealed soil samples were weighed when arriving at the laboratory station. Therefore soil moisture conditions during sampling could be calculated from equation **6**:

$$M = \frac{m_w - (m_{fd} + m_{CE})}{m_w} \times 100 \qquad \textit{(Eq. 6)}$$

Where m_w is the wet weight of the sample and m_{CE} the dry weight of the coarse elements.

Finally, to compare the bulk density of the fine soil with the bulk density from the bulk soil, I applied equation ***(Eq. 7***:

$$BD_{ce} = \frac{m_{fd} + m_{CE}}{V_c} \qquad \textit{(Eq. 7)}$$

3.9.4. Soil properties analyses

Complementary soil analyses were performed to measure aggregation agents. I took all samples for these soil analysis at the same sites where VESS was assessed, BD samples were taken, and penetration resistance was measured in the corresponding 20 fields. Samples were taken at depths 0 – 5 cm and 5 – 10 cm. After fieldwork, they were stored at 4 ℃, air-dried and sieved through a 2 mm mesh before analysis.

3.9.4.1. Particle size distribution and texture

The soils' particle size distribution is one of the most stable soil parameters and is considered a basic measurement for soil descriptions and further soil analysis. The soil's relative particle size composition of the fine soil (< 2 mm) provides information about soils' hydrological properties, ease to be ploughed, the risk for wind and water erosion or surface crusting and ability to retain nutrients or contaminants (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003).

The thresholds to distinguish different particle sizes in the fine soil correspond to the particle size properties. However, the limit for the silt size fraction is difficult to establish and varies between different soil science schools. The European limits for each particle size are described in Table 2.

Table 2. European particle size limits

Particle	Upper Limit	Limit justification
Sand	< 2,000	Bigger particles do not maintain cohesion even in moist conditions.
Silt	50 – 63 µm	Arbitrary limit. 50 µm is the limit most widely used, also applied to the European physical topsoil maps, whereas ISO standards assume 63 µm and the British Soil Classification system does 60 µm.
Clay	< 2 µm	Smaller particles have a surface charge and a high specific surface (surface per weight).

Source: Adapted from (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003)

Soil textural classes are established by the relative abundance of each of the fine soil particle sizes. Then, the sum of sand, silt and clay content is always 100 %, and those parameters are interdependent. Soil textural classes limits also vary slightly between classification systems. In this research, I used the British Soil Classification texture triangle to determine the textural classes.

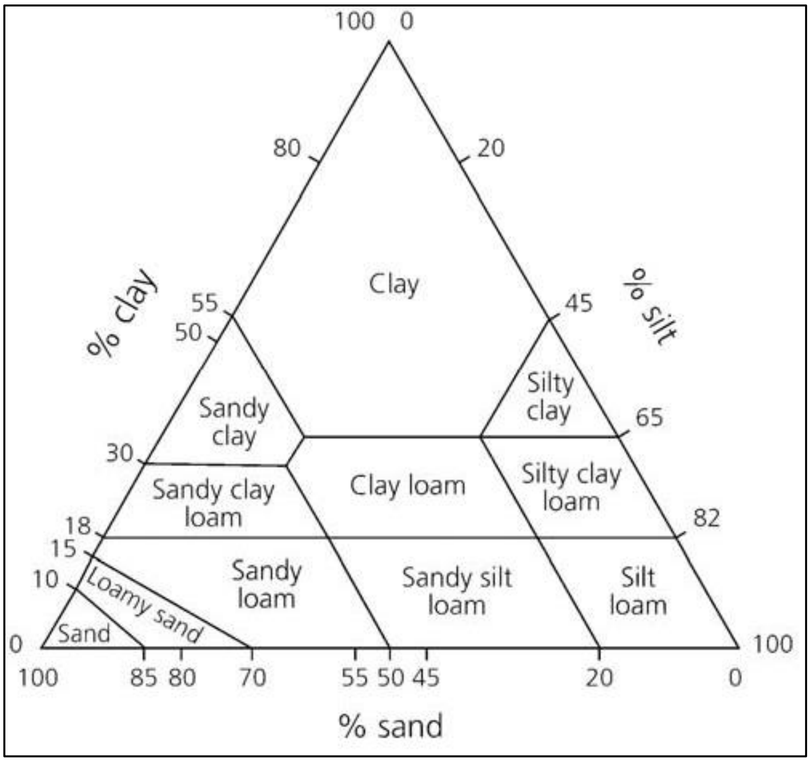


Figure 19. Soil texture triangle. Source: (Natural England, 2008)

There are different methods to study soil particle size distribution. Field methods, touching and moulding a small soil sample, provide preliminary measurements that can then be confirmed and refined with laboratory analysis. The most accurate method for particle size analysis is the densimeter method from Boyoucos and modified by Swartz. This method applies Stokes' law of sedimentation and consists of a series of density measurements of a suspended soil solution (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). However, this method is not time effective. Therefore, in this research, the particle size distribution was analysed by laser diffraction.

In the Laser Diffraction Method (LDM), a small subsample (0.3 – 0.5 g) is used for the measurement. Therefore, it is important that this subsample is representative of the whole soil. This is achieved by using a riffle box that splits the sample into two homogeneous subsamples, as seen in Figure 20. In this project, I used the riffle box repeatedly to achieve a subsample of 5 – 10 g. Samples were then treated so that aggregates broke down to their single particles. Soil organic matter was removed by adding hydrogen peroxide (H_2O_2) ~ 30 % in reiterated additions until no visible nor audible reaction in the form of fumes and bubbles was present. Figure *21* shows the typical reaction of soils to hydrogen peroxide. Then, samples were air-dried, and sodium hexametaphosphate ($(NaPO_3)_6$) 0.1 % was added as dispersant, until the soil sample achieved a paste consistency which was then mixed, and a further subsample was fed to the analyser.

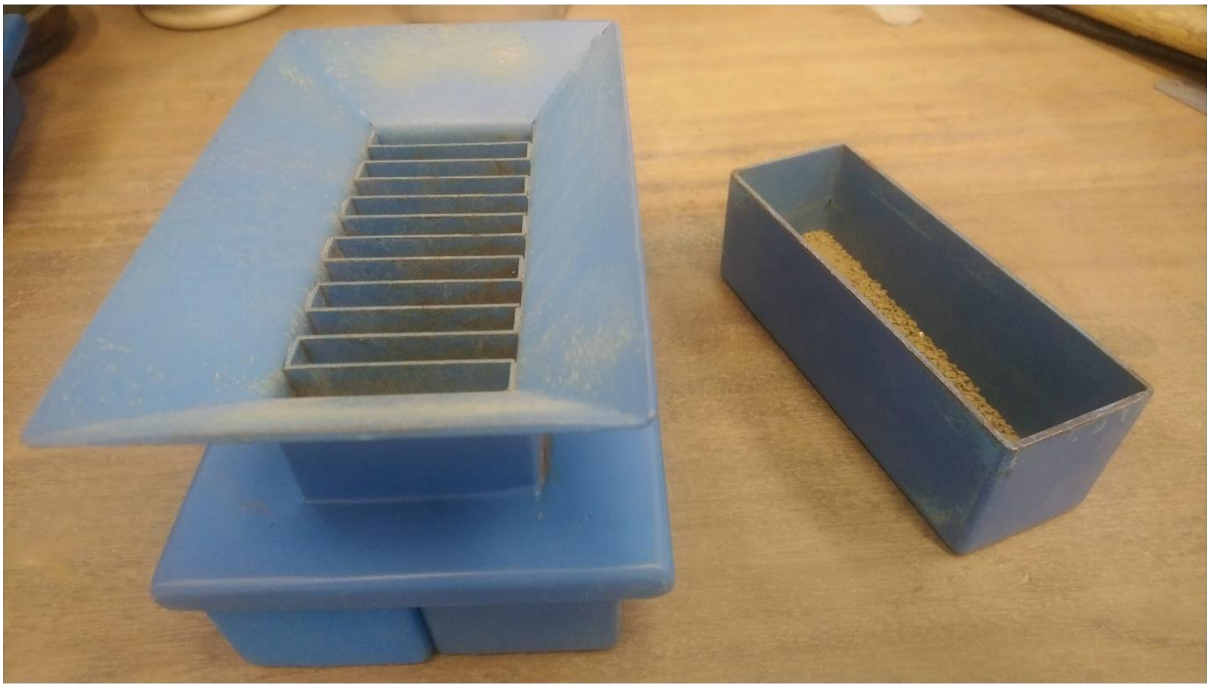


Figure 20. Riffle box.

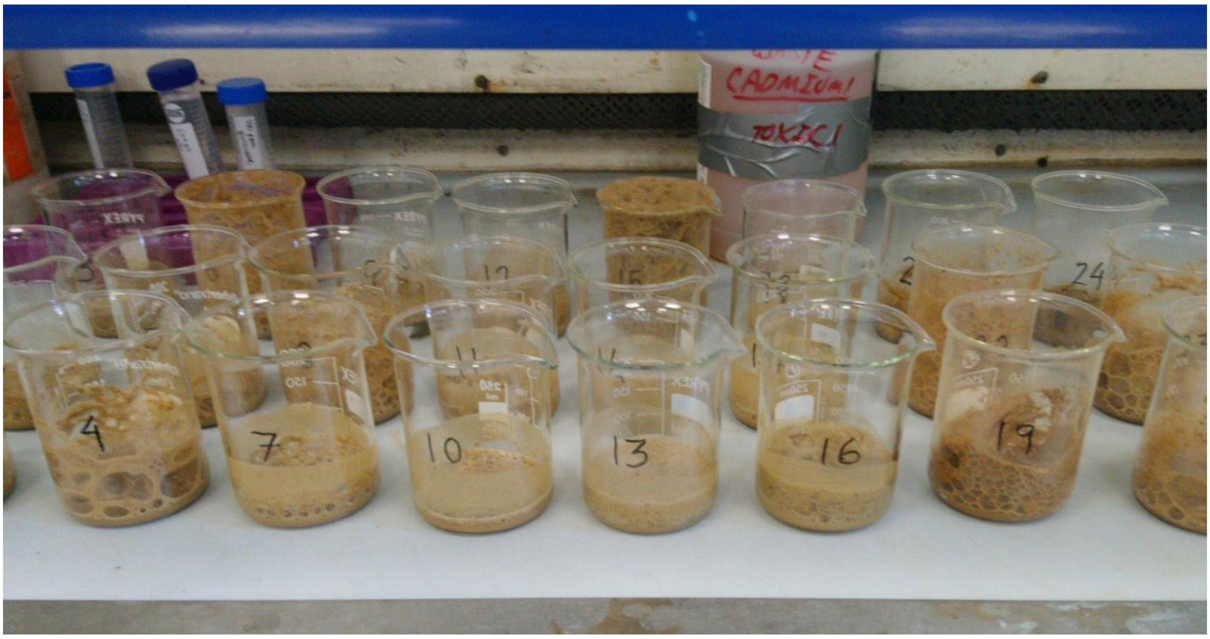


Figure 21. Samples reacting to hydrogen peroxide in the fume hood.

To analyse the soil, it is fed to the Horiba partica LA-950, whose system configuration can be followed on the diagram and real-life setting Figure *22*. An aliquot of the subsample is added to a sampling bath which has an agitator. This is connected to a closed circuit with sodium hexametaphosphate solution 0.1 % to disperse further the soil aggregates. Additional ultrasound is applied for 30 seconds to disaggregate further the soil samples. In the LDM, particle size is calculated from the scattering patterns of the incident light. Those patterns are related to particle size and the wavelength of the incident light. In the particle size analyser model used, a laser (λ = 650 nm) and a LED light are used (λ = 405 nm), and particle size are calculated based on Mie-scattering theory (Horiba, n.d.). These settings enable the machine to measure particles ranging from 0.01 to 3,000 µm (Horiba, n.d.). The only caution that has to be taken by the analyst is to feed enough sample without reaching the obscuration of the flow cell, which is indicated by the software displayed on a PC. The PC software also allows to display and overlap results from different samples in a frequency graph of each particle size. This is used as a measure to decide on the number of repetitions for each sample. In this project, two repetitions were made, and if results showed discrepancies, further repetitions were made. Otherwise, it is an automated process, and the particle size analyser provides the particle size distribution.

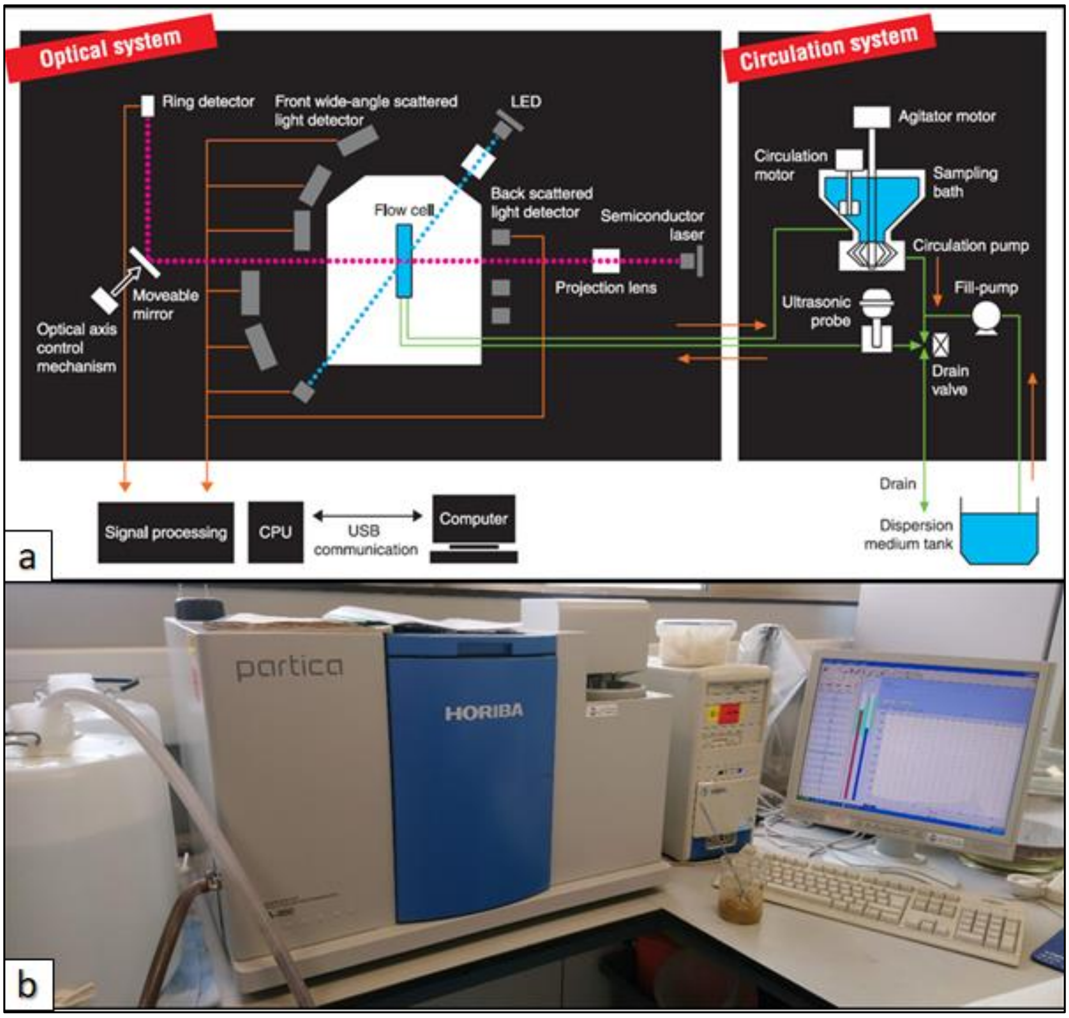


Figure 22. Horiba partica LA-950 system configuration. a: diagram, Source (Horiba, no date); b: real-life.

From the data provided by the particle size analyser in the form of frequencies for different particle sizes, cumulative frequencies of sand, silt and clay were calculated. Additionally, from those percentages, I calculated the corresponding soil textural class for each reading.

3.9.4.2. pH and electrical conductivity

pH is the measurement of the hydrogen ion or proton (H+). One litre of pure, neutral water contains 10^{-7} mol protons and 10^{-7} mol hydroxide ion (OH^-) at equilibrium conditions (750 mmHg and 25℃). This is the threshold to distinguish acid, with more than 10^{-7} H^+ mol·L^{-1}, from base, with less than 10^{-7} H^+ mol·L^{-1}. In aqueous solutions, protons are associated with water molecules forming hydronium ions, which are the measurable ions for the pH probe. Then pH is calculated as shown by equation **8**:

$$pH = -\log\left[H_3O^+\right] \qquad \textbf{\textit{(Eq. 8)}}$$

Strictly speaking, pH measurement is the proton's activity or effective concentration, which depends on the interaction of the protons with surrounding electrical charges. In dilute solutions, the activity is used as equal to concentration. Therefore, soil pH measurements with a pH probe are given as concentrations. However, in soil solutions, ions are attracted to the charged solid phase, and not all of them dispersed in the solution. Therefore, pH can be measured in distilled water to account for the protons in the solution, or in a salt solution (potassium chloride KCl or calcium chloride $CaCl_2$) to account for the exchangeable protons (Conklin, 2014). In the latter, the K^+ and Ca^{2+} cations exchange with the protons and bring them into the solution where they are measured (Conklin, 2014). Because of this, measurements in salt solutions provide more acidic readings.

Table 3. Major soil pH effects for crop development

pH	Assessment	Expected effects
< 4.5	Extremely acid	Adverse conditions.
4.5 – 5.0	Very strongly acid	Possible toxicity by Al^{3+} and Mn^{2+}.
5.1 – 5.5	Strongly acid	Excess: Co, Cu, Fe, Mn, Zn. Deficit: Ca, K, N, Mg, Mo, P, S. Soils without $CaCO_3$. Low bacteria activity.
5.6 – 6.0	Medium acid	Appropriate range for most crops.
6.1 – 6.5	Slightly acid	Maximum availability of nutrients.
6.6 – 7.3	Neutral	Minimum toxic effects. pH < 7.0, $CaCO_3$ is unstable in soils.
7.4 – 7.8	Medium base	Generally containing $CaCO_3$.
7.9 – 8.4	Base	Availability of P and B decreases. Increasing deficit of Co, Cu, Fe, Mn, Zn. Calcareous soils. Iron chlorosis due to HCO_3^-.
8.5 – 9.0	Slightly alkaline	In calcareous soils, these pH values can be related to the presence of $MgCO_3$. Major problems of ferric chlorosis.
9.1 – 10.0	Alkaline	Presence of sodic carbonate Na_2CO_3
> 10.0	Strongly alkaline	A high presence of exchangeable sodium. Toxicity: Na, B. P mobility in the form of Na_3PO_4. Low microorganism activity. Scare micronutrients availability except for Mo.

Source: (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003)

Different methods for soil pH measurements use different soil: distilled water ratios. For example, saturated paste 1:1 is used in USDA procedures, while in many European countries, the standard is 1:2.5. The requirement of harmonised databases for international soil maps (e.g. European Soil map, GlobalSoilMap) call to harmonise this pH measurements to 1:5, and numerous transformation equations are used (see: Libohova *et al.*, 2014; Kabała *et al.*, 2016). In this research, pH measurements were done directly in a soil: water ratio 1:5 in volume.

Soil pH is related to many chemical, biological and physical processes. Major soil pH effects, especially related to crops, are shown in Table 3. Those effects are related to the availability and mobility of nutrients. Additionally, each crop has a range of optimal pH and tolerable pH values, which are discussed together with the results in the following chapters.

In this research, the same soil solution in a 1:5 ratio was used for Electrical Conductivity (EC) measurement. EC is related to salts in the soil. Table 4 provides a salinity classification based on EC 1:5 measurements for different soil textures. Soil texture is considered because values are correlated to EC measured from the saturated paste extract, which is the standard procedure but more time-consuming.

Soil salinity affects crops negatively because crops require more energy for water uptake because they need to maintain the osmotic potential they need to absorb water plus an additional energy expense to separate water molecules from ions (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). In the worst cases, this leads to physiological drought (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). Additionally, soil salinity affects the soil structure as ions interfere in the attraction-repulsion processes between clay particles. The nature of this interference depends on the salt cation. Bivalent cations such as Ca^{2+} and Mg^{2+} have a flocculant effect, whereas monovalent, especially Na^{+}, have a dispersant action.

Table 4. Australian soil salinity classification

Assessment	**EC 1:5 dilution (dS·m^{-1})**		
	Sand	**Loam**	**Clay**
Non saline	0 – 0.14	0 – 0.18	0 – 0.25
Low	0.15 – 0.28	0.19 – 0.36	0.26 – 0.50
Moderate	0.29 – 0.57	0.37 – 0.72	0.51 – 1.00
High	0.58 – 1.14	0.73 – 1.45	1.01 – 2.00
Severe	1.15 – 2.28	1.46 – 2.90	2.01 – 4.00
Extreme	> 2.28	> 2.90	> 4.00

Source: (Anon, 2009b)

In this case, the determination of pH was performed following the British Standard procedure (BSi, 2005). Soil solutions 1:5 in volume were prepared with fine air-dried soil and distilled water in 50 mL centrifuge tubes. These solutions were shaken for 60 minutes at 200 rpm and then left to settle for another 60 minutes. Readings were taken before 3 hours since shaking stopped. pH probe HANNA HI-8424 was calibrated with buffer solutions for pH 4 and pH 7. pH probes measure the electrical potential between a reference electrode and the pH electrode (a selective bulb for pH). The probe used in this test incorporates a temperature probe (because pH is dependent on the temperature), and the pH-meter provides a calibrated and temperature compensated pH reading (HANNA instruments, n.d.). According to the British standard, readings with the pH meter are considered stable if, in 5 seconds, the variation on the pH-meter is less than 0.02 units (BSi, 2005). In this case, stabilisation for most of the samples took less than 1 minute. Calibration was repeated every 12 samples.

After pH measurements, I took EC measurements with a Jenway 3540 probe. For EC, the probe has two electrodes and measures the electric current between them, related to salinity. EC also depends on the temperature, and the Jenway 3540 probe has a temperature sensor included in the EC probe and provides standardized readings for 25 ℃ in $\mu S\ cm^{-1}$ and converted to $dS \cdot m^{-1}$

All measurements for pH and EC were taken in the decanted supernatant. This decision was made to preserve probes from abrasion by the solid particles in soil solution and after testing with the solids in suspension, decanted and centrifuged and decanted samples. This test showed that differences between the sample treatments remained in the range of the standard replicability (≤ 0.15 for pH ≤ 7.00 and 0.20 for $7.00 \leq pH \leq 7.50$ (BSi, 2005)). Therefore, the most preventive and time effective method of simple decantation was used. After EC measurements, the supernatant liquid was mixed with the solids and 250 µL of $CaCl_2$ 1M were added with a 1.000 µL micropipette to achieve a solution of $CaCl_2$ 0.01 M. Samples were shaken for another 60 minutes and left for settling for 60 minutes, and pH readings were repeated in the salt solution.

3.9.4.3. Organic Carbon/ Nitrogen ratio and total carbonates

The organic Carbon: Nitrogen (C/N) ratio is related to soil organic matter decomposition, soil structure and plants' nutrition. Organic residues from different plants have diverse C/N ratios. For example, legumes have C/N ratios ~ 20, while in corn straw it is ~ 60, wheat straw ~ 80, and sawdust > 250 (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). Decomposition of organic matter with a lower C/N ratio is quicker, while higher C/N ratios translate into more recalcitrant organic matter and lower pH levels. Generally, it is accepted that bacteria (with C/N ratios ~ 4 – 5) increase their activity when organic matter with lower C/N ratios is added to the soil, whereas breakdown of lignin, cellulose and hemicellulose (with higher C/N ratios) is dominated by fungi (with C/N ratios ~ 9) (Chavarria *et al.*, 2018; Grosso, Bååth & De Nicola, 2016) who can translocate N through their hyphae, overcoming potential limitations (Grosso, Bååth & De Nicola, 2016). Therefore, the addition of organic matter can induce changes in microorganism communities.

Additionally, it is generally accepted that for plant nutrition, organic matter has to be previously mineralised by microorganisms, as plants only absorb mineral substances (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). Then, in the case of plant nutrition, organic matter with lower C/N ratios are preferred, as then the organic matter is broken down and mineralised at a quicker rate, making nutrients available for plants. Conversely, when decomposing organic matter with high C/N ratios, microorganisms use available nitrogen, which might lead to a nitrogen deficit for the following crop (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003). Then, organic matter addition to the fields can be coupled with mineral N addition to increase organic matter decomposition ratios (Porta Casanellas, López-Acevedo Reguerín & Roquero de Laburu, 2003).

Nonetheless, organic matter decomposition ratios are not only determined by N availability. Research has shown that aggregates physically protect C stocks. In this aspect, soil structure complexity increases with higher soil C/N ratios (Falsone, Bonifacio & Zanini, 2012). However, these are also soil specific processes, as different pedogenic processes interfere in Carbon sequestration (Falsone, Bonifacio & Zanini, 2012). The importance of Carbon and Nitrogen stocks and how they relate, expressed in the C/N ratio, is necessary to account for the soils' potential to sequester carbon and mitigate Climate Change. When studying Carbon and Nitrogen stocks, it is important to account for soil depth, as amounts vary across the soil profile. C/N ratios, stocks and stratification ratios are a way to assess the impact of different soil management practices (Fernández-Romero *et al.*, 2016). Nowadays, it is accepted that overall Carbon stocks are similar in no-tillage and conventional tillage practices, but in no tilled fields, the stratification ratio is higher, whereas, in the conventionally tilled soils, the carbon stocks are equally distributed across the ploughed layer.

There are many methods to analyse soil carbon and nitrogen; among them are CN analysers. In this research, I prepared samples to be analysed in an external laboratory with a CN analyser (Vario EL Cube, Elementar, Hanau, Germany). For this purpose, 5 – 10 g of air-dried representative soil subsamples were ball milled for 3 minutes (Figure 23). From those samples, 60 ± 1 mg were weighed in 1.5 mL tubes on a precision scale (4 decimal digits, b in Figure 23). Samples were then acid stripped to eliminate inorganic carbon. For that, to each sample, 700 µL of 6 M HCl were added, stirred with a needle, left 15 – 30 min, and another 100 µL were added; this was repeated until no effervescence was visible. After 24 h, samples were placed in an oven at 105 °C for 24 h to eliminate residual moisture and acid. From these, 19.5 – 23 mg was weighed in tin boats previously weighed and then folded, ensuring they were sealed (c and d in Figure 23). Additionally, 5-6 mg acetanilide and empty (blanks) tin boats were prepared for calibration. Those samples were arranged for the CN analyser running order and brought to the external laboratory (Department of Animal and Plants, University of Sheffield).

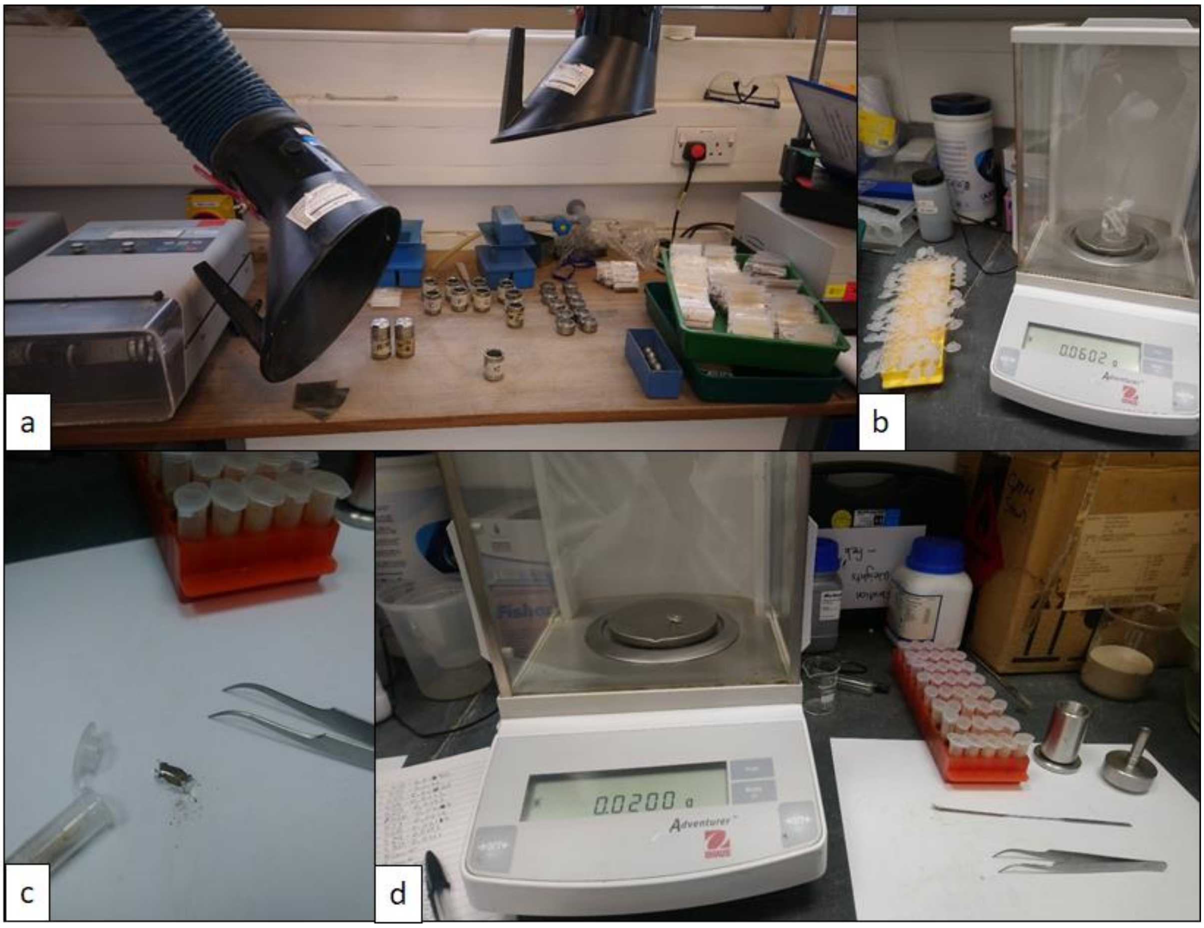


Figure 23. Sample preparation for C/N analysis. a: ball milling samples. b: weighing samples to be acid stripped. c: detail on tin boat filling with 20 mg of soil. d: weighing samples in tin boats to be fed into CN analyser.

In the external laboratory, prepared samples were analysed with the CN analyser (Vario EL Cube, Elementar, Hanau, Germany). Thus, samples were submitted to high temperature in an Oxygen environment furnace to ensure total oxidation. The resulting gas mixture containing carbon dioxide (CO_2) and nitrogen oxide species (NO_x) are transported with an inert gas flow through different columns to that absorb H_2O, SO_2 and CO_2, which then have to be desorbed for determination, while nitrogen is directly determined as N_2 (Elementar Analysensysteme GmbH, 2005).

Additionally, due to the COVID – 19 pandemic and related lockdowns, there was high uncertainty regarding the CN analysis in an external laboratory. Therefore, I analysed soil organic matter (SOM) through loss on ignition (Gale & Hoare, 1991)as back-up data covering soil organic matter. This was done weighing 5 – 9 g of representative air-dried soil samples (< 2mm) into pre-weighed ceramic crucibles, which were oven-dried at 105 °C to eliminate soil moisture, before recording soil weight. Then, those samples were subjected to 430 °C for 18 h in a Carbolite furnace and weighed again to be able to calculate the organic matter based on equation ***(Eq.* 9*)***. Samples cooled down to room temperature after oven and furnace in desiccators.

$$SOM\ (\%) = \frac{W_0 - W_f}{W_0} \times 100 \qquad \textbf{\textit{(Eq.} 9\textit{)}}$$

Where W_0 is the weight of the oven-dried soil sample and W_f the weight of the soil sample after the furnace. The typical conversion factor between SOM and SOC is 1.724, although up to 2 have been used (Pribyl, 2010). Nonetheless, in this project, as both were measured, it was possible to calculate the empirical conversion factor for the data through linear regression analysis.

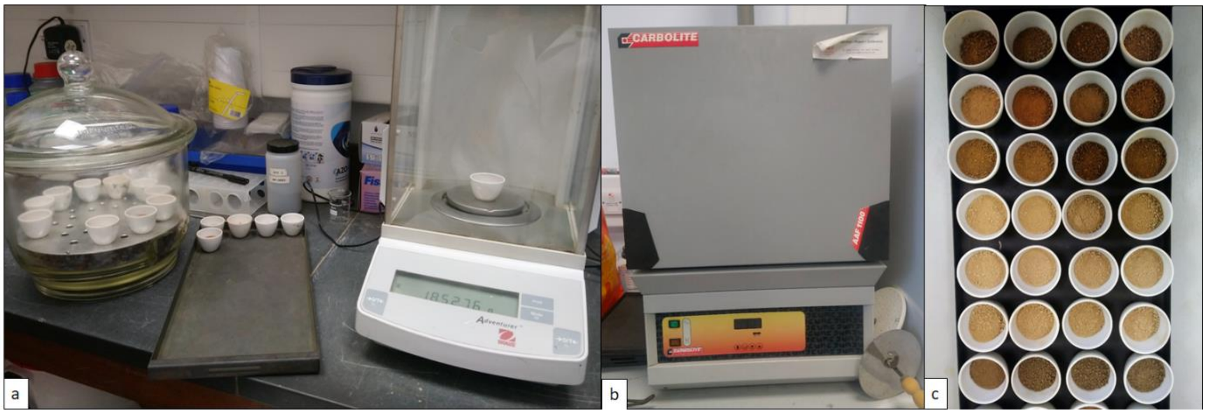


Figure 24. Soil organic matter determination through loss on ignition. a: weighing oven-dried soil samples in ceramic crucibles. b: furnace. c: soil samples after loss on ignition

3.9.4.4. *Calcium carbonate analysis*

Calcium carbonate ($CaCO_3$) is related to aggregate stability, as precipitation of secondary carbonates can act as cementing agents, increasing stability. Total $CaCO_3$ were analysed with the titration method (ICARDA, 2013). In which $CaCO_3$ is dissolved in hydrochloric acid (HCl), and the excess of HCl is titrated with sodium hydroxide (NaOH) solution. In summary, 1 g of air-dried soil samples were weighed in a 250 mL Erlenmeyer flask, 10 mL of 1 N HCl solution was added with a volumetric pipette (repeated in soils with high reactions, after initial reaction settled). Samples were left overnight. Afterwards, 50 – 100 mL DI water was added, and to this, 2 – 3 drops of phenolphthalein indicator. These were titrated with 1 N NaOH solution until the phenolphthalein indicator turned pink, then readings were taken.

Additionally, the 1 N HCl and 1 N NaOH solutions were standardised. First, 10 mL 1 N Na2CO3 solution was pipetted into a 250 mL Erlenmeyer flask, 2 drops of methyl-orange indicator were added, and this solution was titrated against the HCl solution until the colour changed from light to dark orange. From the standardised HCl solution, 10 mL were pipetted into a 250 mL Erlenmeyer flask, 2 drops of phenolphthalein indicator were added, and the solution was titrated against the NaOH solution until the colour turned pink. Calculations followed equations ***(Eq.* 10*)(Eq.* 11*)*** and ***(Eq.* 12**.

$$N_{HCl} = \frac{10 \times N_{Na_2CO_3}}{V_{HCl}} \qquad \textbf{\textit{(Eq. 10)}}$$

$$N_{NaOH} = \frac{10 \times N_{HCl}}{V_{NaOH}} \qquad \textbf{\textit{(Eq. 11)}}$$

$$CaCO_3(\%) = [(10 \times N_{HCl}) - (R \times N_{NaOH})] \times \frac{100}{Wt} \times 0.05 \qquad \textbf{\textit{(Eq. 12)}}$$

Where Wt is the weight of the air-dry soil (g), R is the volume of NaOH used (mL). Note that 0.05 stands for the equivalent weight of $CaCO_3$. This formula was adjusted in the cases in which more HCl solution was added.

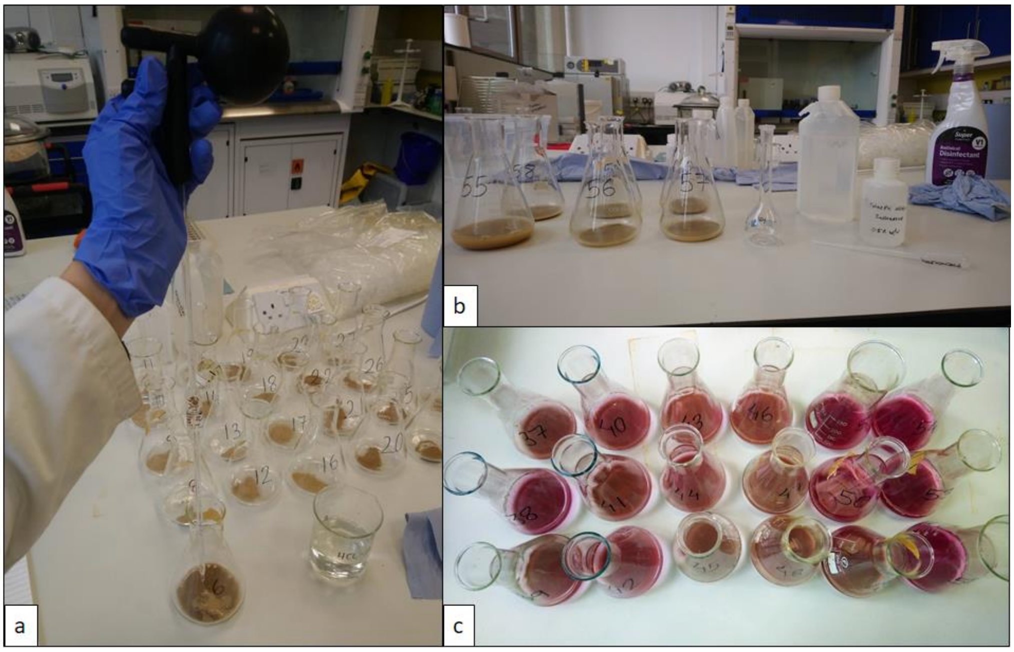


Figure 25. Total calcium carbonates determination through titration. a: addition of HCl to pre-weighed soil samples. b: addition of DI water and phenolphthalein indicator. C: soil mixtures turned pink due to phenolphthalein indicator at the end of the titrations

3.9.4.5. Elemental analysis: X-Ray Fluorescence

X-Ray Fluorescence (XRF) is a technique used in the laboratory and field to assess samples' elemental composition and quantification. When an X-ray beam impacts a sample, it excites the atoms' electrons which, as a consequence, are displaced from the inner-shell, leaving a void (Kalnicky & Singhvi, 2001). This electron void is then occupied by an outer-shell electron, generating X-Ray fluorescence (Kalnicky & Singhvi, 2001). Each chemical element has a unique X-Ray spectrum, which enables the qualitative analysis, whereas the intensity of the detected fluorescence is proportional to the element concentration (Kalnicky & Singhvi, 2001; Ribeiro *et al.*, 2017). Nowadays, two types of XRF analysers are available: wavelength dispersion XRF and energy dispersive XRF. The first one enables readings of a wider range of elements. However, it requires synchronised systems between crystals and detectors, whereas the latter uses superconducting detectors and has higher detection efficiency using lower power X-Ray sources (Ribeiro et al., 2017). Figure 26 illustrates the typical energy dispersive XRF analyser system.

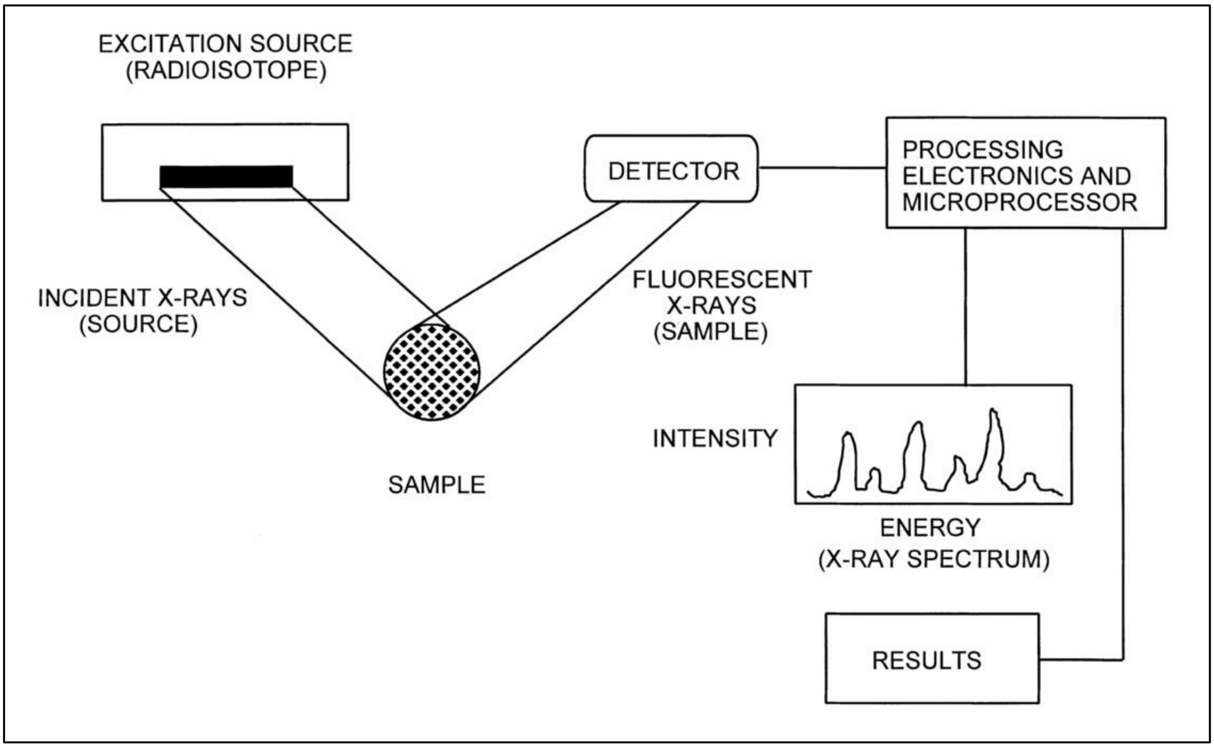


Figure 26. Block diagram for typical Energy Dispersive XRF analyser. Source: (Kalnicky & Singhvi, 2001).

XRF is recommended for soil pollution assessment and to evaluate reclamation projects in the laboratory and field (Olympus, 2012). However, its relation to other soil properties has been studied. For example, XRF has the potential to be used to determine parental material and pedogenic processes for classification and cartographic purposes (Ribeiro *et al.*, 2017). XRF has also been related to pH (see: Sharma *et al.*, 2014), Cation Exchange Capacity (see: Sharma *et al.*, 2015) and Cation Exchange Capacity in compost (see: Li *et al.*, 2018), salinity (see: Swanhart et al. 2014 cited in Li *et al.*, 2018) and salinity in compost (see: Weindorf *et al.*, 2018), soil texture (see: Zhu, Weindorf and Zhang, 2011), secondary carbonates (see: Chakraborty *et al.*, 2017), among others. In this research, I used XRF for elemental analysis to discuss the presence and concentrations of elements potentially acting as aggregation agents.

Figure 27. XRF analyser mounted on the stand and connected to the PC

In this project, an Olympus DELTA 50 Premium handheld XRF analyser was used mounted on the test stand and coupled to a PC in the laboratory (Figure 27). Bagged air-dried fine (< 2 mm) soil subsamples of 5 – 10 g were placed in the test chamber, and analysis was operated through a PC. Two repetitions for each subsample were performed. Sample thickness was greater than 15 mm, and Compton normalisation was performed against standards to ensure the best readings. Compton normalisation reduces backscattering of X-Rays and automatically corrects readings for soil matrix variations, including those caused by moisture content (Olympus, 2012). Samples with greater than 20 % moisture content should be dried (Kalnicky & Singhvi, 2001). Additionally, smaller particle sizes might increase intensity (Maruyama *et al.*, 2008), resulting in higher concentrations for finely milled soils compared to structured soils. Therefore it is recommended to perform laboratory analysis on < 2 mm soil samples (Laiho & Perämäki, 2005). This has to be taken into account if readings are done in the field or if comparing results from field and laboratory. Nonetheless, in the case of this research, all samples were previously air-dried and sieved through a 2 mm mesh. Results are given in concentrations by weight in ppm and % (Olympus, 2012).

3.9.5. Statistical analysis

In this section, the different statistical analyses performed are explained to understand the results and data visualisation presented in the empirical chapters.

3.9.5.1. Descriptive statistics

I used descriptive statistics, such as the mean and standard deviation of the samples, to describe the characteristics of each farms' assessed soil. To visually understand the data, different graphic representations were used, adapted to the nature of the soil parameter. Additionally, outliers were identified, removed, and measures repeated when possible. During data analysis, outliers for each dataset were identified through the 1.5 interquartile range method and the ROUT method performed in the statistical package. Nonetheless, identified outliers were reviewed and assessed in the context of the whole data before the decision of removing the data was taken. All descriptive statistics and graphs were made in the statistics software GraphPad Prism 8.

3.9.5.2. Tillage management comparison: two-way ANOVA

The research design was set to compare multiple soil parameters between no-tillage and conventional tillage neighbours. However, in doing on-farm research, I encountered some difficulties. In the initial statistical approach, data from field measurements and laboratory experiments were to be grouped according to three variables: tillage management (No-tillage and conventional tillage), depth (from 0 – 5 cm and 5 – 10 cm) and location (numbered from 1 – 10, being 1 – 5 Spanish locations of neighbour farms and 6 – 10 British locations), and three-way ANOVA would have been applied. Nonetheless, data were pooled by depth because of its similarity, and soils had to be re-grouped to be able to account for differences caused by tillage management on similar soils. The latter was in response to neighbour soils in each 'location' presenting different properties and related to the nature of on-farm research. In this sense, 'tillage management' did not account for the effects of a single factor as in controlled experiments but included any other difference between fields, such as fertilisation plan or crops.

The aim of ANOVA comparisons was to see if there are significant differences between the data from the fields. When testing hypotheses, the null hypothesis (H_0) is that data comes from the same population, and therefore there are no significant differences between sample distributions. In running a test, a significance level is set, that is α or the p-value reported by many statistical packages, corresponding to the chance that the test rejects H_0 when it is actually true (error type I or false positive). This error increases when performing multiple comparisons between multiple attributes or even testing the same hypothesis repeatedly, increasing the likelihood to get a false positive. Therefore, instead of performing repeated tests, it is recommended to perform a single test in which α is adjusted to the number of comparisons undertaken. In this project, I performed two-way ANOVA with complete datasets (for each soil parameter).

To apply a two-way ANOVA, the data has to fulfil some requirements. Each grouped data has to follow a Gaussian or normal distribution. This is tested together with the two-way ANOVA on GraphPad Prims 8, performing Shapiro-Wilko and Kolmogorov-Smirnov tests, which can run for small groups. Additionally, normality tests for each location are performed to plot readable QQ graphs. Other requirements for two-way ANOVA are the independence of variables, which is difficult to test and depends on the research design, and constant variance. Homogeneity of variance is tested in GraphPad Prism 8 using Spearman's rank correlation test for heteroscedasticity, being the null hypothesis no heteroscedasticity in the data. Additionally, homoscedasticity plots are generated. However, in some cases, single data sets were too small to testing for requirements.

3.9.5.3. *Pedotransfer functions and model-based analysis*

Pedotransfer functions relate measurable soil properties with other soil properties, which are more difficult, tedious or expensive to measure. Their importance lies in being able to infer and predict soil properties from existing or easily obtainable data.

3.9.5.3.1. Nonlinear regression

Regressions are statistical tools that search the best fitting line or curve (the pedotransfer function) to the data, using predefined models.

Nonlinear regression with multiple independent variables was used to model penetration resistance. I collected the data at each farm on different dates, under different moisture conditions, influencing the results. Therefore, to be comparable, penetration resistance data had to be homogenised to a certain soil moisture level. Then, the objective of using a pedotransfer function, in this case, was to be able to fit the curves to each farm properties and then infer penetration resistance values at a particular moisture content.

Vaz et al. (2011) compared 23 different models which relate penetration resistance with water content and bulk density. They found the best fitting results applying equation **13** developed by Jakobsen and Dexter (Jakobsen & Dexter, 1987) and Busscher and Sojka (1987). Other researchers (see: da Silva, Kay and Perfect, 1994; Betz *et al.*, 1998; Benjamin, Nielsen and Vigil, 2003) have used the same equation:

$$PR = \exp\left(a + b\rho_b - c\theta_g\right) \qquad \textbf{\textit{(Eq. 13)}}$$

Where a, b and c are soil constants, ρ_b the bulk density of the bulk soil (in g cm^{-3}) and θ_g the gravimetric water content (in g g^{-1}). In this research, other proposed equations in Vaz et al. (2011) were assessed. After preliminary data analysis with nonlinear regression using SPSS, the best and logical values for penetration resistance were obtained by equation ***(Eq.* 13*)***. After preliminary data analysis using bulk density measures from the full sample and the fine soil, worse fitting was detected on farms with a higher percentage of coarse elements (> 2 mm). This lead to the decision to include an additional term to equation **13**, resulting in equation **14**:

$$PR = \exp\left(a + b\rho_f + c\theta_g + dCE\right) \quad \textit{(Eq. 14)}$$

Where ρ_f is the fine soil bulk density and CE the coarse elements (% in volume).

3.9.5.3.2. Random forest

Random forest is a combination of decision trees built from a random and independent sample of predictor variables (Breiman, 2001). Decision trees are predictors that follow consecutive binary decisions where the tree splits into two branches. Random forest is suitable for soil pedotransfer functions because it can handle numerical, ordinal and categorical data variables and nonlinear relationships (Ramcharan *et al.*, 2017). Accordingly, in this project, the R RandomForest algorithm was used to build models that predict soil structure indexes (MWD and AS) from the relevant soil properties that act as aggregation agents and tillage management. Decision trees are built with bootstrap samples, which are same size subsamples randomly selected from the original data with replacement. Splitting thresholds are selected by calculating regressions for each subsample and selecting those values that minimize the square residuals from each regression (best fitting). Splitting continues until no further reduction in the squared residuals is obtained. Then, to predict with the forest, each decision tree's outcome counts as a vote. Data not included in the bootstrap samples are used to test the fitting from the built random forest.

However, I mainly used the random forest models to assess the relative importance of tillage management (no-tillage and conventional tillage) among other soil properties in explaining soil structure indexes. To that purpose, variable importance was calculated for each model as the percentage of increase of mean squared error (MSE). The calculation of the percentage of increase in MSE is done with the OOB data (out of bag data - not included in the bootstrap). First, MSE is calculated between the predicted values from the model and the OOB data. Then, the particular variable's values are randomised in different positions (data entries, rows, or soil samples in this case) while maintaining all other predictive variables unchanged. This way, the original association between the variable and the response is broken. Then, MSE is calculated again as well as its increase, which is averaged for all trees.

3.9.5.3.3. Model-based cluster analysis

After statistical analysis of soil variables per farm, I found that some neighbour farms presented soil differences that could influence aggregation. Therefore, comparing tillage management between neighbours, assuming that other variables were similar, would have been incorrect. To solve this problem, I decided to group soils according to similar characteristics.

For that purpose, I performed model-based clustering for the Spanish and the British soil datasets after visually analysing scatter plots of aggregation agents. Reasonable agreement between the initial visual analysis and the model-based clustering was achieved by selecting aggregation agents that had a significant correlation (p-values < 0.05) and Pearson correlation coefficients ≥ 0.5 for the model fitting.

Model-based clustering uses a probability-based approach. As explained by Broehmke and Greenwell (2019), this means that the method assumes that data comes from probabilistic distributions, and the model tries to find these distributions. I employed the model-based clustering package Mclust in R. This package compares a range of models that assume multivariate normal (also known as Gaussian) distributions. Accordingly, each cluster (a subset of data) has a multivariate normal distribution, with a different mean and covariance matrix. The further the data points are from that mean, the lower the probability they pertain to that particular cluster. Mclust algorithm models randomly choose Gaussian parameters and fit them to data. Then, iteratively it optimises the parameters to improve the fit.

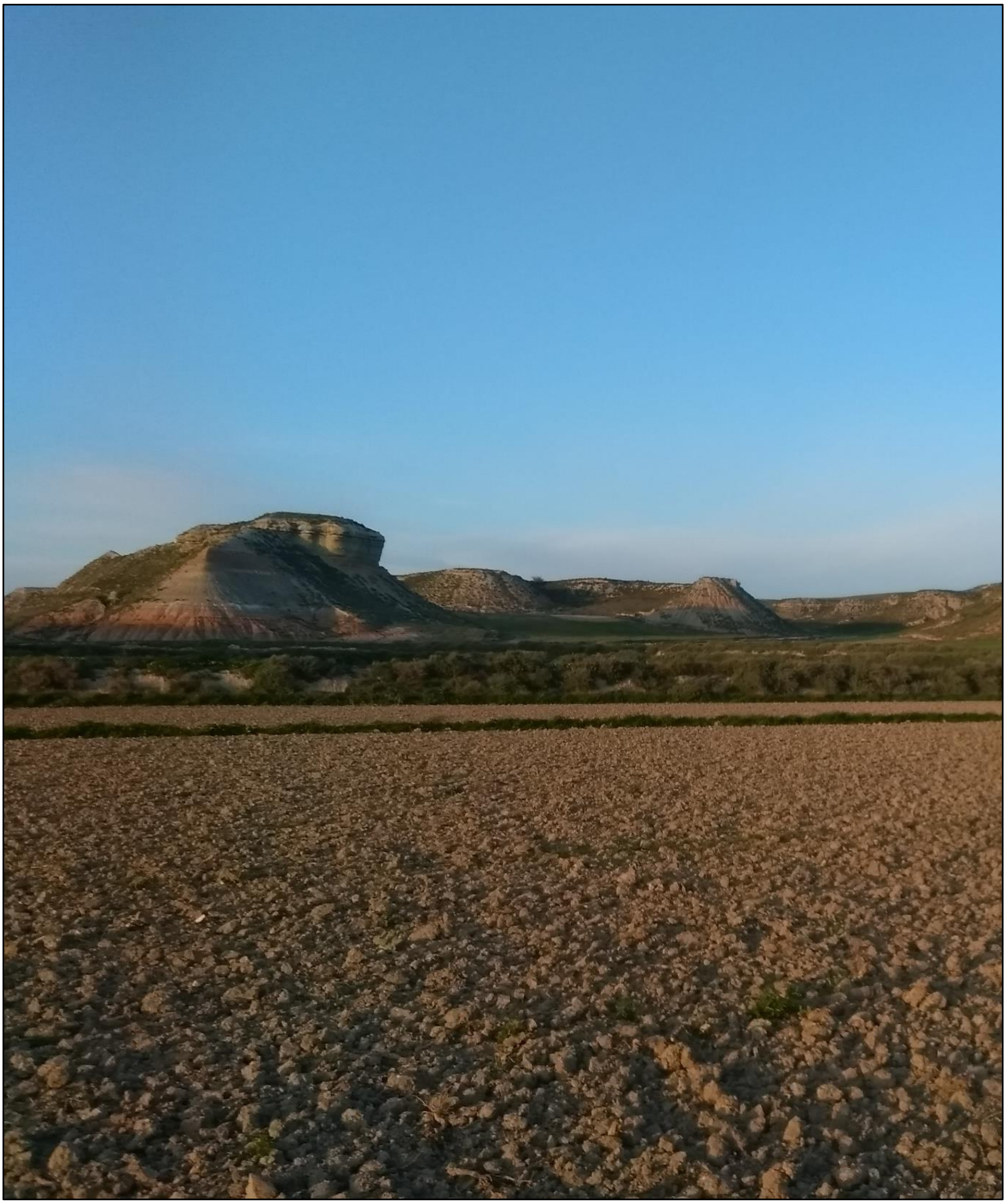
The different models that Mclust compares differ in the covariance matrix. Particularly they might have an equal or variable variance for volume (same number of values), shape (spherical distributions), or orientation (axis-aligned) in all possible combinations. Furthermore, the way Mclust chooses the best model is based on BIC (Bayesian Information Criterion). This is calculated from the loglikelihood (which returns the best fit) but also the number of parameters and the number of observations in the fitting data, as shown in equation ***(Eq.* 15**.

$$\mathrm{BIC} = -2\log(L) \; + m \; \log(n) \qquad \textbf{\textit{(Eq.} 15\textit{)}}$$

Where L is the maximised likelihood for the model and data, m the number of parameters and n the number of observations in the data.

3.9.5.3.4. Principal components analysis

Principal components analysis (PCA) was performed to represent clustering results and how the different clusters are situated regarding multivariate dimensions. PCA, as explained by Broehmke and Greenwell (2019), analyses the covariance between variables and combines several variables in new uncorrelated variables, called principal components (PC). These are weighed combinations of the original variables. The method generates the number of original variables minus one PCs, to explain 100 % of the variance. Generally, the first PCs explain the majority of the variance and are selected to perform further analysis of the data. Nonetheless, in this project, PCA was only used to visualise multivariate clusters in a two-dimensional form (PC1 vs PC2).



Chapter 4.
Farming actor-networks

Figure 28. Chapter 4 cover photo: Ploughed field at the Bardenas Reales in Navarre, Spain

4.1 Introduction to the farming actor-networks

In this chapter, I address the research question

- Which are the drivers and constraints of no-tillage adoption?

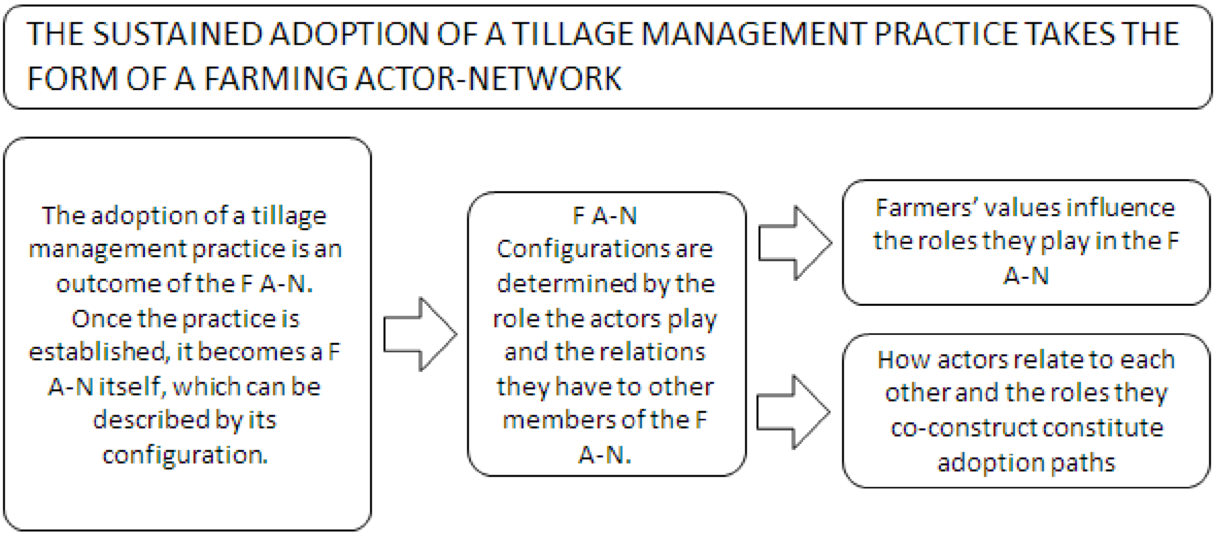


Figure 29. Main arguments to understand adoption of a tillage management practice. F A-N: Farming Actor-Network.

To answer this question, I used the evidence from the semi-structured interviews with no-tillage and conventional tillage farmers from Spain and the UK. My analysis was based on ANT, through which I reassembled farming actor-network configurations. Figure 29 shows the main arguments for the analysis. Farming actor-networks are the networks described and limited by the farmers around their farm management. I did this by identifying the actors and the relations that bind them together in configurations that operated according to repeated patterns, but which also created tensions. On the base of the farming actor-network configurations, I traced back particular causalities, following the circulation of money, materials, information and other flows, through conduits (relations) and actors' translations. In doing so, I also analysed how farming actor-networks co-construct actors and the networks' themselves by negotiating meanings and roles.

In line with the ANT conception of actors as networks, I assume actors are multiple and can adopt multiple roles as a consequence of being enrolled in multiple actor-networks. Moreover, I assume farming actor-networks become actors themselves once they operate in coordinated patterns (referred to as punctualisation). Based on these assumptions, I present the first two sections focusing on farmers' and no-tillage's multiple roles, similar in both countries.

The following subsections are separated by country and focus on farmers' values, the location of farms and examples of field operations, and the mentioned adoption paths. Farmers' values, together with their multiple roles, enable the understanding of their translations and negotiations in the farming actor-network. Additionally, presenting farms' location and providing examples of field operations, I anchor the farming actor-networks to place and further describe them. This chapter's core are the no-tillage adoption paths, which I summarise in tables followed by detailed descriptions.

I finish the chapter by comparing no-tillage adoption paths in Spain and the UK.

4.2. Farmers' multiple roles

This section outlines the multiple roles farmers adopted in the farming actor-networks based on patterns found in the interviewed group. Research studies focusing on farmers show that farmers' identities are varied, complex, and overlap (Sulemana & James, 2014). When applying the ANT approach, farmers' roles are outcomes of negotiations between different network members and co-evolve with the networks (Schneider *et al.*, 2012). Moreover, as farmers are enrolled in different actor-networks, farmers become multiple (Law & Mol, 2008). Thus, the following farmer roles are not to categorise farmers in exclusive categories as for example, in the 'farming styles approaches'(see: Van der Ploeg, 1992; Vanclay *et al.*, 2006), instead show the multiple roles they occupy in the farming actor-networks, sometimes simultaneously. Moreover, the diverse roles a farmer might adopt do not always share values and meanings, resulting in tensions and conflicts in negotiating their own identities.

4.2.1. Business farmers

In their business farmers' role, farmers thought about the farm in economic terms. When this role was dominant, the engagement with their economic balances went beyond the need to sustain their lifestyles. Indeed, they made emphasis on financial details, profit maximisation and risk minimisation. Thus, they were economically driven and wanted to maximise yield, but not at any cost. The farm needed to be economically sustainable in the long term, which included investing in machinery, infrastructure, etc., and caring for the land's long-term productivity.

As business farmers, socio-economic constraints were seen as the primary threats to their farms. These constraints were low grain prices, difficulties to access land, difficulties to market their products, etc. The solutions the participants had applied to those problems were constituting partnerships, diversifying income by doing contracting work, reducing investments, applying for government financial support, or, in Spanish cases, becoming active in the cooperatives' management marketing the products. As an example, 1NT reflected on their business partnership.

> "We started being 4, now a partner has left, and we are only 3. What we do is… the land owned by each of us is included in the partnership. We continue being landowners individually, but we have the land in the partnership. Then, […] because not all of us have the same quantity and quality of land, what we did was weighing the land since the first day [to distribute profit]. […] We buy everything through the partnership. We think it is much better this way; it can't compare with farming alone. […]" (1NT)

4.2.2. Small farmers

In this role, farmers were subjugated by socio-economic and agro-environmental constraints. In this role, farmers accepted that they were at the mercy of grain market prices, policies, manufacturers lobbying, and weather or soil conditions because of their small size.

Small farmers in Spain saw agricultural cooperatives as their means to subsist, despite having to follow the cooperative's norms and conditions.

> "[…] moreover, with these farms, we couldn't be out of a cooperative. With this!? You would have left already to the companies. Obviously! There is a lot of logistics! Storage, how to sell… we have been in the cooperatives all our life… so, all our life in the cooperatives!
> […] because we are small, we have to settle; there isn't anything else!" (1CT)

4.2.3. Hobby farmers

Not all farmland was worked by professional farmers; some was worked by part-time or hobby farmers. Moreover, their socio-economic constraints were different, although their hobby had to be profitable to sustain itself or add to the primary income. When the role was dominant, farmers did not see their activity as part of industrial farming but as a hobby. Nonetheless, professional farmers also occupied this role when the joy of farming drove their negotiations.

> "[…] it has to be a cost-effective activity because otherwise, it doesn't work, but I don't see it exclusively as an industry. The crops as an industry, isn't it? I see it in a different way. I like it; I like the countryside, yes, I enjoy it! Even if it is not my main activity […]" (2NT)

4.2.4. Traditional farmers

Tradition was deeply internalised in the farming community. When the traditional farmers' role was dominant, farmers strongly advocated for the slow pace and calm of rural lifestyles and traditional, experiential, inherited and local knowledge. Moreover, the production was diversified (e.g. vineyards, olive, and almond orchards) and often included some kind of husbandry or beekeeping, although many products were for self-consumption.

> "Because you grew up here and you live very well. At least I live very well. Without stress… They tell me 'You are the happiest person in the World' and I say 'you are right'" (5CT)
> "I mean, most of our neighbours are now reverting back to the way we've been farming for the last 100 years really on the farm. We farm virtually the same way as my grandfather farmed, with a bit of mixed farming and a little of livestock." (8CT)

Spanish farmers could adopt this role concerning particular practices or locations. For example, when they talked about fallow, straw burning or rotating the land between farmers and shepherds or when stating that farming was maintained as a symbolic value of the traditional land use in specific locations (e.g. the Bardenas Reales).

> "No, it is a thing, it is a land that my father always worked… if it depended on me, I wouldn't continue farming it […] but my father… here there has always been a lot of tradition with those lands. People went there… it was different as there were no tractors, they went with horses and all the things… There were huts, and people spend there a week eating… Working, but when they finished work 'let's go to this guys hut' […]" (4CT)

4.2.5. Innovative farmers

In their innovative role, farmers searched for innovations from external sources and tested them or implemented them on their farms. The innovations took the form of ideas, machinery, technologies, bio-engineered and different crops or farming practices.

Farmers always adapted innovations to their farm. Consequently, innovating involved learning about the innovations (e.g. the details of a machine) and adjusting them to the local environment or farming needs (e.g. DIY work on drillers to cut through crop residues). Testing and experimenting with innovations also included mixing inputs, such as seeds or agrochemical products or recovering abandoned practices. The innovations that were more widely adopted and easier accepted were linked to machinery or crop varieties. In this sense, all farmers tested varieties on their land and shared experiences with local communities.

Access to new information regarding those kinds of innovations was through familiar means such as organised talks from agri-businesses and manufacturers, magazines, machinery fairs, and in Spain through the cooperatives. Additionally, new information sources, such as the internet or smartphones, were integrated into farming lifestyles, except for a few older farmers.

When the innovative role was dominant, farmers took pride in their drive for innovation, distinguishing themselves from traditional farmers. However, their innovative activities could be questioned and criticised by the local farming community. The peer pressure and the lack of experiential knowledge generated insecurity in innovative farmers. The pride came, then, from overcoming those insecurities and taking risks, as 3NT mentioned.

> "In these things, like in many others, you have to have some personality! Besides, you risk your money… because nobody plays with… you need personality and become aware of the standard not always being more, better…" (3NT)

4.2.6. Environmentalist farmers

All farmers had a nature stewardship role, independently of the practices they employed, which linked to the relationship between farmers and nature that develops from working outdoors.

> "[…] the other day the ecologists were talking on TV… but we are the main ecologists! Those who care the most about nature." (4CT)

Nonetheless, when the environmentalist role was dominant, farmers were more conscious about the potential harm of some of their activities or the agro-chemicals they used, and these potential impacts drove their farming decisions. Some farmers linked environmentalism and caring for nature to conservation agriculture, others to biodiversity, organic production or the reduction of agro-chemical inputs.

> "One of the things… that's where it began, I started in 2007, then it was purely for biodiversity. Because at the time, we would have stubble left after the combined crop. […] There was a value in that, but I started to think, 'we can probably get more value if we sow something that's fast-growing, flowers and provide more hides, more cover' […]." (10CT)

4.3. The multiple no-tillage practices

In this section, I discuss the multiplicity of no-tillage. The theoretical background for the analysis was that tillage management decisions are negotiated outcomes of particular configurations of farming actor-networks (Schneider *et al.*, 2012). Furthermore, practices reshape and regroup to adapt to different conditions (Hinchliffe, 2007). Nonetheless, when a tillage management becomes a practice, the farming actor-network operates in repeated patterns that hold the actors together over time in the particular configuration that enables the practice. Within these configurations, actors share similar values, meanings and objectives. Then, actor-networks achieve punctualisation (as discussed in the literature review section Networks' punctualisation) and become actors themselves. Thus, tillage management practices are created and co-evolve in the form of farming actor-network configurations. Through this understanding, I was able to distinguish different 'no-tillage' practices.

The analysis of the interviews distinguished three no-tillage practices that co-existed in both countries. No-tillage was not a homogeneous practice. No-tillage was multiple: a machine, a technological package and a farming system.

4.3.1. No-tillage as a tool

Farmers possessed numerous farming equipment to do different field operations according to field conditions. Field conditions included soil moisture, weeds, crop residues, etc. Each field had particular needs, and those were assessed individually.

As a tool, farmers used no-tillage very flexibly; some farmers took advantage of no-tillage seed drills to improve seeding depth after ploughing or doing minimum-tillage because no-tillage machines were more accurate than conventional ones. Other farmers used the no-tillage drill for specific crops or specific fields without foreseeing a complete farm conversion to no-tillage management. In these circumstances, some had a shared no-tillage drill, and others approached their no-tillage neighbours to do the seeding for them.

> "[…] but under that name, people do so many different things! People say they have been doing no-tillage for 20 years, but it turns out that they use the chisel or power harrow and what else… and then, we also don't have to be so strict and not touch anything! […]" (2NT)
> "Because we had proved the fact that, no-till was working, we'd also proved that if we wanted to drill in a min-till situation for [no-tillage] drill would do it." (9NT)
> "Yes! I have a 3 meters drill. That I… in the paramount, to not remove the stones, I do no-tillage. […] And then, if someday I have a small piece and to not… […], I think peas work better with no-tillage, or those [fields] in the paramount always turn out to establish well!" (3CT)

4.3.2. No-tillage as a technological package

As a technological package, no-tillage was practised in a stricter pattern, in a combination of farming practices that included herbicide use, particular seeds etc. As a technological package, no-tillage was recommended in the productivist agriculture paradigm to enhance yields. Although due to local conditions, other factors came into play, such as the dry climate. In this sense, no-tillage was often adopted through the influence of agri-businesses suggesting the use of their products and seeds and made agronomic recommendations.

No-tillage as a technological package, was mainly used by business farmers with high planning requirements. These included big farms in which practices were adapted to soils but were less flexible to adjust the pre-established plans to changing field conditions.

> "No, you have to plan it better than that; you can't just sort of wake up in the morning and think I will do this. You just have to plan it out. You can't have 500 hectares of sugar beets all committed to one technique, and then the weather changes, and you can't do it, and you don't have a crop." (7NT)

4.3.3. No-tillage as a system

As a farming system, no-tillage was part of the conservation agriculture paradigm. No-tillage, cover crops, rotations, leaving crop residues on the surface etc., were practices adopted to increase soil health (particularly soil biological properties). Moreover, when no-tillage was adopted as a system, the interest was in the interactions between the different farm components to increase overall system health and functionality. The objective was to mimic eco-systems, which were productive by nature. Farmers took a proactive approach to prevent problems (weeds, pests, diseases) and increase yields instead of solving those problems separately when they appeared.

Figure 30. Rural landscape near location 2

4.4. Spanish farmers' values

This section provides an overview of the results regarding Spanish farmers' values and an important 'innovation' meaning-making process in the analysed Spanish farming actor-networks. Results help understand the construction of farmers' professional identities within the farming actor-networks and the influence of land consolidation and irrigation modernisation in building ideas of farming innovations. Furthermore, these insights provide the base to understand how values and experiences shape farmers' translations and negotiations of tillage management practices.

4.4.1. Values of freedom, naturalness and pride of growing food

In this section, freedom, naturalness and pride of growing food are discussed. During the interviews, Spanish farmers identified those values as central to their valuing of farming. Values are co-constructed in the farming actor-networks and are core to farmers' identities and their differentiation from other actors. Thus, values show which relations were meaningful in negotiating and building farmers' roles in the farming actor-networks.

What the participant farmers enjoyed most about their work was the '*freedom'* and the pride of *'growing something'*. 'Freedom' was mentioned in relation to the control over their own time and regarding working outdoors, in contact with nature. At the same time, pride in 'growing something' referred to how effort and care translated into crops developing in the field and obtaining yields, which eventually became nutritious food. These values were reported as important both by no-tillage and conventional tillage farmers. Moreover, it was not an idealistic view of the rural lifestyle. Farmers appreciated their freedom working the land, even if it was under demanding conditions. Additionally, those values show the importance of non-human actors in defining farmers' identities.

> "[…] I like everything from the start when I prepare the soil, then seeding, then how it germinates and having to take care of it and watching it grow, for me that is… it is… very beautiful, isn't it?" (4NT)
> "Well, if now I go to see the peas, I go to a field in the Bardenas, for example, and I see that… I see a roe deer, some rabbits, a wild boar… I go somewhere else, and I see nature…" (4CT)
> "Freedom. The freedom of being in the field although sometimes it pissess you off with the mosquitoes and all the rest… and you have to be! The sun that eats you, that beats you, that burns you…" (1CT)

The concept of freedom regarding time management relates to the freedom of choice in rural sociology literature. In the latter, farmers' freedom is treated concerning the control over farm management decisions and how it has been increasingly conceded to public administrations and private food manufacturers and retailers by means of the establishment of standards (Mikkola, 2017). In the course of the interviews, farmers acknowledged socio-economic constraints and referred to their coping or negotiation strategies, which involved human and non-human actors and, in some cases, included the adoption of no-tillage. These strategies relate to the idea of *'farming self'*, which includes the farm into the relations that enable and constrain farmers' actions (Stock & Forney, 2014).

Furthermore, their freedom linked to working outdoors, in contact with nature. Research focusing on the farming self links the activity in nature to loosening social constraints and experiencing the freedom to become the true self (Stock & Forney, 2014). Moreover, research also highlights farmers' self and cultural identification as *'food producers'*, used to distinguish themselves from environmental stewards or foresters (Burgess, Clark & Harrison, 2000; Burton, 2004a). Certainly, farmers' identity and what is generally considered a *'good farmer'* is strongly defined by food production, and high yields were a symbol of that role (Burton, 2004b; McGuire, Morton & Cast, 2013; Marr & Howley, 2019). The satisfaction and pride of 'growing something' expressed by the farmers related to this role. Moreover, all participant farmers acknowledged that they work to obtain high yields. This was to distinguish themselves from the wrongdoing, unprofessional, or not even farmers, who seed the land to access EU subsidies without caring for food production. Thus, farmers stated that they 'go for yield' as a symbol of being a 'good farmer' who works hard and cares. 4CT made this distinction between farmers and those who take advantage of the subsidies:

> "[…] Who are we farmers? Those who take care of the yields! Those people seed and forget about it: if there are weeds if it establishes or not… They will cash in anyways! They have that money assured; why would they care if they don't get enough? […] the more you produce, it means the more you took care, the more you worked, isn't it? […]" (4CT)

In summary, freedom in relation to choice and working in nature, together with the pride of growing food, are values that define farmers' roles in the farming actor-networks. Moreover, they show the importance of the relationships with both human and non-human actors as enabling and constraining farmers' roles, negotiations and actions.

4.4.2. Spanish farming innovation characteristics

In this subsection, I discuss land consolidation and irrigation modernisation as they had a significant impact on how Spanish farmers related and conceptualised innovations. In the regions under study, land consolidation, including irrigation modernisation, when applicable, were done between 7 and 30 years ago, meaning that it was part of farmers' life experiences.

For the interviewed farmers, land consolidation indicated progress and was seen as beneficial for professional farming. It was part of agricultural modernisation and innovation.

Land consolidation was an administrative process based on technoscientific knowledge and with the involvement of the farming community. The process started with farmers deciding which fields would be included. Then, the land was assessed and classified according to its agricultural productivity potential. Soil scientists did this assessment, but farmers attended the fieldwork. These experiences, in turn, had a significant impact on farmers' relations with soils (chapter 5). The next step in land consolidation was pondering all farmers' fields in a municipality by class and size so that farmers could choose between extending their land property (with the land of a lower class) or increasing their land quality (by decreasing their farm size). Finally, the land was consolidated and distributed, together with infrastructure work. 3CT claimed that if it had not been for land consolidation, he would not have continued farming. Other farmers agree with these modernisation claims, how it improved farming infrastructure, decreased workload, and even helped maintain the rural lifestyle.

> "[…] We won by doing the consolidation… I would have left farming otherwise. […] Because there were fields of half a hectare. Nowadays at least… well, there are many fields of one and a half or one, but there are also of 10 or 9. Well, the field operations… there is no comparison! […] And you can produce more. This is a humid village. Before, there was water everywhere, and now we have, but it is not the same. They did ditches and country lanes…" (3CT)

In other places, land consolidation was done, including land-use changes from rain-fed to irrigated land and irrigation modernisation. In these cases, land consolidation, access to irrigation and irrigation modernisation were equally seen as beneficial innovations for professional farming. However, access to irrigation or the modernisation of new irrigation systems meant significant changes in farmers' actor-networks. Farmers had to change their machinery to adapt to the new field sizes and the irrigation infrastructure (as 4CT explained), incurring major costs despite some regional government aid availability.

> "Since we did the irrigation modernisation, eight years ago… That leads us to have to change the majority of our machinery. Before, a flood irrigated field had no obstacles within it, and now we have sprinklers […]" (4CT)

With irrigation changes, new market opportunities arrived. Opportunities that farmers seized, even if they meant learning about new crop cycles and growing requirements, to later market the products through new, previously unexplored paths. These paths included new actors, the manufacturers, who negotiated their own ways into crop production. Manufacturers provided the seeds, which they charged for after harvest, which was also done by them. Additionally, manufacturers provided recommendations from professional agronomists regarding fertilisation and irrigation plans.

> "Here, lately, since they changed the irrigation systems, all crops have changed. […] Maize is almost not grown, as now the profit is very low. What is grown also are crops for deep-frozen products manufacturers: spinach, peas, green beans… […] This was more of a foraging area, alfalfa… […] We were able to change to crops that before… we learned a lot, crops that before we didn't know about." (4CT)

However, land consolidation did not affect all regions in Spain. Some rain-fed land remained with traditional fields. Thus, not all types of farming had the same priority in the administration to foster innovation strategies, as 5NT comments suggested.

> "[land consolidation] There isn't here, here not. In this area nothing has been done: it is rain-fed land." (5NT)

The analysis of land classification and consolidation, and irrigation modernisation, enables to list their characteristics which made them positive innovations in the farming actor-networks:

- Reduction of workload,
- Introduction of new products and technologies,
- Introduction of new crops with higher economic profits,
- In relation to the above, optimisation of farming resources (land, time, water),
- Support from the public administrations.

Those changes were celebrated as rural development despite:

- Learning requirements,
- Machinery and equipment upgrading costs,
- Property modifications,
- Landscape changes.

4.5. The Spanish farms

This section introduces Spanish farms by presenting research locations and examples of field operations conducted at a no-tillage and a conventional tillage field.

4.5.1. Spanish farms

Spanish farms were located in the agricultural regions of Ejea de los Caballeros (Aragon), Navarra media, Ribera alta Aragon, Ribera baja (Navarre) and Pisuerga (Castille and Leon) as shown on the topographic map in Figure 31.

Most of the farmers farmed alone or with a family member. Some farmers occasionally hired contractors for specific field operations, except for two farmers who were in business partnerships. 4NT was in a two-person partnership, and 1NT was in a three-person partnership with two permanent employees and provided contracting work for other farmers. The partnerships worked more land (around 600 ha 1NT and 240 ha 4NT), while when the farmer worked alone, the farm size was smaller (between 26 ha and 170 ha).

Farmers owned their land, or part of it, working also rented and communal land. Rights to work communal land rotated between the municipalities' farmers each 8 – 15 years, and sometimes shepherds had the right to graze (sheep) after harvest. The exception was 1CT, who worked solely on communal land.

Farmers at location 1 and 4 also worked irrigated land, which provided them with broader farming experiences, although these are not included in this analysis.

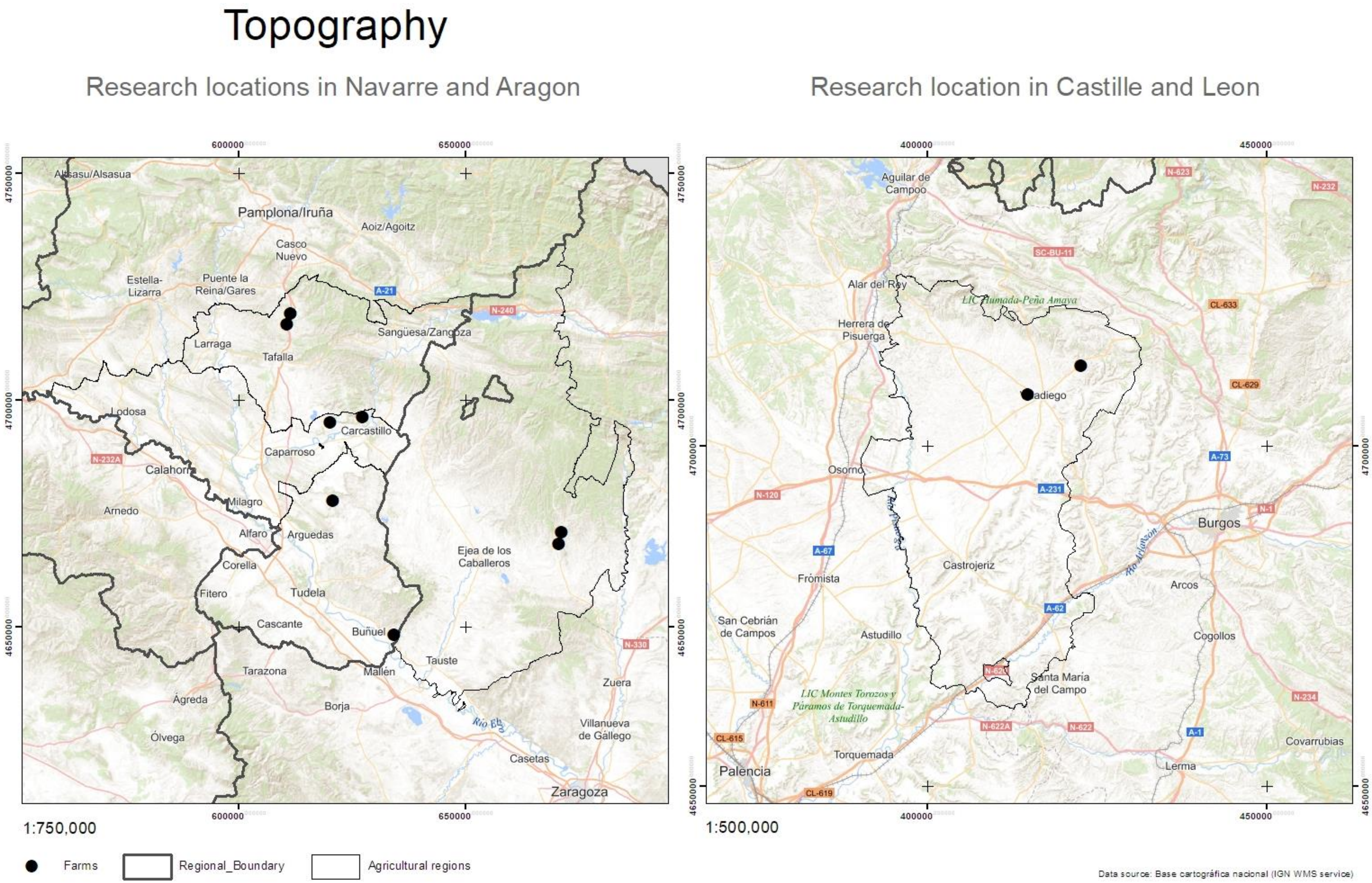


Figure 31. Topographic map of research locations in Spain

4.5.2. Farm operations: an example of the investigated fields

Table 5. Example of a cropping calendar for a no-tillage field in Spain

	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
2017			BARLEY									
2016		WHEAT										
2015			BARLEY									
2014		WHEAT										
2013			BARLEY									
: Herbicides; : Fertilisers; : Pesticides												

Not all farmers participating in the research filled in the questionnaires about field history. However, as examples, Table 5 illustrates field operations performed by a no-tillage farmer and Table 6 by a conventional tillage farmer. Those farmers were not neighbours, and tables do not represent general cropping calendar models.

Table 6. Example of a cropping calendar for a conventional tillage field in Spain

	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
2017			WHEAT									
2016			OAT									
2015		WHEAT										
2014										SUNFLOWER		
2013		WHEAT										
: Herbicides; : Fertilisers; : Pesticides; : Tillage; : Cultivator; : Harrow; : Roller												

4.6. Spanish no-tillage adoption paths

This section presents the results of the different no-tillage adoption paths across chains of actors in different Spanish farming actor-network configurations. The analysis focuses first on identifying actors and their bonds forming different farming actor-network configurations; second, how they operate and which tensions appear; and third, how the normal dynamism or the tensions favour or limit no-tillage adoption. The section starts with a summary table, to then explain in detail the actors enrolled in particular paths, how they are related and how they co-construct each other, holding the farming actor-network or creating tension and favouring change.

Table 7. No-tillage adoption paths in Spain

Path	How farming actor-network operated	Tensions	Adoption barriers and drivers
Income, subsidies, markets, cooperatives and yields	CAP subsidies were core to farmers' subsistence Cooperatives had central roles in farming actor-networks and economic flows Occasionally accessed niche markets directly through manufacturers Farmers adopted non-food producer roles to negotiate income	CAP subsidies were decoupled from yield and land Farmers competed in international markets with low grain prices Farmers complied with public standards, which increased production costs Expansionist strategies were constrained due to high land prices	NT adopted as misconduct by large landowners to benefit from subsidies NT adopted as an optimisation strategy to reduce production costs High yields' symbolism representing the 'good farmer' started to be exchanged for being 'cost-effective', favouring less productive practices
Weather and water: managing the risks	Climate patterns and soil conditions ruled field operation timings, translated by experiential, local and traditional knowledge The Mediterranean climate had irregular rain patterns and droughts Insurances and crop diversification as strategies to manage meteorological risks	Narrow time window with right conditions for field operations increased stress due to increasing workload per farmer Meteorological events disrupted and constrained field operations Climate change challenged farmers' knowledge Crop development was uncertain	NT adopted as it required fewer field operations NT not adopted as it required better field conditions (long-lasting compaction consequences) NT adopted as a risk management strategy to reduce production costs and potential losses NT not adopted to avoid investment and risk-managed reducing field operations
Crops: crop innovation, rotation and cover crops	Experiential, local and traditional knowledge ruled crop selection Crop innovation created higher-yielding and more resistant varieties CAP introduced rotation and greening areas	Introducing new and different crops was constrained due to difficulties in buying seeds or selling products through cooperatives CAP restricted herbicide use in greening areas	Introducing cover crops or different crops in rotations was constrained, favouring most common crops Conservation agriculture practices adopted to comply with CAP, favouring NT adoption Leguminous crops (e.g. peas) abandoned due to agronomic and economic constraints, returned to fallow, favouring conventional practices The meaning of 'crop innovation' was starting to include systemic approaches, favouring conservation practices and NT adoption
Weeds and herbicides	Total and specific herbicides were used Traditional straw burning for weed management had been banned, increasing herbicide use CT relied mainly on tillage for weed management NT relied on glyphosate as a total and cheap herbicide	Glyphosate safety for human health was questioned, threatening being banned Roles of herbicides as necessary phytosanitary products or toxic agrochemicals products created conflicts regarding farmers' environmentalism Herbicides' prices were increasing, and weeds were becoming resistant to herbicides, questioning herbicides efficiency and becoming just agribusiness marketed products Traditional fallow meant land not producing benefits	NT not adopted due to reliance on herbicides, particularly glyphosate Herbicides role as necessary phytosanitary product favoured NT adoption Herbicides roles as toxic agrochemicals and as agri-business marketed products favoured conventional weed management strategies, including fallow and tillage NT and the conflicting roles of herbicides were changing the *'neat fields'* as a symbol of *'the good farmer'*

Path (continued)	How farming actor-network operated	Tensions	Adoption barriers and drivers
Machinery and contractors	Machinery embodied technological innovation and followed expansionist and optimisation strategies, becoming bigger and improving precision Experiential, local and traditional knowledge together with price and pride ruled machinery suitability assessment Machinery markets were widely spread, and access was not limiting Contractors were hired when not owning the appropriate machine or testing practices and crops Farmers co-created innovation by always adapting machines to their farm needs	Huge NT drill had high prices and required additional investments in powerful tractors NT drill had higher maintenance costs Sharing drills constrained due to narrow time windows with optimal conditions to perform seeding	NT not adopted due to high investment requirements for big drills NT adopted as cost-effective in the long term NT adopted through small drills NT tested through contractors NT as machinery innovation was co-created by farmers
Knowledge and trust	Experiential, local and traditional knowledge acquired through interaction with the farm, family and neighbour farmers Local farming communities negotiated the 'good farmer' model Bars and social spaces in cooperatives were places of farmer-to-farmer knowledge exchange Agronomists were available in cooperatives to provide advice; in Navarre, they were from the regional extension institute The internet was used to search and contrast information Global farming communities were crated online, particularly by NT farmers who followed or became influential farmers through social media Global communities supported NT innovative roles, not directly related to 'food production'	Research trials were seen as unrealistic farming Regional extension institutes were distant to farmers and had low budgets (with the exception of Navarre), not producing locally validated data Trust in agronomists was compromised by short-term relations Agronomists working for agri-businesses provided free but mistrusted information due to marketing bias Information needed to be empirically validated by farmers The internet was not a source of trustful information due to the lack of control NT or conservation agriculture farmers' associations were distant or lacked funding Magazines were considered publicity pamphlets, with the exception of Navarre's regional extension institute	Regional extension institutes, with long-term relationships with farmers through their advisors, were trusted and favoured NT adoption Distant and low budget regional institutes, research centres, or farming associations were not particularly favouring NT adoption The internet and global farming communities favoured NT adoption and maintenance in time

*NT: no-tillage

4.6.1. Income: subsidies, markets, cooperatives and yields

4.6.1.1. Common Agriculture Policy subsidies and entitlements

The EU subsidies stemming from the CAP were core to the economy of Spanish agricultural businesses.

> "I have a CAP [subsidies] that is the spinal column of my economy, of my farm, and I secure that." (3NT)
> "If it wouldn't be for the CAP [subsidies], virtually we farmers wouldn't be able to subsist, and that is the CAP, and every time they reduce it more." (4NT)

The CAP was created in 1955 to stabilise agricultural markets by increasing agricultural productivity, to ensure food availability at reasonable prices for consumers and a fair standard of living for farmers (Cong & Brady, 2012). In 2005, a European Council Regulation added food safety and high-quality non-food products, the protection of the environment and the harmonious development among the different regions to CAP's objectives (Cong & Brady, 2012). CAP directives were implemented by member states with some flexibility, including subsidies distribution.

Interviewed farmers disagreed with how subsidies were being distributed. Initially, Spain translated the European directives in subsidies linked to the land surface and production by region. So, subsidies became decoupled from farmers' actual production. Meaning that subsidies did not compensate farmers' efforts to increase yields, whereas bigger farms received more money than smaller ones. Afterwards, CAP worked with entitlements, linked to people who declared to work the land instead of to the land itself. That way, entitlements covered a land surface under a particular use, but the physical fields were exchangeable. Moreover, from this model, a market of entitlements developed, and people speculated with them, while interviewed farmers struggled to acquire enough entitlements to cover the surface they were farming. That is to say, there were tensions in the farming actor-networks because of the barriers to access entitlements to obtain CAP subsidies.

CAP did not promote no-tillage, but entitlement owners took advantage of subsidies being decoupled from production. No-tillage was used as a tool to seed fields at minimum cost to comply with the norms to obtain subsidies. This practice used the reduction in petrol costs with no-tillage compared to conventional tillage. Even no-tillage farmers admitted that this practice of no-tillage existed. However, it was never acknowledged as a farming activity. It was described as misconduct of large landowners, including nobility, taking advantage of subsidies intended for farmers.

> "How it influences? [EU subsidies on no-tillage adoption] If I had 600 € entitlements I would seed with no-tillage and wouldn't care about what turned out! Which is what many are doing!" (3CT)

4.6.1.2. *Cooperatives, markets and grain prices*

All interviewed farmers were members of an agricultural cooperative that played a central role in the farming actor-networks, especially for small farmers. Cooperatives could achieve better deals than individual farmers would. Thus, cooperatives marketed grain production and negotiated better prices for grain with higher protein content (e.g. with breweries), which in turn required adapting farm operations and inputs (e.g. higher fertilisation). Additionally, cooperatives bought inputs in bulk (seeds and agrochemicals) so that individual farmers could access them at lower prices. Moreover, cooperatives provided consultancy on CAP legal requirements, subsidies, and some provided connections to banks for crop insurances. Finally, all cooperatives had a technical advisor for agronomic advice. For all these reasons, farmers were members of cooperatives and those played central roles in farming actor-networks.

Occasionally, some farmers dealt directly with manufacturers for specific products accessing niche markets. The manufacturers mentioned during the interviews were deep-frozen vegetable manufacturers and wine breweries. Those experiences were not related to cereal crop, but they increased farmers' knowledge regarding the need to manage payment risks, which otherwise was shared by the cooperatives' members. Moreover, manufacturers' terms and conditions constrained how those crops were grown. So, farmers experienced how in niche markets, one of their core values, their 'freedom of choice' (see section: Spanish farmers' values), was restricted by private manufacturers' and retailers' standardisation (Mikkola, 2017).

In the case of cereals, farmers' grain production under European standards had to compete in the global market. In this sense, food safety and environmental regulations affecting agrochemicals were the public standards constraining farmers' choice (Mikkola, 2017). Moreover, they increased farmers' production costs, which, in turn, increased their grain prices to cover costs and eventually make a profit. Therefore, high production costs hindered Spanish and, in general, European farmers' competitiveness against international products produced under different regulation frames. Economic pressures can drive farmers to unethical environmental and social practices (Hendrickson & James, 2005; James & Hendrickson, 2008). In this sense, 3NT speculated that this tension would end with Spanish farmers producing for niche markets of high price products. In any case, private standardisation for niche markets offered farmers certain financial security.

> "We are in the global market of cereal prices where Chicago rules, Paris rules, and we have to compete with Argentina, with Brazil, Africa, with Australia, with Ukrania, Kazajistan, with all Christ! If you want to produce in Europe, protect the farming it has […]." (2CT)

> "And Europe has a problem with that, you know? Because here, very soon if it continues like this, […], there will only remain the guarantees of origin, everything very good, but it will be expensive, or they will bring sh** from other places. That clear." (3NT)

In addition to pertaining to cooperatives or accessing niche markets, farmers adopted a variety of strategies to relieve the economic tensions caused by low grain prices in global markets. In their farms, farmers followed expansionism, intensification, diversification or optimisation rationales, or a combination of them, as explained in the next section. Outside the farms, farmers took roles that differed from their 'food producer' role to negotiate policies or grain prices. Examples were their involvement in cooperatives' directives to negotiate prices with manufacturers or in farmers' trade unions to deal with local and national policymakers.

4.6.1.3. Expansionism and optimisation: land access and production costs

In the productivist farming paradigm, higher income is guaranteed through higher yields. In turn, this is accomplished through intensification (by means of innovations) and land expansion. Therefore, some farmers' reaction to low profits was to increase their investments in technology or land.

However, land access was constrained because of low land availability and high land prices. The low land availability in the market was a consequence of CAP subsidies from which non-professional farmers could benefit (hobby farmers). High land prices (to buy or rent) resulted from speculation, taking advantage of the money that circulated because of the young farmers' governmental financial support. 1NT reflected on farms' need to extend acreage to make a living out of farming and the lack of access to buy land as their primary problem at the farm. Indeed, extending farmland was almost a requirement to sustain their farming business, particularly for business farmers.

> "Well, the main problem that we have is not on the farm. It is that there is almost no access to land. Why? We think that it is due to CAP […] It is thought to give subsidies to everyone, so all those lords that have those big land extensions maintain them, make money and don't work anything, in plain language… but the farmer who works never has an option to buy [land]. […] I need land to work. That is my job! And I am fed up with the landlord calling and saying: 'listen, you have to pay more'. […] It has been said that 'every time there are fewer people in the field' but who stays needs an extension that is… exaggerated, to make a living, and there isn't any [land]!" (1NT)

High land prices and lack of access to buy land drove farmers to farm all available land even if not suitable. Moreover, intensive continuous cropping was chosen over practices with environmental and agronomic benefits, such as fallow, because farmers could not afford to implement land uses that did not generate any income, as 3NT expressed. Nonetheless, traditional and environmentalist farmers had positive attitudes towards these practices.

> "I mean, it is a loop of many things… First, of course, here we have to make money every year! You think about a field and 'well, I leave it on fallow or forage or so on' but you have to… if you pay the rent and those things, you have to exploit it! You have to make a profit every year!" (3NT)

Different farming actor-network configurations were those of hobby farmers, including those farmers with part-time or full-time jobs outside farming. In these cases, farming might still represent the core income in their household. Nonetheless, their relation with yield was less dependent, which had consequences regarding the risks that they were willing to take to experiment with innovations and how they budgeted investments, as 2NT explained:

> "[…] You have an income from another side, that is so. Nonetheless, numbers have to turn out, obviously! […] Thus, when you spend some money to buy a drill […], you might finance it from the other side, although you have to recover it here [in farming]." (2NT)

Nonetheless, the majority of the farmers, due to low grain prices and high climate-related risks, decided for optimisation strategies on their rain-fed land, reducing production costs to increase their benefit margin. Interestingly, in some instances, optimisation required farmers' investment in innovations that ensured producing the highest yields at the lowest costs. Among farmers who followed this path were no-tillage farmers. Cost reduction was achieved through reducing fuel consumption compared to conventional tillage, in which fuel was used in repeated ploughing and associated field operations. Indeed, in most of the Spanish interviewed cases, cost reduction, compared to conventional tillage, was the first reason driving the adoption of no-tillage.

> "There is no other way! With the low prices, if you don't cut costs… then it's difficult, isn't it?" (4NT)
> "[…] Thus, I assessed the cost of farming with the conventional tillage system and what could turn out by organising the conservation agriculture, and I saw it suited me. So I did that." (5NT)

In these farming actor-networks, there was a rupture with the productivist farming paradigm, in which more inputs meant higher yields, and these meant higher profits. The argument remained the same in the market, and higher yields turned into higher profits. However, the final profit farmers made from their yields was insufficient for sustaining their living even if yields were high due to low grain prices. Therefore, economic sustainability relied on CAP subsidies.

Albeit yield had lost its significance in farm income, it was still maintaining its traditional role as a symbol and measure of the 'food production' virtue of the 'good farmer' role. Consequently, during the interviews, it was rare for no-tillage farmers to share that no-tillage produced lower yields than conventional tillage. In most cases, farmers valued the reduction in production costs but wanted to maintain or even increase yields compared with conventional tillage. Interestingly, some environmentalist farmers expressed a logic of intensification based on conservation agriculture principles. While their farming was less intensive in inputs (e.g. agrochemicals, plough, etc.), it was based on technology and controlling ecological cycles. This was, negotiating with non-human actors to enrol as inputs and labour, with the ultimate goal of producing higher yields.

4.6.2. *Weather and water: managing risks*

4.6.2.1. *Climate, weather and water translated through traditional knowledge*

Climate, weather and water had dominant roles in Spanish farming actor-networks. Those actors determined crop development and the amount of yield. Local and traditional knowledge gave farmers a frame to assess which crops were suitable to grow at their local conditions and the right timing for field operations. Even then, farmers had to deal with weather irregularities and meteorological events that damaged crops in many Spanish locations.

Indeed, Spanish rain-fed agriculture was at the mercy of irregular rain patterns. Rain-fed land depended entirely on pluviometry as its water source for crop development. In many cases in Spain, low rainfall, irregularities from standard rain patterns, or droughts were the main causes of yield losses below the profitable thresholds. Moreover, crops' water requirements varied with temperature and a bad combination of both produced additional yield losses. In different climatic regions, the meteorological risks were related to an excess of water, cold temperatures, or frost, whereas hail was a general concern across Spain. Consequently, farmers in Spain dealt with highly erratic weather and the potential loss of yields and investment.

> "[…] The major problem that we have on rain-fed land is water. That it rains very little, very little. Now we had a few years that pluviometry has increased, but the norm here is that you have years that you seed, and it doesn't emerge." (4NT)

To assess how climate impacted their farming, farmers relied on local, traditional and experiential knowledge, although these were challenged by climate change. Farmers knew which weather patterns translated into the highest yields in their location. This knowledge was not only based on their own experience, but it had also been transferred through generations inside farming families and the farming community. Additionally, traditional knowledge had translated the weather patterns into the right timings for field operations. Nonetheless, among farmers, there was an awareness of the impact of climate change on their farms and their productivity. Moreover, climate change was affecting the possibility to enter the fields at the right timings.

Figure 32. It almost rained on 1-CT field

> "[…] if you do everything at its time, there are no problems. If it is time to seed, then seed. At its time! When it is the date for seeding, then seed, don't wait for… seed! Here, in October, seed. Don't wait for November! In October, start seeding." (5CT)
>
> "Actually, here, the feelings of climate change is at the inverse… for what I see. Because it is raining more. I do feel the seasons, they are not like before, the transitions are more… the four seasons… now it is more… well, not tropical rains and dry, but it doesn't resemble […] we had it tricky to enter the fields" (2CT)

Actual weather and weather forecast determined, on a daily basis, which farm operations were suitable. For example, seeding was unsuitable after heavy rains because it caused soil compaction (further discussed in the next chapter) or if there was a negative weather forecast that compromised crop emergence. Similarly, applications of fertilisers or herbicides were not suitable if rain was forecasted because it could leach the agro-chemicals causing environmental problems and the loss of the required effect. Therefore, farmers still needed to confront the decision of entering the field with the pressure of crops developing successfully until harvest.

4.6.2.2. Managing meteorological risks: insurances, diversification and cost reduction

Monitoring weather was essential for farmers managing meteorological risks. In this sense, new technologies such as the internet and smartphones allowed farmers to access real-time meteorological information and weather forecast. As seen above, this information was crucial for farmers to decide to perform field operations and plan their work.

A generalised strategy to deal with meteorological risks affecting yield loss were insurances. There were many types of insurances. The interviewed farmers mainly insured for hail and wildfire and flooding when applicable. Insurances were made yearly per field, crop and the expected yield with saving banks and through cooperatives. If the damage had been done, an insurance expert verified and assessed the damage in a field visit and farmers received financial compensation. This way, farmers ensured some income to cover costs and reduced stress associated with unexpected weather irregularities. Nonetheless, farmers' attitude towards insurances was as a last resource. This related to the 'good farmer' role, who makes a profit through 'producing food' and does not take advantage of other ways to make money without the same effort and care.

Besides crop insurance being a generalised practice, there were problematic circumstances. The cases mentioned during the interviews were low return coefficients of particular crops such as leguminous plants, high investment costs for comprehensive insurances, benefit loss when discontinuing insurance and the consequent high costs for resuming insurance. Additionally, there were no insurances for land left at fallow. In this case, the land was not in production; however, for example, flooding damage could affect the capability to grow the following crops. Those problematic circumstances restricted the adoption of certain crops or practices.

Farmers also managed weather-related risks through crop diversification. With irregular weather patterns or unexpected events, having different crops reduced overall farm losses, as different crops would be at different vulnerability stages due to having different growing cycles. Moreover, 4NT explains the potential of irregular rain patterns benefiting at least one of the seeded crops.

> "Because here… I always repeat the same thing, here everything depends on rainfall. Then, there are years when you say that barley comes out well, which comes earlier, and maybe it comes out better, one year, better than wheat because ... because it has rained earlier, but maybe the spring rains came later and maybe it has rushed the barley and the wheat... I mean... it is... It is very difficult here!" (4NT)

Finally, farmers managed potential yield losses due to meteorological risks by reducing production costs on rain-fed land, especially in regions with a high incidence of drought or irregular rainfalls. Advisors from extension institutes and cooperatives also recommend this strategy with the objective of minimising the potential economic loss and ensuring economic sustainability.

> "So we always go thin with the fertilisers. Recommended by the [extension service] I mean, they come and tell us 'careful, careful' because we don't know what the pluviometry… here it is very irregular." (4NT)

In relation to cost reduction, farmers adopted no-tillage or performed fewer field operations to reduce production costs when profit margin could not be ensured. Conventional tillage farmers decreased the number of field operations to reduce time and petrol investment. This way, they reduced production costs without investing in no-tillage machinery. Whereas, for no-tillage farmers, changing their tillage management was the only option in the long term.

> "What convinced me was, first, the fact that when there are years that rain is scarce [no-tillage] reduces costs and then, if you yield the same with fewer costs, then it is the only option that we have." (4NT)

4.6.3. Crops: crop innovation, rotation and greening areas

4.6.3.1. Crops and crop innovation

Crops were the actors that embodied 'growing something', which was core to farmers' values. Additionally, farmers drew on tradition and experience regarding crop requirements to assess their suitability on their farms. Nonetheless, it was a generalised practice among farmers to keep informed about new varieties and test them at their farms. Sometimes farmers relied on shared experiential knowledge from neighbour farmers or cooperative's field trials. However, this reliance was not merely based on trust; it involved empirical validation by the farmer visiting the fields.

> "Well, many crops are discarded here, but not because they aren't profitable, but because you can't grow them… it is the issue with the alfalfas, here we don't do alfalfa, I don't have the machinery, and the climate doesn't…" (2NT)

Farmers valued crop innovation because it resulted in an increase in yields and ease of crop growth. For example, crop innovation had produced varieties with shorter growing cycles, making it possible to adapt them to local climates. However, the focus of crop innovation on increasing yields had generated weaker varieties against pests and diseases.

> "I think that […] that by increasing the yield, the plant is weaker or more stressed, at its limit… to say it somehow. You look at it, and it is healthy, but crops are… I think they are more at their limit of production, and when anything enters, diseases affect much easier." (2CT)

Farmers learned about crop innovations through cooperatives or their direct engagement with research centres and extension institutes. Cooperatives informed farmers through their agronomist or through talks and workshops organised by extension services or agri-businesses. Furthermore, farmers maintained contact with research and extension institutes to be informed about new varieties. Additionally to searching for crops and varieties that maximised productivity and resistance, farmers searched for plants that had some specific agronomic traits, provided access to niche markets or were different from the most common varieties to decrease disease incidence.

However, when farmers tried to introduce new crops, they faced many challenges: lack of traditional and experiential knowledge regarding particular crops' management, lack of specific machinery, lack of recurrent access to seeds and lack of commercialisation paths for the new products. Indeed, new crops or varieties challenged traditional knowledge, which normally provided the links between crop production, local climate and farm operations. The adoption of different crops or new varieties increased stress levels for farmers because of the risk of not getting the right fit between crop requirements and climate that could end in economic loss. Moreover, introducing new crops increased the difficulties to commercialise production because, in the cooperatives, less attention was paid to the marketing of marginal crops. Thus, climate, weather, cooperatives, and the market had also major roles in influencing the adoption of different crops or crop varieties.

> "[rapeseed] […] is more profitable; it is more profitable… but it makes us suffer a lot because it is more difficult to establish. If it gets established, then it's perfect, but that it emerges in the timing, we seed them it is difficult because it almost doesn't rain." (2CT)

4.6.3.2. Rotation and greening areas

CAP introduced rotation and greening areas, affecting crop management. Those were included in CAP's cross-compliance norms, which required farmers to follow Statutory Management Requirements and ensure Good Agricultural and Environmental Conditions to qualify for full subsidies payments. The first concept was crop rotation with at least three different crops. This applied to the whole surface that was declared. The second concept was greening areas or environmental focus areas, where many restrictions applied to ensure environmental benefits. In this case, the surface only represented up to 7 % of the total area declared. Before, farmers generally grew only cereals, alternating between wheat and barley. Therefore, both CAP concepts increased pressure on farmers to grow a diversity of crops.

Farmers planned their rotations on the basis of the main source of income: cereal production. From that base, they selected crops they grew at high revenue but low quantities for niche markets. These fields were subtracted from the required surface for rotation by CAP norms, which were then fulfilled with fields growing *'rotation crops'* or fallow.

> "The major crop is wheat. Barley, rapeseed, oats, peas…peas, vetch… these in lower percentages. It is a system that we follow since… buff, I can't remember. More or less 25 – 30% we do rotate, to not grow always cereals…" (2CT)

Figure 33. Rural landscape near location 3

Despite farmers dedicating major surface to cereal production, they saw rotations as beneficial in two ways: legumes fixing nitrogen and the possibility to use specific herbicides. Furthermore, for some farmers, having a profitable legume was the clue for farming business success in the current farming actor-networks.

> "[…] That aligns a bit with the rotations that I mentioned. There are crops that you know are nitrogen fixators, then, well, this is why we use them. Then, at the same time, because there are some specific weeds that you can't kill with the crop, because you can't spray a specific herbicide. But with a different crop, you can spray that herbicide that kills that herb, so these are the constraints that lead us to do rotations. Nothing more!" (1NT)

Greening policies applied restrictions on the use of agrochemicals, and therefore they were seen as causing negative impacts on the farm economy. The first impact was the difficulty of achieving profit with leguminous crops because it could be almost impossible to grow them without pesticides and herbicides. Then, if the costs were not covered, farmers went back to fallow, which was another admitted option for the greening areas. The second reason was that greening areas were seen as sources of the proliferation of pests, diseases and weeds, which linked with farmers' ideology of controlling nature. This was even the case of farmers who adopted other conservation agriculture practices (see 3NT comment). Consequently, the general trend was to avoid establishing greening areas on productive land but leave it on marginal land.

> "[…] Nowadays, what sense do greening areas make? I mean, 5% without spraying, that is… that is anti… Why? Phytosanitary products are to fight pests, and against a sanitary

> measure… who says I should leave 5% of the population without vaccination if there is an epidemic? It doesn't happen, but well… That is a reservoir for weeds for other places! Who invents this? Of course, [agri-businesss] invents it…" (3NT)

Many farmers used fallow as both a third crop in rotations or as a greening area. This was related to tillage management because no-tillage farmers often included conventional, vertical or minimum-tillage in their rotations, mainly after fallow, to terminate weeds.

Conversely, those policy restrictions could drive conventional tillage farmers to adopt no-tillage on marginal land. In those cases, farmers seeded leguminous crops in greening areas on marginal land with minimal investment. There, no-tillage was used as a tool by traditional or hobby farmers, who used conventional tillage as the better practice for production. The seeding was performed by no-tillage neighbours or with small machines that did not require huge investments. Accordingly, this use of no-tillage did not highly impact their farming actor-network configurations. In fact, it aligned with the tradition of having diverse equipment and applying the *'right'* practice according to the field conditions.

4.6.3.3. A new meaning of crop innovation

Crop innovation had two meanings that coexisted in the farming actor-networks. One meaning was the new varieties, which were developed in the laboratories from researchers or manufacturers. As seen above, farmers accessed those innovations through the extension services or cooperatives, but also proactively through relations that they had built with research centres, seed manufacturers and other farmers. The other meaning of crop innovation had a systemic approach and was related to concepts of rotation (more widely accepted), cover crops, crop associations, etc. The second meaning was endorsed by conservation agriculture, and European administrations were integrating them in their policies and in European farming.

Innovative farmers saw these two policies, rotation and greening, as opportunities to try different practices. Particularly environmentalist farmers were introducing practices to test options following conservation agriculture principles. Indeed, cover crops were being introduced in greening areas.

> "Cover crops? It is the first year that I grow them in response to that European norm of environmental focus areas. In my management… I thought I had to do it that way so that I grow cover crops on that surface where I am obligated to not spray phytosanitary products…" (2NT)

However, environmentalist farmers were experiencing difficulties in implementing innovations. Similarly to the problems that farmers faced when introducing new crops, they lacked the reference of traditional and experiential knowledge to grow cover crops. Additionally, it was hard to access seeds that were not normally provided by their cooperatives or sell potential by-products. Moreover, as these no-tillage environmentalist farmers were quite strict with trying to avoid ploughing their land, they faced the added difficulties in terminating cover crops. As a consequence of those difficulties, some farmers limited the extension of their innovations, which means that they limited the surface of testing conservation practices to the minimum required by CAP for greening areas.

> "For example, that thing with the cover crops, you might find that it is time to seed them, but you don't have seeds, because normally those seeds aren't available at that time during the year, isn't it?" (2NT)

Nonetheless, occasionally farmers adopted and tested even more conservation agriculture practices than required by CAP. In these cases, there was a strong connection to conservation agriculture principles, which was even referred to as *'faith'*. Without belittling that connection, in the cases where farmers adopted innovative conservation practices, there was also a strong connection with innovation itself.

In contrast, some farmers enjoyed the calmness of an assemblage that worked. This meant that they were not driven towards the insecurity of innovation, growing completely different crops or uptaking different practices. Nonetheless, those farmers would test and introduce new varieties or new crops when those new enrolments did not mean major changes to their farming actor-network configurations. Nonetheless, these farmers also had to integrate rotations and greening areas, as those innovations were demanded by European policies, whose subsidies farmers relied on to sustain their businesses.

> "I would like to try… 'nothing', which means everything is going well, […] I want to remain like this." (2CT)

4.6.4. Weeds and herbicides

4.6.4.1. Weeds and herbicides in the farming actor-networks

Traditionally, farmers eliminated weeds and pests through a combination of fallow, straw burning and tillage. Besides straw burning becoming banned, for some farmers, it still was a better option to eliminate pests and diseases. Moreover, banning straw burning caused an increase in herbicides' use.

Herbicides were used in two ways: a total herbicide before seeding and a specific herbicide during the crop growth. Total herbicides affected all types of plants, whereas specific herbicides targeted a specific group of plants. The latter could be used during the growing cycle of the crop, as long as the targeted weed was from a different plant group. Therefore, rotations benefited weed management in the sense of alternating different plant groups to apply different herbicides. Nonetheless, in many of the interviewed cases, herbicide application was not a routine field operation. On the contrary, the farmer assessed each field's quantity of weeds and if these would cause problems due to competition for water and nutrients with the crops.

Herbicide use was regulated due to potential harm to human health and the environment. Consequently, in the farming actor-networks, there was a flow of information regarding food safety and environmental regulations and its compliance. For the latter, farmers had to maintain a field notebook with all products and application methods. However, to select a herbicide, farmers needed to be informed not only about which was the most effective product but also about which agrochemicals were banned and how they had to be applied. Mastering agro-chemical products' information – including fertilisers and other pesticides – was a knowledge that *'professionalised'* farming, as 5NT suggested.

> "Before I was more interested in 'professionalise', to learn about what herbicides, fungicides, or fertilisers… there are […]" (5NT)

In Spain, cooperatives and their agronomist advisors had a major role in herbicide information and product circulation. Farmers usually bought their herbicides through the cooperatives. Additionally, cooperatives provided advice on keeping the field notebook updated and treatment options. This advice was more trusted than the biased information from the agri-business salesperson, who advertised products directly to the farmers. Nevertheless, farmers still contrasted any information with their experiential knowledge and other information sources, for example, through the internet and smartphone's farming apps.

4.6.4.2. The multiple roles of herbicides

Herbicides took three different roles in the farming actor-networks: as a toxic agro-chemical, as a phytosanitary treatment and as agri-businesses marketed product. The first role was sustained by environmentalist farmers who agreed with environmental principles and regulations aiming to reduce herbicide use. In those farming actor-networks, the enactment of herbicides as toxic-agrochemicals led to their use being associated to environmental or human harm, although sometimes they were used reluctantly to control weeds. The second role was built and supported in farming actor-networks in which farmers disagreed with how the risks of the products were assessed and how regulations were established. In those farming actor-networks, herbicides were enacted as phytosanitary products, necessary for weed control and safe if used correctly.

The third role was emerging as a result of questioning herbicides efficiency. This rationale came from weeds becoming resistant to herbicides but also from a lack of recent innovations in herbicides and pesticides, as mentioned by 5NT. Moreover, the combination of toxicity, loss of effectivity, increasing normalisation and increasing costs increased farmers' mistrust in agri-businesses. Then, herbicides and pesticides became just marketed products whose agronomic value was not guaranteed.

> "Indeed, weeds are one of the major problems because they are becoming resistant to herbicides, because…. I guess it is because of wrong management… our management, certainly. And as I see it, they aren't coming out with any products with new active ingredients that could control that. That could give us another solution." (5NT)

Farmers' relation to different herbicide and pesticide roles determined different farming actor-network configurations. Contrasting positions were found among innovative and traditional farmers within the group of environmentalist farmers that related herbicides and pesticides as toxic agro-chemicals and tried to avoid them. Innovative farmers strongly connected to the conservation agriculture paradigm were attracted to organic farming. In contrast, traditional farmers tended towards applying fallow, tillage and, due to the impact of CAP policies, rotations. On the contrary, business farmers who related to herbicides and pesticides as phytosanitary products generally related to the conventional productivist agriculture paradigm. In this case, farmers applied herbicides and pesticides by default instead of assessing each field individually. Still, those extreme roles co-existed in farming actor-networks, meaning that in many cases, integrated weed and pest management was used, and herbicides and pesticides were both necessary phytosanitary treatments and toxic agrochemicals that should be minimised.

Figure 34. Poppies and other flowers and spontaneous crops proliferate at field margins and access lanes near location 5

In other instances, the co-existence of herbicides as toxic agrochemicals or as necessary phytosanitary treatments led to conflicts related to farmers' environmentalist roles. 2NT explained the tensions between no-tillage and organic farmers. This tension further divided farming actor-networks, affecting the meanings of environmentalism, ecology, food safety and ultimately the role of the environmentalist farmers.

> "[…] I had many discussion with ecologists, farmers, who grow organically. […]
> - 'Yes, of course, I spray.'
> - 'So then, how is it that you do it ecologically?'
> - 'Because ecology is something else f***! Do you want a product free from residues? Ok, call it… call it 'product free from residues' But don't call it ecologic! That is something different! If the product doesn't have chemical residues, ok, I will call my product 'free from mycotoxins' does your product have some?'
> - 'I don't know.'
> - 'Well, find out because maybe it has some mycotoxins due to not having chemicals!'
> Not everything is black or white, you know? But nobody talks about that!" (2NT)

Innovative environmentalist farmers tried to find different practices for their weed management and decrease reliance on herbicides. Thus, farmers started experimenting with cover crops on marginal land, among other reasons, to grow crops that suppress the germination, development and proliferation of weeds. Interestingly, another idea was to change the role of weeds, translating them into *'service crops'*, with the aim of obtaining benefits from plants usually classified as weeds.

4.6.4.3. Tillage management and the neat field

Farmers controlling weeds and pests through tillage was enacted by their farming actor-network configurations. As discussed, this practice was related to traditional and experiential knowledge, the conventional productivist agriculture paradigm and more recently to the increasing complexity of regulations, the toxicity of herbicides and pesticides and the increasing costs, loss of efficiency and mistrust in the marketed products. Moreover, it was related to producing a clean product to sell because cooperatives would ask for clean grain, not mixed with grains and straw from weeds; and in the same sense, it was also related to the neat field as a symbol of 'the good farmer'.

> "We have faith in [tillage]! Don't you see that it cleans the fields, it gives them furrows, it aerates them…? Afterwards, the following year it prevents using more herbicides; you have the security that in two or three years, you won't have big weed problems… so." (1CT)

No-tillage farming challenged the ploughed fields symbolism of good farming. In no-tillage, crop stubbles and residues were visible on the fields. Additionally, weeds grew until they were treated with herbicides. Consequently, fields did not look homogeneous anymore, nor did they represent the work and effort of the farmer. No-tillage farmers translated that messiness into a notion of caring. It could be assumed that no-tillage promoted an alternative symbolism of 'good farmers' in which they cared for the environment. However, during the interviews, besides the environmental rationale, farmers always explicitly linked those practices to the benefits for crops. Accordingly, the traditional concept of the 'good farmer' caring for their crops had not changed that much. 3NT talked about the placebo effect that conventional tillage farmers felt about work being done when fields were ploughed, whereas his messy fields looked better (greener) once crops were growing.

> "[…] But… people now… as I tell you… here, ploughing, ploughing, for example, this year they couldn't plough because they couldn't enter the fields [moist soils]. But with minimum-tillage, a lot of people… and people turn it [the soil] around a lot… and maybe it rains a bit, and people don't know what to do, and they say 'buff!! I go to turn it down!'. And they feel that placebo effect of saying 'well, I have them ploughed'. Do you know? I will show you now, my land […] is much better than the other! I mean, you will see it right now!" (3NT)

Ligneous weeds also challenged the symbolism of the *'neat field'* in no-tillage farming. Moreover, the presence of ligneous plants was penalised by the CAP subsidies requirements. 5CT talked about the negative image of ligneous plants in the field, while some no-tillage farmers confirmed their problems with those weeds because the most used herbicide was ineffective against them. 4NT explained how, in his case, the risk of ligneous weeds proliferation drove him to do tillage in his rotation after fallow. As seen above, no-tillage could be enacted as a tool for specific purposes, whilst in this situation, conventional tillage or minimum-tillage was used as a tool in no-tillage farms.

> "[…] Those are plants, so to say, pluriannual, that are there. That is not allowed. Fields are fields, and they have to be kept as fields! You can't keep them as you go on your own.
> - 'No, that is a field.'
> - 'how? A field?' […]
>
> Obviously, what does a tree in the middle of that field? […] " (5CT)
>
> "We had a problem here with no-tillage, that is why… it is what glyphosate doesn't control. Then, the ligneous plants that are here… then we have problems. And then we have to, how to say it? Break them. I mean, all those fields start bringing them inwards, we have to go to break them because otherwise, they get full of ligneous plants. In the beginning, there shouldn't be any problem, but when you are doing no-tillage, every time there are more. So, as you don't control it with glyphosate, you have to turn it. Especially… maybe only the borders of the fields. […] neither is it necessary to turn it a lot, with the upper layer might be enough to remove the weeds." (4NT)

The changing role of herbicides and weeds was also affecting the symbolism of the neat field for conventional tillage farmers. In this case, having some weeds on the field represented the reduced use of toxic agrochemicals. 3CT ratified that he preferred to have some weeds on the field rather than applying herbicides:

> "[applying herbicides] Very little, if I can… if there are some thistles, I don't get offended." (3CT)

The general understanding among farmers was that no-tillage relied on the use of herbicides and pesticides, particularly on the total herbicide glyphosate. Thus, tillage was exchanged for the use of total herbicides before seeding to terminate any weeds that could cause competition. This reliance on pesticides and herbicides was a major barrier for conventional tillage farmers who were tempted to adopt no-tillage due to other benefits of the practice. For those farmers, no-tillage could work as a tool to seed specific crops, in rotation with conventional or minimum-tillage, but never alone. Particularly because of the reliance on glyphosate, a cheap total herbicide used by all no-tillage farmers, whose safety and legitimate use were questioned.

> "[…] I mean, I don't like herbicides. I prefer… Although they… [no-tillage farmers] say they spray fewer herbicides, I think that it requires more. Me… I don't completely like herbicides. I spray them because of obligation. But… I don't know. I think that mixing a bit everything. No-tillage sometimes, medium or minimum-tillage other times, and others traditional. I think that playing a bit there… that is ideal! I mean, I won't say 'I am not going to do no-tillage' But… yes. Not everything! […]" (3CT)

The possibility of glyphosate being banned due to potential carcinogenic effects caused increasing concern among the farming actor-networks. Notwithstanding that all farmers used glyphosate, no-tillage farmers were the most affected because of their greater reliance on it. However, different no-tillage farmers had different approaches to the regulation: as a threat to no-tillage, as an increase of costs, or as an opportunity to develop other weed management alternatives.

> "Right now, we were frightened due to glyphosate, that it was pending if they would ban it, although at the end not. […] Glyphosate if they take it away… it is no-tillage glyphosate. […] No-tillage is glyphosate. […] Yes, it is totally dependant. If glyphosate disappears, no-tillage possibly too." (1NT)
> "Obviously, what happens is that instead of doing it with a cheap herbicide, I will do it with a more expensive one. […]" (2NT)

Some no-tillage farmers were experiencing major problems with weed control. For some environmentalist innovators who had adopted no-tillage, the increasing weed problem was a result of them not applying correctly the principles of conservation agriculture. Improving and combining with more conservation agriculture principles was their solution. In contrast, other farmers with looser strings to conservation agriculture would re-introduce ploughing in their rotating practices, generally after fallow.

> "But now, I already have serious weed problems, you know?
> […] it is worth to leave the land on fallow a year and then spray it with glyphosate, or with the knife roller, which is what I am looking at now, rather than treating each crop." (5NT)

4.6.5. Machinery and contractors

4.6.5.1. Machinery and contractors in farming actor-networks

> "Well, the tractor is like having a good car, but you know… there is a lot of marketing in this." (3NT)

3NT comment helps to establish two ideas: farmers liked their machines, and it was a business for machinery manufacturers and traders. Similarly to farmers' 'professionalization' regarding learning about agrochemical products, the 'professional farmer' had to know about machinery and tools.

Accordingly, information and material flow across the farming actor-networks developed in mutual interest. Thus, all interviewed farmers went to agricultural fairs to keep updated on machinery innovations, reviewed magazines they received from cooperatives (produced by machinery manufacturers) and searched for information about machinery on the internet. Particularly, farmers used the internet to search for specific machines to compare prices between traders, to access the second-hand market or to access forums and Facebook pages looking for experiential knowledge from other farmers of the global farming community. Moreover, many traders, in addition to having their branches in the cities, visited cooperatives to show and sell their products in talks or workshops. Additionally, some farmers had direct bonds with machinery manufacturers. For example, machinery manufacturers rendered equipment as a marketing strategy to sell the tool after being tested or to use farms as showrooms. 1NT talked about their experience with a particular manufacturer.

Farmers possessed a range of tools and machinery to respond to diverse meteorological, soil and crop demands. As 2CT explained, farmers needed powerful tractors to perform all field operations in a constrained time window. However, diversity in tools allowed farmers to adapt to farm diversity. Even having multiple tractors helped to adjust the right size and power to the different field operations, taking into account weight and petrol consumption.

> "Well, you are at the mercy of the climate. Here, the truth is that we always had to have a bit more powerful tractors and a bit bigger because the time window to enter the fields and do field operations is… sometimes you can relax a bit more, but generally you have to sweat otherwise you don't make it…" (2CT)
>
> "And then the small [tractor], that one I have there, is the one I use for fertilising, spraying phytosanitary products, and all of that…" (3NT)

When farmers did not possess a particular machine or tool, they hired a neighbour farmer or a contractor for the specific task. Those situations could be to harvest or seed a specific crop or work under specific conditions for which their own machines were not suitable. Other farmers used contractors in a routine way, commonly for harvest, particularly if they were small farmers or hobby farmers, with less time or not enough production to benefit from investing in machinery. Contrastingly, farmers could start contract work for neighbour farmers when they possessed a specific machine.

4.6.5.2. Machinery, DIY and innovation

Machinery innovations were linked to the wider farming paradigms of expansionism and optimisation. First, machinery had grown in size, following an agricultural expansionist strategy, increasing farmers' possibility to work more land in a quicker manner. Accordingly, business farmers who were focused on increasing farm size were upgrading their machinery in size as well. Second, the latest machinery innovations followed an optimisation strategy, including precision and automatisation equipment, as these improved the efficiency of seeding and agrochemical applications. Nonetheless, not all farmers assessed all these innovations positively; some farmers contested the need for precision farming in rain-fed cereal agriculture.

> "I remember: last year we bought the spreader we have there, which is automatic, with GPS, it is amazing! […] I have never been able to do that [being accurate on the fertiliser quantity] by hand, never! The machine did that! How wouldn't you change to that?" (1NT)
>
> "[…] over there, people in the fields are very fond of machinery. People talk about machinery… buah! […] the GPS… yes, in some kind of agriculture that requires a lot of precision, but here, a precision of 2 cm…" (2CT)

Nonetheless, machinery prices had increased in a disproportional way compared to farmers' income. Consequently, many farmers did not find it cost-effective to upgrade their machines due to the combination of economic investment and learning requirements, especially small farmers, hobby farmers with small farms and older farmers with no prospect successor.

No-tillage drills were particularly expensive machines. Despite the higher price to buy and maintain them, no-tillage farmers assured that it compensated. Other no-tillage farmers claimed that the overall cost was not more expensive than the conventional tillage equipment, taking into account all the tools that the no-tillage drills substituted.

> “yes, the machine… talking about the no-tillage machine, the no-tillage drills, it is more expensive. It is quite more expensive than the conventional one. Without a doubt. And if you ask me, the maintenance might also be a bit more expensive than in a conventional one, which is understandable as it has more things.” (1NT)
> “Well, yes… but if you look at all the work that no-tillage drills do and the tools it substitutes, it isn’t so expensive. However, the initial investment is high.” (5NT)

The huge initial investment hampered no-tillage adoption. Small or hobby farmers who assessed the practice positively did not adopt no-tillage because of the high investment in machinery. This situation was the case of 1CT, who wanted to buy a no-tillage drill but, on top of the cost of the drill, was advised to upgrade his tractor. Additionally, the price barrier stopped adoption for many conventional tillage farmers who would have used no-tillage as a tool, as a secondary practice on some part of their farm but would not replace their existing conventional machines.

> “We went to buy a drill, and they asked for more money than I was thinking to spend. We went years ago, but they told us we had to change the tractor and so on… That year we did conventional tillage! We wanted to buy a no-tillage drill, and look what we did! The opposite! And then we got cold, and that was it!” (1CT)

Although many no-tillage drills were big machines that required powerful tractors, there were smaller options available, or farmers could recur to contractors. Indeed, the availability of those smaller machines enabled no-tillage adoption both at the whole farm and as a tool in particular fields. Alternatively, farmers hired neighbour farmers to perform no-tillage for specific crops or particular fields.

> “[…] I started with a no-tillage machine that required low power, to not change tractors and all that.” (3NT)

Figure 35. 3NT no-tillage tyne drill

Sharing machinery was sometimes a strategy to overcome the price barrier, as it distributed the costs among several farmers. Additionally, in Navarre, the local government was providing financial support to farmers who associated in small buying groups. However, this was not suitable for all types of machinery and tools, especially not for drills that were needed at the same time by all farmers because of the narrow time window to perform seeding in the right conditions.

Additionally, to access machinery at reduced prices, many farmers approached the second-hand market. Sellers were machinery traders or private farmers, and they advertised in magazines or in online forums. These were especially used by farmers looking for rare tools or specific innovations, even internationally.

On another note, farmers needed to access machinery that fulfilled their particular needs. Machinery had to be suitable to farmers' investment possibilities, to their local conditions, and also to the combination of practices they did at their farms. Thus, not all no-tillage drills were appropriate for any farm. When some of the no-tillage farmers bought their drill, there was less variety of machines available in the market. With time, the range of available machines had become wider and, as 2NT said, deciding on which was the most convenient drill was more difficult than accessing it. Indeed, there was a range of no-tillage drills to adapt to soil types, crop residue amount and climate. Disc drills had a front disc that cuts through the residues and opened the furrow for the seed and a rear tyre that closed the furrow. On the contrary, tyne drills had a hoe that opened the furrow for the seed.

Additionally, there were combinations of these features and their dispositions. However, as 2NT highlighted, there was no perfect drill that fulfilled exactly all farmers' needs in all situations.

> "Finding it, yes. The question is which one. That is the most complicated part. What is it what I want? And then, of course, everything is very expensive, so how much can I spend? Can I get what convinces me more, or do I have to compromise?
> […] although there is no perfect drill, and when all have a problem… […] In some conditions you would like to have one and in others a different one. So, you can't have it all, you know?" (2NT)

Therefore, adapt newly bought machinery to their particular needs was a normal practice among farmers. No-tillage farmers did DIY to their no-tillage machines to adapt them to soil types, crop residue amount, introduce fertilisation options or update them along with other changes they were making at their farm. Additionally, innovative environmentalist farmers who were strongly connected to conservation agriculture build DIY tools to test different conservation principles. Farmers did not do this alone; they networked with local smiths or other farmers to develop their ideas together. Those adaptations and machinery designs show how innovations always require farmers' participation to be successful, meaning that farmers are active agents in the creation of the innovation and are not only end-users of a final product.

> "[knife roller] I haven't bought it… […] I agreed on it with a smith from here, and I have an old roller which we possibly will turn into a knife roller, to see how that works…" (5NT)
> "[…] it will get patented because of the positioning of the cutting and seeding tools because the system is not new; the new thing is the positioning of its elements. And well, we are doing that… and I like it! I like it! Let's see how it works!" (2NT)

4.6.6. *Knowledge and trust*

4.6.6.1. *Experiential, local and traditional knowledge*

Farmers contrasted incoming information flows with their experiential, local and traditional knowledge. Knowing their farm was crucial to be a 'good farmer'. Moreover, farmers assessed the suitability of products and innovations not only regarding the local agronomic conditions but also regarding their business and personal objectives. Additionally, their experiential, traditional and local knowledge often reassured farmers to continue performing the established practices, which produced trusted results.

> "[External advise] Well, these are some references. You have to know where you are! Do you understand? […] You don't need so much, but… you have to know what you want in everything! To have an objective!" (3NT)
> "We farmers always think that our way [of farming] is the best. So, yes, maybe you see something and think that it might work, but in the end, we always continue with the traditional way; we are very conservative." (4NT)

Farmers gained this knowledge through their interaction with their farms and their broader farming actor-networks. The main actors and processes involved in this knowledge co-creation were the non-human actors in the farm farmers connected to through 'learning by doing'. Additionally, farmers co-created knowledge with family members when farmers came from farming families, other local farms by performing contracting work or by *'looking over the hedge'*, and other farmers in the community through farmer-to-farmer knowledge exchange. Farmers particularly valued processes in which they could see and experience the results of the knowledge claims as an empirical validation.

> "[…] as we do contracting work for many people, well, then we might go and seed and then to fertilise or spray herbicides. Or maybe we visit the fields. So, well, we see them because we work them." (1NT)

Additionally, bars and cooperatives' social areas were important spaces where farmers shared their experiences in an informal but trusted environment. Many farmers met neighbour farmers daily or weekly at the bars for brunch, where they strengthened their friendship and talked about their farms. Through these practices, farmers self-organised around ideas they wanted to develop in DIY projects, shared experiences with particular products and innovations and spread the news about pest or diseases infection in the area. Therefore, these places were important for the circulation of information.

> "[Sharing information with neighbour farmers] As a group, a group of… we do that in the bar, ok? We come, drink a coffee and 'Hi, how are you? What are you doing now?' 'Well, I am doing this, and a friend says, 'then we know what not to do!' OK?" (5NT)

Moreover, those informal meetings also added to the co-creation of the communities' 'good farmer' model by discussing and critiquing neighbours' ways of farming. Consequently, innovative farmers were assessed in comparison with the local 'good farmer' model. This often resulted in innovative farmers being assessed in both ways, negatively due to acting out of the communities negotiated norms of good farming and, at the same time, positively due to farmers' respect for independence and courage to taking the risk.

Regarding no-tillage, if adopters were identified as role models for communities' 'good farmer', they had an impact on the local spread of the practice. So, when these farmers supported no-tillage as a beneficial practice, this resulted in farmers' positive attitude towards the innovation. On the contrary, if they spread negative information about no-tillage or dubious information, it resulted in neighbour farmers building a negative attitude towards no-tillage.

> "Moreover, the guy who bought the [no-tillage drill] the first […] was from a village up there. Well, we had the same tool and met at a workshop in [city], and he told me, 'don't spend 3,000,000 in no-tillage! – of pesetas – On a hidden field, if you can't plough it, then go over it with a power harrow and then seed, it is the same!' And then, because he

> already told us that, that it wasn't so necessary and all of that, we got cold feet, do you understand?" (1CT)

4.6.6.2. Advisors

Cooperatives acted as centres of information to spread new crops, technologies and practices. Agri-businesses, machinery traders, etc., organised talks and workshops at the cooperatives to introduce new products. Those activities were marketing campaigns from private businesses, and the goods and information that circulated in those events carried an inherent bias from the brands. Therefore, this information and goods were translated by farmers not as factual data but as marketed products.

Additionally, each cooperative had an agronomist, whose advice was valued according to trust. In Navarre, cooperatives' agronomists were from the regional extension service, which had a good reputation. Additionally, the relationship between farmers and extension workers was strong, long-term and close due to their weekly presence at the cooperatives, attending personal calls, doing field visits, and organising WhatsApp groups. In other regions, extension services had less budget and agronomists were hired directly by cooperatives. This resulted first in a more distanced relationship with the extension services. Indeed, extension workers were not part of the everyday life of farmers, nor their field trials were validating farmers' local conditions as they were done far away. Second, the independent agronomists from the cooperatives did not benefit from the backup of a good institutional reputation. Furthermore, these relationships between farmers and advisors were short-term due to higher job mobility. Other factors, such as lack of experience associated with young age or little dedication to particular problems due to the number of responsibilities they carried in the cooperatives, impaired farmers' trust in their advice. No-tillage farmers in those regions complained about the conventional ideas of cooperative agronomists, while farmers who had adopted no-tillage in Navarre recognised the extension services' expertise and guidance in no-tillage adoption.

Furthermore, farmers maintained connections with agri-businesses as information sources through salespeople because the information was free of cost and intensively distributed. Indeed, agri-businesses salespeople were trained agronomists, and besides visiting the cooperatives, they visited the farms directly to sell their products. During the interviews, farmers referred to these salespeople as their *'advisors'*. Nonetheless, farmers were cautious with the information they received because it was biased towards branded products. Therefore, many farmers strengthened their request for independent advice. Nonetheless, in many regions, independent, local and individual advice from institutions to farmers was lacking due to budget limitations and hiring an independent agronomist was too expensive for the majority of farmers.

To further search and contrast information, many farmers accessed farming institutions' websites at regional, national and international scale. Farmers did this to search for different agrochemical products, different crops and varieties and especially for practices related to conservation agriculture. Sometimes this was caused by the lack of available local information, which farmers attributed to budged shortages for research. However, the implementation of this international knowledge did not always work in the local conditions. Moreover, the English language was a barrier for Spanish speaking farmers.

Indeed, farmers trusted and valued more free information online than the information they were obtaining from subscriptions and magazines. Farmers were receiving magazines from machinery manufacturers and agri-businesses through cooperatives and directly through their membership of trade unions, extension institutes and farmers' associations. However, for farmers, magazines turned into marketing leaflets they reviewed to keep updated on the available products. Moreover, magazines focused on conventional agriculture practices and did not include relevant information for farmers following conservation agriculture principles. Furthermore, subscriptions to conservation agriculture magazines were not worth the cost compared with the quality and availability of free information on the internet. The exception to the negatively valued magazines was the one produced by the extension service institute from Navarre. Regional farmers were subscribed through their cooperatives' membership, and farmers from other regions subscribed to their online version. In this magazine, farmers accessed valuable information about regional field trials' results and yield statistics. Thus, this publication was technical and had the role of research outreach in the farming actor-network, not as publicity leaflets as the other magazines.

4.6.6.3. Research

Knowledge co-creation in the farming actor-network also involved field trials. As mentioned in the machinery subsection (Machinery and contractors), manufacturers let machinery and equipment to farmers, free of charge, in exchange for on-farm marketing activities. In the case of agri-businesses and extension institutes that developed or tested crop varieties and phytosanitary products, the deals with farmers were coordinated field trials. Agri-businesses or extension institutes provided the new product and the farming protocols, farmers tested it at the local conditions, reporting their own perceptions, and agronomists from the agri-business performed control visits. Despite valuing having some kind of references of crop varieties and other products that best adapted to their local conditions and maximised yield, farmers mistrusted the information of the field trails. Farmers' mistrust was because of the experimental protocols with agri-businesses manipulated normal field operations, favouring products effects. Less mistrust was in the trials in collaboration with the extension services, but still, the strict protocols regarding field operations and the small size of the land strips for tests were assessed as a distortion of farm reality. Consequently, the insights into formal field trials reinforced farmers' idea of disconnection between formal research and farm reality.

Farmers built links with universities and research centres at a regional, national and international scale. Despite the disconnection between research and farm reality, farmers valued research because of its independence, rigour and contribution to yield increase. Research independence was attributed to any research centre and extension institute in comparison with agri-businesses, while the rigour was in comparison with their own field tests. Then, just like with any other inflow of information, farmers contrasted the trial conditions with their local agro-environmental conditions to assess the suitability of the crop, crop variety or practice.

> "For me, the researcher, first of all, has to be independent, ok? Forget about brands and products and all that… all that b*******!" (5NT)
> "Well, [research centres] do more studies… in a systematic manner, more… because, no, we are not as rigorous. Their parameters are more like 'plas,plas, plas, plas' whereas we relate more to our senses, more or less… and then, researchers have more scientific explanations. Because with the technician here, in the field visits we do, I also learn. Then you arrive at the village, and it is not like that, but obviously, you learn a lot.
> All the yield increase was thanks to researchers." (2CT)

Looking forward, farmers envisioned researchers' role in the farming actor-network in different ways. Some farmers agreed with how research had been operating and supported that researchers' role was to innovate on agrochemical products and crop development. Other farmers expected research to become closer to farm reality. Additionally, other interests were towards new approaches to farm systems or innovative techniques unknown to farmers today. Finally, some farmers expected research to take sides and bolster no-tillage in public administrations to obtain a standard certification to increase their social acceptance and products' economic value.

4.6.6.4. Global farming communities

Besides the talks organised through the cooperatives, farmers attended agricultural fairs, workshops and talks related to machinery, crop development, conservation agriculture and specific practices. Repeatedly attending these events led to networking and binding with other farmers through mutual interest. These connections led to knowledge exchange among farmers who lived in different agro-environmental conditions. Moreover, farmers built connections with foreign farming knowledge through visits organised by manufacturers and agri-businesses. Farmers saw these networking opportunities as beneficial idea inputs, although contrasted foreign practices with local conditions to assess their suitability.

> "I went to many meetings about no-tillage, I am interested in it, I search on the internet a lot to see how it works over there… [Agri-business] took me, to Argentina, to see how they were doing it there. […] that experience is useful, it can be handy, but because the soils are different, I mean, we can't do those rotations here on rain-fed land." (4NT)

Conservation agriculture associations operated regionally, nationally and internationally. In Spain, there was one national conservation agriculture association based in Cordoba, Andalusia. Many no-tillage farmers had problems with the validation of their data because they were based further away and did not have the resources to produce empirical data closer to farmers' agro-environmental conditions. Furthermore, not all regions had farmers' associations, that was the case of Navarre, due to the omnipresence of the extension institute, which had dealt with conservation agriculture practices as well. Regional conservation agriculture associations found barriers to access to regional governmental subsidies for research and outreach, limiting their resources to do field trials and provide advice. What some 5NT highlighted about his association was the networking opportunities among members. Additionally, his association organised conservation agriculture fairs with talks and machinery exposition. Moreover, his association had hired an agronomist to provide advice to members. Despite agreeing with those benefits, some no-tillage farmers found the conservation agriculture farmers' associations too broad, including all types of no-tillage and minimum-tillage practices, whereas they were more interested in focusing on no-tillage as a system.

> "[regarding regional conservation agriculture association] I think it is good because the simple fact that those members are linked implies that what happens to you could have happened to someone else, and he might have the solution. Sharing knowledge is very good! And we shouldn't lose that." (5NT)

Farmers also build a farming community on the internet. In addition to access advisors' knowledge, farmers accessed farming forums and different social media such as Facebook pages and Twitter. Nonetheless, those internet platforms for farmer-to-farmer knowledge exchange tended to lose their respectability because they were not supervised, people enrolled for 'fishing' information, gossip and criticise rather than share experiences. Therefore, the interviewed farmers acknowledged they were members of those platforms and groups, but they rarely found them useful or trustworthy. However, some environmentalist innovative farmers interested in conservation agriculture had made some contacts on the internet in the past, and their relationships had migrated from the forum to WhatsApp and in-person farmer-to-farmer experiences visiting each others' farms.

In those online farming communities, farmers who adopted no-tillage as a system engaged with influential farmers or even became influential farmers themselves. Influential farmers or advisors had built a reputation through the internet and social media, and farmers followed their publications, as has been found in England by Mills et al. (2019). They were sharing their experiences applying conservation principles at their farms on online platforms, receiving interested farmers on their farms, travelling to events and giving talks, engaging with conservation agriculture associations or informal farmers' groups, etc.

> "Now I look more… I don't search so much about no-tillage itself, but an organic type. I have, more or less I have two or three guys, people of reference. Those are with whom I guide myself, you know? And with them, I have learned a lot! Very much! […] They are consultants, there, from the international, as they call it.
> […]
> Because I have been doing this for a while… [Farmers], not only from this area but other locations too, have called me, have asked me. Have come to the fields. Some ask, 'how can you seed here with the straw!?' […] yes, yes, I think I might have influenced some of them, somehow at least." (5NT)

In those cases, farmers enjoyed farming because of participating in innovation and establishing new bonds that further sustained their farming actor-networks. Those innovative farmers became connected to actors outside their local communities. Their innovative activity involved meeting researchers, other farmers, influential people, etc. Additionally, they searched for information through those contacts or through the internet, magazines, talks and visits. Afterwards, they translated those ideas into practices at their own farms. This translation was risky, sometimes overwhelming, but maintained their interest in farming. Additionally, they pertained to a collaborative effort to create and sustain an innovation while their enrolment in the process built their own innovative roles. Indeed, those farmers enjoyed their 'innovative' role as much or even more than their 'food producers' role.

> "Conservation agriculture, what it has done is that I enjoy my work. Yes. Because it has done, first of all, that I got motivated to confront the problems I had. Do you know? It motivated me to search for solutions, and it made me relate to leading people in farming." (5NT)

Figure 36. British farming landscape near location 8

4.7. British farmers’ values

4.7.1. Values of producing food, doing nature and hard work

British farmers valued being farmers due to being able to work outdoors and experience crops and animals growing, as 6NT mentioned. 9CT even referred to farming as *‘doing nature’*. However, little economic reward and heavy workload led farmers to value their effort, regardless of the compensation. Consequently, many farmers said farming was not a job but a way of life, as 9CT explained.

> “It’s just always amazing when you put the seed in the ground, and it grows, and you can go out, and then it’s a crop. It’s just really satisfying.” (6NT)
> “Farming is something. I don’t believe it’s a job. It’s a way of life to do it right. You don’t do it for the money. You do it for the love of the job you’re doing. It is actually a way of life. It’s the hours you put in it. It’s just unbelievable. When farming was 60-70 pound a ton, I think the hours we did, I think we’re for a pound an hour.” (9CT)

Indeed, from field preparation and seeding, farmers followed crops’ development and related their success to their hard work even more because British farmers considered themselves as having control over farm decision making, which came with the responsibilities of doing a good job.

> “[…] Being outdoors is good. The variation in work is an awful lot of work, dealing with a lot of difference. In my case, I’m my own decision-maker. I’m my own boss. But it’s also

a case of live by the sword, die by the sword. So if I don't put the effort in, I won't reap the reward, but the reward is very tangible as well. You nurture the soil, which is a very long-term project. You plant a head row of some trees, and you see it through the season, and in the case of the crop, you obviously sow the crop and manage it and harvest it and then market it." (10CT)

"I love being my own boss, and it's quite rewarding when you see that you're actually producing something. It is stressful at times, but it's quite a nice office to be in when you're outside all day. It is not a bad job. You're not doing it for money." (8CT)

Despite their sense of independence, farmers relied on the cooperation of other members of their farming actor-networks. The climate, crops, weeds, etc., had a great impact on the success of the farm, the yield and the income. The complexity and dynamism of the farming actor-networks was both a stressful struggle to overcome difficulties and make a living out of farming, and an interesting lifestyle with a diversity of tasks to never get bored and have new opportunities to learn and improve every year.

"[…] it's just being independent really, and you are your own boss and the satisfaction of actually producing something from nothing, virtually. I mean, you never get fed up with seeing a new calf being born […]. Then you get pretty fed up when you get droughts and crop failures and things. We've seen it all before, and you just have to accept it and get on with it. That's been it, really."(8CT)

"There are times when I think; you know actually if I wasn't farming, and I wake up in the morning and didn't have all the worries that the farmers have, wouldn't that be nice? But there's another part of me that thinks actually… I mean, when it's going well, I enjoy it, but you know when it's not going well, and I'm losing a lot of money, it's just stressful […]." (7NT)

4.8. The British farms

4.8.1. British farms

British farms were located in the districts of North Yorkshire and East Riding and Yorkshire (Yorkshire and the Humber), Cambridgeshire, Suffolk, Essex Haven Gateway, and Heart of Essex (East of England), as shown on the topographic map in Figure 37.

Most of the farmers farmed alone or with a family member. Some farmers occasionally hired contractors for specific field operations, with the exception of 7NT, who was in a business partnership with the other two directors, three managers and two employees. Moreover, they provided contract work, as did 9CT. Additionally, 8CT and 9NT were mixed farms, and many farmers had other jobs on or off-farm. Farmers or their families owned their land, or part of it, working also rented and contracted land. The exception was 8CT, who worked solely on rented land.

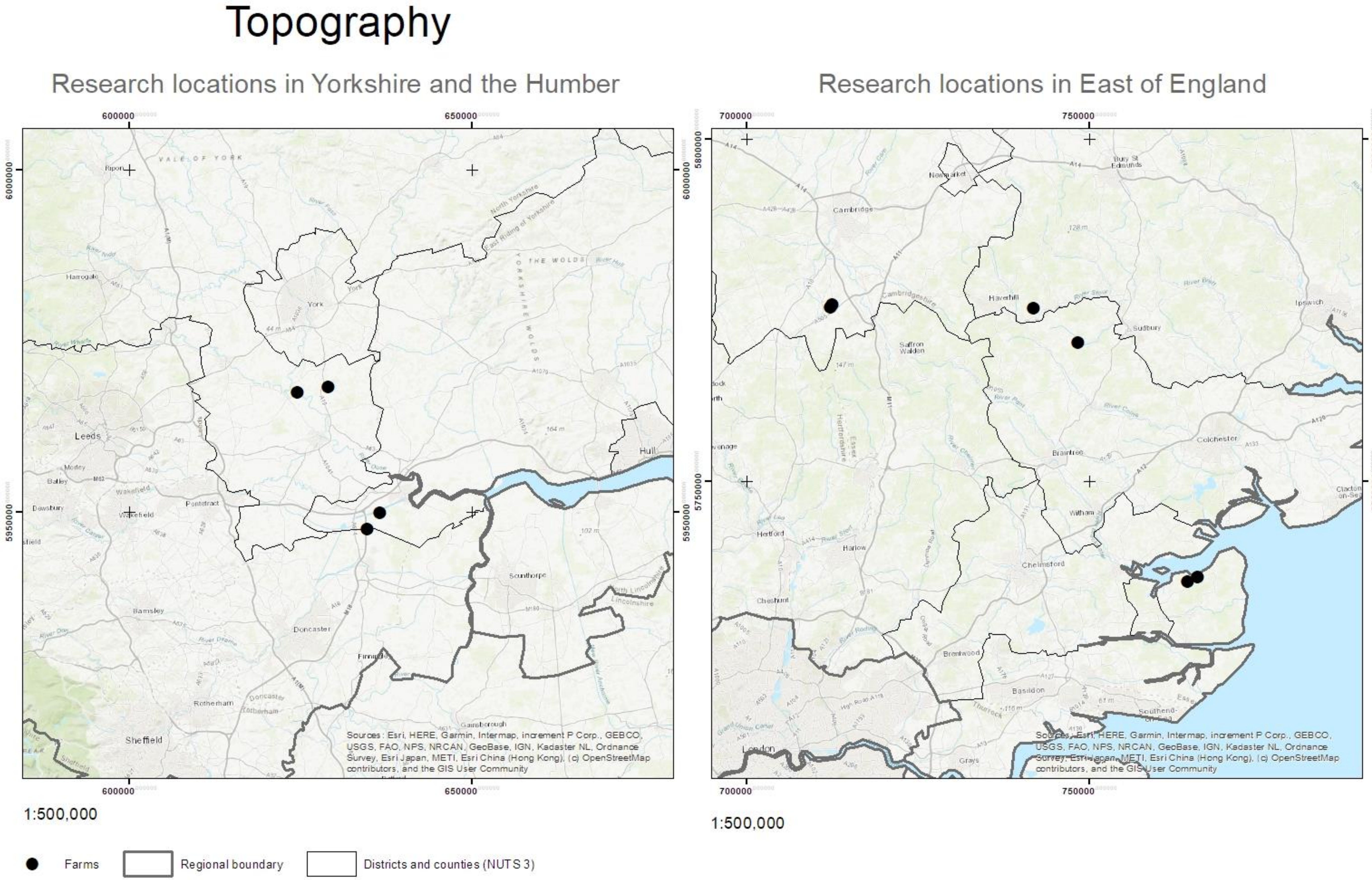


Figure 37. Topographic map of research locations in the UK

4.8.2. Farm operations: an example of the investigated fields

Table 8. Example of a cropping calendar for a no-tillage field in the UK

		SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
2017		WHEAT											
2016	RAPESEED												
2015		BARLEY											
2014	SUGAR BEET		WHEAT										
2013									SUGAR BEET				
: Fertilisers; : Tillage; : Minimum-tillage													

Not all British farmers participating in the research did fill in the questionnaires about field history. However, as examples, Table 8 illustrates field operations performed by a no-tillage farmer and Table 9 by a conventional tillage farmer. Those farmers were not neighbours, and tables do not represent general cropping calendar models.

Table 9. Example of a cropping calendar for a conventional tillage field in the UK

	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
2018		WHEAT										
2017	COVER CROP							POTATO				
2016												
2015	COVER CROP								HEMP			
2014	BARLEY											
: Fertilisers; : Tillage; : Cultivator; : Harrow; : Subsoiler. *Herbicides and pesticides not given												

4.9. British no-tillage adoption paths

This section presents the results of the different no-tillage adoption paths across chains of actors in different British farming actor-network configurations. As in the Spanish section, I start with a summary table to then explain in detail the different paths.

Table 10. No-tillage adoption paths in the UK

Path	How farming actor-network operated	Tensions	Adoption barriers and drivers
Income: Brexit, markets, grain merchants, land and yields	CAP subsidies supported farming Some farmers had other jobs and businesses in or off the farm to diversify income Farmers sold their yields to grain merchants, committing to signed contracts Potatoes and sugar beet had high prices Farmers farmed family-owned or contract farms; others farmed on rented land Some fields were rented to potato farmers obtaining more benefits than if growing other crops	Brexit related uncertainty regarding subsidies and markets was complicating planning for the future CAP subsidies favoured big farmers Grain prices were low and were established in a competitive global market Growing potatoes and sugar beets required high investments and soil disturbance Subsidies and non-farmers buyers increased land prices	Subsidies reduced competition, favouring conventional farming/ subsidies provided economic stability, enabling some risk-taking, favouring NT adoption NT adopted as a way to adapt to possible reductions in subsidies by reducing production costs NT not adopted because all investments were on hold until the political situation cleared NT adopted as an optimisation strategy to reduce production costs NT not adopted to not compromise yields Strategic tillage or other soil disturbance used in rotation to grow potatoes or sugar beet on no-tillage farms NT not adopted to continue growing potatoes and sugar beets NT not adopted to avoid the risk of yield reduction and not being able to pay rents NT not adopted to avoid risks on contract farms NT adopted because land ownership provided economic stability, enabling taking some risks
Weather and water: managing the risks	Farming was constrained by the local climate. However, the timing of modern farming operations followed a pre-established agenda	Floods destroyed yields and hampered timely re-seeding Insurances were not available to cover flooded areas Flooding uncertainty reduced the amount of agreed yield in contracts with grain merchants	NT not adopted because the use of a variety of tools provided more flexibility to adapt to weather conditions NT adopted as a way to quickly re-seed fields after floods increasing farm resilience
Crops: crop innovation, rotation and cover crops	Crops and varieties were selected to obtain the highest income Potatoes and sugar beets had central roles in many farming actor-networks Some farmers followed a diversification strategy to reduce risks Cover crops were grown to comply with ecological focus areas, and in some farms, they were wider spread for conservation and environmental purposes	Some crops that farmers would grow had no market, reducing diversity Cover cropping increased farm complexity and operations including, seeding and termination Cover crops affected the following crop in water and nutrient availability, allelopathy and pest proliferation	Conservation practices adopted as part of a farm diversification strategy NT maintained due to having a range of drilling machines Interest in cover crops favoured no-tillage adoption

Path (continued)	How farming actor-network operated	Tensions	Adoption barriers and drivers
Weeds and herbicides	Weeds presented competency to crops for water and nutrients Weeds were controlled by herbicides	Black grass was widely spread and herbicide-resistant Farming actor-networks with heavy clays and compaction enhanced the proliferation of weeds NT dependent on glyphosate Environmental regulators threatened to ban glyphosate	NT adopted to maintain weed seeds dormant in depth NT not adopted to eliminate weeds NT or CT used strategically on some fields with weeds Independence from glyphosate made CT more resilient to environmental regulations constraints The 'neat field' after tillage was an illusion of a fresh start
Machinery and contractors	Farmers had a range of machines for different uses, supporting the machinery market Minimum-tillage and strip-tillage were adopted NT drills were used with other tillage practices, and machinery was built combining concepts	Narrow seeding time windows led to the acquisition of big and quick machines, able to perform many operations at the same time	NT, and CT with single machines, adopted as resistance to productivist farming (with high inputs including machinery) Minimum-tillage and strip-tillage favoured transitions to NT adoption Limits between NT and CT were softening due to the combination of practices and machinery
Knowledge and trust	Local farming communities judged innovative farmers but were also interested in their progress Some farmers required scientific data supporting innovation to adopt it The internet and social media enabled the creation of international online farming communities to exchange experiential knowledge and ideas All external ideas had to be tested on-farm to be trusted Innovative farmers built their online presence and influence Scholarships available for farmers to conduct research and visit farms internationally Agri-businesses and machinery manufacturers financed international farm visits	Farming clubs were disappearing There was not enough scientific data supporting nor contradicting conservation practices Scientific data produced under unrealistic field trials Innovative farmers were judged by the local community Conservation agriculture farmers' organisations were not providing the information no-tillage farmers required	The internet and social media enabled connections between innovative farmers, favouring NT adoption and maintenance Lack of scientific data around conservation practices favoured CT NT adopted as a way to innovate and experiment, co-creating knowledge based on real farms Scholarships for farmers favoured innovation, including NT The internet, social media and innovative farmers participated in the definition of farming communities and practices, and their limits (including different roles of NT)

*NT: no-tillage; CT: conventional tillage

4.9.1. Income: Brexit, markets, grain merchants, land and yields

4.9.1.1. Brexit, subsidies and uncertainty

Interviews with British farmers were held in winter 2018 and 2019, after the referendum in 2016 determined the UK exit of the EU. Among the interviewed farmers, there were different political opinions regarding the impact on the future of British farming. Some farmers were worried about how the subsidies' landscape would change; others thought Brexit would enhance British farmers' competitiveness. However, a general trend among farmers was the difficulty to plan in such uncertain times.

> "Because we have no idea what the policy will be when we leave the European Union and this could be very… It's throwing everything into the air, and we don't know where it's going to land. And that's very difficult to plan for the future if you don't know where the future is going to be and what the government's policy is going to be." (7CT)

Regardless of supporting or not the exit of the EU, farmers had contrasting reliance on subsidies. For some, farming could not subsist without governmental support. Indeed, in some years, EU subsidies represent more than half of farm income (UK Parliament, 2016, cited in Marr & Howley, 2019). For others, the support was constraining their businesses. Similarly to Spanish farmers, some British farmers, despite agreeing on the need for economic support, did not agree with how CAP subsidies were distributed and the consequences of such a distribution model. Indeed, they stated that subsidies were favouring big farmers to the detriment of the small farmers' community.

> "[…] the rural payment money what everybody's getting, I think it's totally wrong […] when the big farmers get in 100, 200, 300 million pounds of subsidy, I think it's absolutely wrong. Because all that's doing is giving them the money to buy us out and buy the smaller person out, making all the fields bigger and making us end up with a lot less farmers, a lot less people in the farming community." (9CT)

Farmers' reliance on subsidies and the uncertainty caused by Brexit was related to the adoption of no-tillage. In some farming actor-networks, innovation was hindered due to subsidies being decoupled from yield and not favouring more profitable ways of farming. On the contrary, in other farming actor-networks, subsidies were providing certain stability that made it less risky to change farming practices and adopt innovations, including no-tillage. Finally, the threat to lose subsidies due to Brexit was also causing different reactions: it incentivised the adoption of innovations that could reduce costs in the future and, in other instances, it held investments until the uncertainty would clear.

> "I'd say [subsidies] probably stopped innovation in farming as in general because they make it so that you don't have to farm particularly well in order to make a living, but they don't generally affect what we're going to do." (8NT)

> "I think the threat of losing [subsidies] has given us a motivation to experiment with no-tillage. I mean, you know there's a fairly cold wind blowing in all directions at the moment […] I mean the worst-case scenario is we could lose all our subsidies, and we would be on well tariff organization rules. You know we could be receiving less for our wheat and less subsidies." (7NT)

4.9.1.2. Grain merchants, standards and grain prices

British farmers sold their products to grain merchants, searching for the best price. Farmers with bigger storage facilities could decide when to sell according to market prices. However, normally they established long-term relationships with local grain merchants. Additionally, farmers had contracts with direct customers, such as breweries. In this case, growing standards were established in contracts but had no reference on tillage management.

> "I have probably three grain traders, whom I work with, and you know we just see who wants what and who wants to pay the most. Simple!" (8NT)
> "We yielded better than we thought, so we had some still left in the shed. By the time we moved that, we'll leave that a bit and gamble with it, and the price is going down and down and down ever since." (9CT)

Brexit created uncertainty in farmers' relation with the markets. Farmers who were selling to European markets were worried about the need to comply with European standards (food safety requirements to access European markets) without subsidies' support nor the UK being able to participate in the negotiations of such standards. Moreover, farmers worried about losing the positive discrimination of the EU internal market.

> "If we're selling into the [European] market, we're still going to be bound by the same rules. So we're not going to have any say in the rules, but we're now going to be trying to sell into. So that's a bit daft. And the third thing is that I think that we will not have the same preferential treatment that we've had in the past and it will be very difficult to sell these things, so to say, where are our markets? […]" (7CT)

In the past, low grain prices in the market had enhanced farmers' adoption of minimum and no-tillage as ways to reduce tillage related costs and obtain higher benefit margins (as explained by 7NT). Other strategies were to diversify income sources (as 9CT comment). This way, many farmers had other businesses or jobs on or off-farm. Moreover, potatoes and sugar beet represented the most important income sources for many farmers. Those crops had more difficulties growing under no-tillage or minimum-tillage, which had made farmers abandon those practices or at least include tillage in the rotation coupled with those crops. Similar constraints due to the importance of potatoes and sugar beets were found in The Netherlands when adopting non-inversion tillage (Bijttebier *et al.*, 2018) despite conservation agriculture advocates defend the principles' suitability for any crop (see: Kassam, Friedrich & Derpsch, 2019).

> "I mean wheat price was… you know 60, 70 pounds a ton […] and we were not making any money. We were ploughing every hectare, ploughing up […] and then it would be big bits like that, and then we'd go down and make the big bits into smaller bits, and then the smaller bits even into smaller bits, and you know, the cost of that was a fortune!" (7NT)
>
> "That was about '96 or '97… I think it was. It was just no good. I mean, you had to really keep the check on what you were spending on things, and I think everybody was struggling. Like I say, we were trying to do everything that was… to keep going and make some money. Well, since [then] we've been working for these Natural England jobs and stuff like this." (9CT)

4.9.1.3. Land access and production costs

In the UK, land access was constrained by high rent and selling prices. People outside of farming were buying the land. As a consequence, the local farming community was changing.

> "The land around here is really, really, going to be expensive. Really, really, expensive. You'll make no money out of it. […] But what it's doing [land speculation] is spoiling the community, because before there were old small farms all the way through here and they are selling these off, it's not farming people buying the farms. As normally like this one, it's people outside farming buying that." (9CT)

Farmers who were working on rented land had these costs reducing their income. Land prices had increased due to farmers receiving subsidies that could be invested in land. However, when a review of the tenancy contract was due, farmers could negotiate the prices for the next years until the contract ended to make a better profit from the land.

> "Well, the rents are all based on the subsidy we get. So, we're basically farming without subsidy anyway." (8CT)
>
> "Yeah, I would like to rent more land but probably in this area. The rents are high. […] Lose money for three years, renegotiate and then hopefully get profit out of it after that. Because once you've got it, you've sort of got it through, you don't take it back off. If you pay your rent, look after yourself, it's a 5-year tenancy." (9CT)

On the contrary, many farmers stemming from farming families had been able to buy the land since their relatives started working it. Farmers in business partnerships had a mixture of member-owned land, rented land and contract land that they worked.

> "[…] traditionally we have contract farmed further away, but we found that actually, that hasn't got us very much money. But now we've been able to consolidate all our lands together recently because of Brexit. Our landlords decided they wanted to sell, and we were willing to buy. Because having your farms in a block is cost-effective." (7CT)

Interestingly, some farmers rented out particular fields for potato cropping if they could not grow potatoes by themselves. This was when they did not have the necessary equipment to grow potatoes, particularly because the necessary specialised equipment was very expensive. Moreover, due to high potato market prices, renting the land out for that specific purpose could generate more benefits than growing other crops. Nonetheless, potatoes could not be grown continuously because of building up pests. Thus, the land was rented when potatoes were suitable in farmers' own crop rotations but not continuously.

> "Within a rotation. If it fits in with their rotation, when they would have a break crop, they can get more money letting the land to me to grow potatoes than they can by growing their own break crop. So they get a bigger income, they get no risk, and they don't have to do the work. It's quite of an easy decision." (10CT)

In relation to adopting innovations, owning their land provided farmers with economic stability that enabled them to take some risks. However, this was also related to keeping a smaller farm size that allowed them to handle the workload by themselves, not investing in the land to avoid debts, or growing cheaper crops to have less money invested in the crops. On the contrary, farmers who were working on rented land saw the experimentation with innovations (with uncertain benefits) as a '*luxury'* that they could not afford, whereas conventional tillage was a known strategy that provided a guarantee. Similarly, farmers who did contracting work were less willing to implement innovations on contracted land to not risk their contracts.

> "Financially, being a rented farm as we are, we don't have the luxuries he has to fail as much. […] we're on a smaller acreage, and it's all tented. We've got to try and make a pay. I mean, that's virtually where we are really with it. It comes down to finances, and are you brave enough to gamble? Whereas conventional farming is what we've done. You're virtually guaranteed that you're going to get the crop established, and you know what you're doing" (8CT)
> "Yeah, I mean, there are a lot of factors that come in; you know… suitability of soils, risk… we're dealing with money. We don't want to put someone's entire financial stability at risk through what is a technique that we don't fully understand yet. So there's risk management." (7NT)

4.9.1.4. Yield

In British farming actor-networks, yield also had a variety of roles. Thus, conventional tillage farmers, despite being interested in minimum or no-tillage, did not want to compromise their yields adopting those practices. Furthermore, some farmers who had adopted no-tillage would return to conventional tillage if their yields and profitability were affected. Contrarily, other no-tillage farmers were focusing on optimization and overall profitability rather than yields.

> "I think I've always got to be looking at reducing our tillage to getting a seedbed, but at the time, I don't want to compromise yield. The whole thing is never to compromise yield because yield drives farming, not no yield. The quickest way out of farming is to not get the yield. So you constantly have to be driving the yield factor." (7CT)

4.9.2. *Weather and water: managing risks*

4.9.2.1. *Climate, weather and water translated through traditional knowledge*

No-tillage farmers criticised conventional farming for not engaging with the non-human actors negotiating farm operations timings. However, in the interviews, it transpired that conventional farmers adapted their practices to weather and soils. Moreover, conventional farmers applied a range of tools according to field conditions. On the contrary, it was no-tillage farmers who worked with fewer tools, and their farming was, therefore, more constrained by field conditions.

> "[…] Basically, farming is ruled by your soils and the weather. Not by the calendar, which conventional farming is. They are only marching spring barley no matter what the soil moisture or soil temperature is. Trying to establish spring barley. No soil is too cold, too wet." (10NT)
>
> "We plough when the weather lets us. As in, if it's too dry and we're going to plough a lot of lumps, […] we're working […] that earlier, we do like to plough certain fields." (9CT)

4.9.2.2. *Managing meteorological risks*

In some British farming actor-networks, floods were the main actors challenging farming. This, in addition to the intimate relation between weather and soils that determined the right field conditions to perform field operations, with which all farmers had to negotiate. Indeed, floodings had an important impact on farmers' economy, particularly because mitigation strategies such as insurances were not available.

> "I think it's the biggest challenge that I have, yeah, is the flooding, has been for all my farming life, it has been the biggest challenge.
> […] There is no insurance. Because it was so widespread in [the region] and other areas, so to say. There was a small amount of funding I managed to claim." (10CT)

Moreover, floodings affected farmers' relation to grain markets. As mentioned earlier, farmers *'gambled'*, waiting for the best price to sell their products, sometimes in advance through contracts. However, the yield agreed on the contracts would always be less than the potential yield from the farm in order to be able to meet the agreements even in adverse weather conditions.

> […] I was happy with the price this coming November, so I sold some of my crops. You can't sell it all because of the risk that you know to get the same yields. What I haven't mentioned here is that third of our land floods. And we've had a lot of floods since 2008." (10CT)

Figure 38. Farming landscape near location 9

In some farming actor-networks, no-tillage enabled quick seeding after floodings, increasing farming resilience.

> "The last time we grew rape, we had 45 acres which flooded off in the Boxing Day floods […]. When the land eventually dried enough, I spread more crop and then drilled the cover crop. […] I just drilled straight into it with the [manufacturer, no-tillage] drill. I will never have been able to do that with the strip-till drill." (10NT)

4.9.3. Crops: diversification, cover crops and innovation

4.9.3.1. Crops in the farming actor-network

Crop selection by British farmers was mainly to obtain the highest income. Thus, farmers chose crops that had the highest prices on the market and assessed the suitability of growing them on their land-based on experiential, local and traditional knowledge. On the contrary, some farmers were following a diversification strategy to help secure profits, which enabled farmers to take risks experimenting with a range of crops and practices, representing smaller portions of their land and their income.

> "Because they're the crops that we can grow well in this region. We've been cereal-based here for a long time, oilseed-rape, which was introduced in the late seventies. The profitable crops that we can good yields, also the main reason, yeah" (9NT)
> "The thing is that since I've gone no-till, it means I can grow a whole range of different crops, and I always have about seven different crops in the ground when we used to grow just wheat and rape. That was much riskier than having lots of different crops. So some

> crops sometimes might not do very well, but it's only a small portion of the business you see. So I've spread my risks over a lot wider, so I don't have such. If something doesn't work well, it's not a big worry to me. I mean, sometimes you know some crops aren't very good, but it's only a small proportion." (6NT)

Additionally, some farmers who adopted no-tillage as a system were applying other principles of conservation agriculture to reduce pests or pesticide usage. Thus, one of their strategies was to grow short-cycle crops to reduce their vulnerability (as time on the field to be infected).

> "It needs to be sprayed all the time all through the year, and that's why I'm growing a short spring crop. It's a lot less chemicals going into the ground because of that. And so that's just less opportunities of things knocking it back, you see." (6NT)

However, for some crops that farmers assessed would make a positive impact on their farms, there was no market.

> "If I could get a contract to grow something like vining peas, […] I would probably switch from oilseed-rape to vining peas. But they're not available in our area because you have to be in a certain proximity of the factories." (10CT)

In many farming actor-networks, the crops that sustained farm income were potatoes or sugar beet. Therefore, the configurations of the farming actor-networks were build to enable growing those crops. In terms of tillage management, this meant sacrificing no-tillage favouring strip-tillage, minimum-tillage and conventional tillage. In the case of business farmers, who additionally were more constrained by farming more land and by commitments with employees and/or contract farming, these relations resulted in more planning requirements and less flexible management. On the contrary, smaller farmers working alone and owning their land adopted more flexible approaches to crop selection.

> "[…] we can't take decisions on the go; we have to plan it; we have to plan it out really. So you know we would like to do everything zero till, but the sugar beet crop is worth a lot of money; and you know it's the most valuable crop we grow, so we can't sacrifice that for just zero-till. […] So we have the rotation going with the sugar beet; it is very, very important to us, and we can't do the sugar beet through zero-till. So we've then moved to do strip-tillage." (7NT)

4.9.3.2. Cover crops and innovation

Cover crops were mainly grown by no-tillage farmers, but also some conventional tillage farmers used them in their rotations.

> "Personally, I like having spring sowing crops. Because that allows me to cover crop which is something that I do as much of it as I can, I'll do cover cropping." (10CT)

Some farmers required more scientific evidence to adopt cover crops more extensively on their farms. Nonetheless, those farmers were experimenting with cover crops. Indeed, farmers used cover crops to comply with the Ecological Focus Areas requirements for CAP subsidies. This way, cover crops were introduced in the farming actor-networks, and farmers were learning about different relations between cover crop species with soils and crops.

> "I have a bit of a love-hate thing with cover crops. I would love some nice science behind them. I would love to know some disease and pest interactions between the crops that are grown and cover crops. The implications, properly, on weak growth and whether allelopathy is a proper thing or not. It's nice to do a bit more... This year, I was [about] to be using more cover crops for our EFA's […]. I can't see much benefit beyond that. If I could see a long-term, that's okay. But I cannot really see it.
> […] My ideal cover crop is what I call a low-density cover which would be mostly barley-based, not related to anything that I'm growing. […] because I've tried black oats, and they were a waste of money. […] Yeah. Hard to say cover crops. I don't love them. I don't hate them. It just needs to be cheap and not too thick." (9NT)

On the contrary, innovative farmers had adopted the practice on wider fields and worked out the difficulties. Particularly, farmers had experienced problems with seeding and nutrient management. Those tensions in no-tillage farming actor-networks were solved through the capabilities of disc drills cutting through the cover crops or enhanced as nutrient availability was reduced by the lack of tillage.

> "We were only growing very basic cover crops then and certainly won't be able to strip drill through the cover crops which I drill through now, with the strip-till drill." (10NT)

Moreover, some innovative farmers were establishing long-lasting relations with agri-businesses. Thus, farmers hosted field trials at their own farms, visited other field trials or participated in international trips to contact cover crop specialists.

Nonetheless, the higher the complexity of farming actor-networks, the less control farmers had over the interaction and their outcomes, which increased stress.

> "Different cover crops have different interactions with the subsequent crop. I mean, it is terrifying! If you get it wrong, you could not have a crop after the cover crop. You can get nothing! or you can have a tremendous result…" (7NT)

On another note, some farmers associated the renovated interest in no-tillage to cover crops. Indeed, no-tillage had been explored in the '70s and '80s but abandoned when straw burning became banned. Nowadays, the media that was promoting no-tillage was relating it to cover crops.

> "[…] I suppose it would have been in there in the 80s. It was adopted by a lot of people over here. They came in, and they talked about min-till, direct drilling, and then it went out of favour again. And then, just recently, it seems to be the buzz word now. Well, not so much, just that min-till and direct drilling, is more of the cover crops that associate with it now." (8CT)

4.9.4. Weeds and herbicides

4.9.4.1. Weed management: suppression and elimination

No-tillage farmers used glyphosate as a total herbicide just before main crops germinated and occasionally to control weeds during cover cropping.

> “So, my general practice is a week after drilling. I will go with a dose of [glyphosate] to kill up everything and say just before this emerge. That’s my main herbicide, really. With cover crop, it depends on what’s in your cover crop, what’s in your drilling. I may spray off before that as well.” (10NT)

Moreover, no-tillage farmers controlled the weed population by not cultivating. This control was through leaving weed seeds at depth, at which seeds would not be in the optimal conditions to germinate and would stay dormant. Even some conventional farmers complained about this effect of tillage promoting weed germination and used no-tillage to control weeds.

> **“**Weeds are a result of cultivation. […] Yeah, if you cultivate the soil, you get weed. Weed seeds are not stupid. […] They know exactly where they are in the soil; they know what the moisture quality is; they know exactly whether they can enjoy that; whether they’re going to live or die.” (7NT)
>
> “We have got fields, what we’ve had in no-till in no plough for a fair amount of years. I think we ploughed it about four years since-- wish we hadn’t ploughed it because it ploughed lots of seeds and stuff from underneath, what. It laid dormant for the past 14 years. We ploughed a lot of grass weeds, wild oats and things.” (9CT)

4.9.4.2. Black-grass: resistance and enrolment

Black grass was a major problem for many farmers across the UK. Black grass had been difficult to eradicate from the fields. Its seeds would keep dormant, surviving for years and germinate from deeper soil layers. Moreover, the threat of black-grass proliferation also came from neighbour fields or roads.

Strategies to suppress and eliminate black grass would differ between no-tillage and conventional tillage farmers. The first would leave the seeds dormant in-depth, letting them rot and be attacked by insects while eliminating those plants that germinate with herbicides. However, black grass had become resistant to herbicides. Indeed, herbicide resistance has been an increasing concern in weed control in the UK, especially when not controlled through the plough (Morris *et al.*, 2010).

> “So if you cannot move the soil at all, then you’ll only get that, and then the population that’s below the soil surface will rapidly diminish, and then any that’s shed on the surface quite a lot will be predated by insects as I understand it. […] and what does emerge, or what does germinate, the herbicides will have a lot better chance of controlling or killing.” (10NT)

> "It is the biggest problem in all—really all farms. The chemicals don't kill it anymore. I mean I do have black-grass." (6NT)

Interaction with other non-human actors would favour black grass persistence in the farming actor-network. Thus, in addition to producing herbicide-resistant seeds, black grass was favoured by heavy clays and compaction, which limited drainage. Farmers had to address those actors to eradicate the weed, trying to favour drainage or rotating crops to use different chemicals.

> "We don't have such a problem [with black grass]. We always have to have it in the back of our mind. So from the very beginning, from every operation we do on the farm, we're thinking about how we're going to reduce or keep our black-grass down. And there are fields on the farm which still have a black grass problem. Drainage is very important in the control of black-grass before you even think about chemicals. And drainage is not just about having good drains; it's also about getting the water down through very clay soil to the drains. So compaction are big issues we must look at and think about." (7CT)

The difficulty to control black-grass through tillage management or herbicide control was forcing farmers to attack them individually. This, in turn, was time-consuming, required co-workers, spraying herbicides individually and pulling the plants manually out of the soil.

> "We have a little bit. No-till is certainly helping control it. But you are talking sort of 4 to 5 years minimum. That's assuming that you're controlling everything that grows on by chemical and by hand and pulling.[…] It's not in every field, and it's certainly not in populations that it is elsewhere in the country. We probably spent a week or two weeks on the whole farm. So it's not bad." (10NT)
> "Yes, on foot and spray them off on foot. Probably spend 3 or 4 days a year like really with that system." (9CT)

Other farmers identified the absence of black-grass as a symbol of their good farming management.

> "We've no real problem. We don't have black-grass, which you might have heard some people talking about. There's nothing that we have that is a hindrance to growing good crops. We're lucky in that. Well, lucky is being good management over the years that we haven't gone into that situation. One of that is to do with the diversity of crop." (10CT)

4.9.4.3. Glyphosate

In the UK, conventional and no-tillage farmers saw no-tillage as heavily dependent on glyphosate. In contrast, conventional tillage farming was not dependent at all, even if glyphosate was used for specific purposes.

> "Where would no-till farmers be without glyphosate? I could live without glyphosate; it would make my life harder. No-till farmers I don't think could live at all without glyphosate." (7CT)
> "I can manage weeds better in no-till, but that's heavily dependent on glyphosate." (9NT)

No-tillage dependence on glyphosate made it more vulnerable to threats of glyphosate being banned. In comparison, conventional tillage was more independent and resilient on changing environmental regulations regarding herbicide use.

> "Banning glyphosate would be difficult, and really that would be the only reason to potentially change things I can see at the moment." (10NT)
> "And with the—I mean the glyphosate topic. […] We only […] desiccate the rape. I think that's probably the only time we use it. But apart from that, we don't ever use it. So a ban on that wouldn't have affected us. So that's a plus." (8CT)

Indeed, through conventional tillage, farmers got a fresh start, or at least the illusion of it with a neat field.

> "It's because it's a quick and easy- […] seen ploughing done really well; it looks lovely. It really does look clean, and it looks nice; you get a fresh start. You're destroying the ecosystem and disturbing for work […] these days with 300 horsepower tractors and ten furrows ploughing going along 10 kilometres an hour, taking a lot of soil and it throwing it wrap and inverting it, it does a bit of fallacy in there. But it does look… to the gist of a casual glance; it looks clean way to start." (9NT)

4.9.5. Machinery and contractors

4.9.5.1. Machinery and contractors in farming actor-networks

Having a range of machines was common among British farmers, especially conventional tillage farmers, to select the right tool depending on field conditions. This way, farmers were supporting the assessment of field conditions and responded to its demands in a flexible manner. Moreover, these farming actor-networks enabled the existence of an active machinery market. For some farmers, having a single machine to seed was a rebellion against the machinery manufacturers. The latter, together with other agri-businesses and intermediaries, were considered to shape farming business, constraining how food had to be produced (Hendrickson, 2015). Indeed, farmers who had adopted no-tillage reduced also the number of tractors, even if performing strategic tillage.

> "We use less chemicals, yes we do. And we use less machinery, less tractors, and that doesn't please advertisers because they want to sell chemicals and stuff." (10NT)
> "When we started off this joint venture […] which was two years ago, we had seven tractors[…]. We're now down to three main tractors, one for doing tillage. So we've cut the number of tractors almost in half; we use less fuel, a lot less fuel." (7NT)

Employing a contractor was normally left to the crops or field conditions for which the farmer did not possess the appropriate machine. Otherwise, farmers showed a preference to do field operations themselves, as they related *'doing the farm'* to their farmers' identities, even if that would go against economic rationales. Additionally, farmers had to perform field operations during the narrow time windows with adequate field conditions, which constrained contractors' availability as their time had to be shared with other customers. Then, farmers would prefer to invest – even at a high price – in a machine that increased their speed and flexibility and would allow them to perform different field operations in one pass.

> "I'm sure you can employ the contractors, and they would come and drill it for you. And perhaps that would be the way to go if you mean reducing power and labour and the machinery fix costs, […] We enjoy doing the farm ourselves, and perhaps that's the fact why we keep doing this, it's because we enjoy doing it so much, but perhaps on a business… I know that is probably the way to be looking at it" (8CT)
>
> "It's about flexibility and these machines; they're about 40,000 pounds. I can't afford to have that machine and another one. Some would say: 'well, you need to get somebody else to use their machine'. But timeliness is quite important, particularly when we have such variability in weather. Sometimes you can get a day. That's one day for a fortnight, and you can't have, if you're using a contractor, you can't have that contractor on your farm and everybody else's farm at the same time. […] I'm just being able to do that, very intensely for that short period of time that was worth a lot of money. Otherwise, we would have been waiting for three weeks, and later, stuff doesn't tend to yield as well." (10CT)

4.9.5.2. Transitions and no-tillage drills

Many British no-tillage farmers had transitioned to no-tillage from conventional tillage farming through minimum or strip-tillage. Some farmers experimented with no-tillage through demo equipment loaned from the manufacturers. Minimum, strip and occasional no-tillage taught farmers how their farms responded to less tillage while new machines were fixing previous design problems they had encountered.

> "Yeah. I just decided. Rightly or wrongly, I decided to use strip-till—to go strip-till first than to go disc drill. Strip-till was good, but we sometimes had problems with the drill bringing up with waste […] and certainly won't be able to strip drill through the cover crops, which I drill through now." (10NT)

The range of available equipment across different tillage managements was huge, and farmers kept themselves informed about new machinery, particularly through machinery fairs. Indeed, not only farmers used no-tillage drills with minimum-tillage, but also machinery manufacturers were selling combination machines. Thus, the contrasting differences between tillage managements were being blurred by farmers and machinery manufacturers. Notwithstanding the increase in machinery diversity, some farmers did not saw any reason to change their management. Moreover, no machine fulfilled all needs, nor no machine was used without farmers' investment (money, time, knowledge, etc.) in modifications to improve and adapt equipment to their needs. Therefore, machinery innovation were dynamic processes in which farmers (and non-human actors in farms) were actively enrolled.

> "We go to these [machinery] shows, and we look at [machinery innovation] kind of thing. But I haven't yet seen anything that has convinced me to change my strategy too." (7CT)
> "There's always space for improvement. It's a [machinery manufacturer] drill; they don't take criticism very well. It's got some regular features. But getting them to improve from farmer feedback could be impossible. How many modifications I've made?! […] " (9NT)

4.9.6. *Knowledge and trust*

4.9.6.1. *Local community knowledge exchange*

In the past, young farmers' clubs hosted meetings that promoted farmer-to-farmer knowledge exchange in the communities. They used to gather in schools or pubs and had organised talks with more experienced members of the farming community. However, those young farmers' clubs seemed to be decreasing due to a lack of generational replacement. Then, rather than meeting regularly in person, farmers kept in touch on the phone.

> "In the pub… no, not really, no. I keep in touch with them on my phone and stuff. […] farming has changed; it's changed a lot in my lifetime. When I was younger, we used to have; we still have these in farming, we'd have 40 members, some of the bigger clubs would […]. These clubs were very close together, and there was a lot of farming people involved with them. But now, what I think by the sound of it, a lot of clubs are shut down and merged, they are struggling, because there aren't as many people in farming. These clubs are really struggling. […] There aren't the young people in farming." (9CT)

However, some sense of the local farming community remained. Neighbours contacted each other for specific work or asked questions regarding specific equipment. However, among neighbours, innovative farmers were both an object of curiosity ('looking over the hedge', visiting fields, etc.) to follow the results of their experiments and an object of criticism when farming out of the community norms.

> "I'm interested to see it because he's farming much more difficult soils than I'm farming […]. And then I think also you have to look at… I'm interested in seeing… Yeah, I think that all around, my neighbours are all very good farmers. So I'm always looking to see their area of interest. But I think a farmer is always interested in what other farmers are doing anyway."(7CT)
> "So we started mantling in and in the mid-1990s when everybody else was ploughing. And I can remember all the arguments and all the accusations; 'oh, you are mad'; 'it's all crazy'; 'it will never work'; 'it's a load of rubbish'; 'I can't understand what you're doing'." (7NT)

4.9.6.2. *Facts and inquiries*

Farmers attended meetings organised by extension institutes, research centres, or agri-businesses. These experiences were in the form of more traditional linear knowledge exchange between institutions and farmers, but at the same time, they also provided a platform for farmer-to-farmer knowledge exchange, done through networking and information share among attendees (farmers and agronomists).

> "Yes, they all provide you with information. Yes, there is a social aspect to it as well because you get to meet other farmers. But there is a lot of information, and that's what I'm pouring in is the information from different sources." (7CT)

Figure 39. Farming landscape near location 1

Some no-tillage farmers questioned mainstream farming knowledge broadcasted by the agri-business industry. Moreover, those farmers did not feel their concerns and inquiries were attended by independent research either. Consequently, they tested their ideas on their own farms following a '*trial and error*' approach. Moreover, these farmers built farming communities where to discuss those ideas and contrast experiences.

> "There's so much science from the chemical and fertiliser companies pushing farmers to do this and it's constant, and you've got to go against all the advice that you're given […] it was only by just saying, 'Right, I'm not going to do it' and doing the trials and getting confidence that I've got reasons why I'm quite happy not to do that anymore.

[…] As farmers, we don't really feel like we've had any help from universities or researchers or anybody. It's just been 'trial and error' and doing it for ourselves, and there's been not really a connection." (6NT)

On the contrary, conventional tillage farmers had greater trust in the scientific data or their own experiential knowledge. From those, the first group was requesting solid scientific data proving the benefits of no-tillage, cover crops, or other questioned farming practices to consider adoption. In contrast, the second group would require a personal empirical experience to sense the benefits and accept them as true.

"I need the science. The only ones that are going to change my… are the scientific facts. I need science to prove it. […] I need science to prove it. If you can produce me with science that will prove it and I can see it… I don't go with all this kind of like going around the farm and seeing it. That doesn't prove… I want to see the figures, and I want to see the statistics." (7CT)

Regardless of the source of information, farmers had to enrol the new ideas into their farming actor-networks to trust them. Thus, there was no information from scientific or extension institutes, market-oriented agri-businesses, nor fellow farmers that could stand as truth, or real, on its own. Ideas could circulate through their farming actor-networks via temporary connections but would not become real if not enrolled.

"Unfortunately, this sometimes makes the research not applicable to farming. Because in farming, we can't take all the variables down, and it's such a complex system that when you look at something, the more precise the research becomes, maybe the less useful it is to the farmer. […]
That's why I think it's good to use that as a base and also see what other people are doing as a base, but then you just have to try it yourself on your farm." (8NT)

4.9.6.3. Global farming communities

Farmers used a combination of the internet, farming forums and social media with experiences in farm visits to widen their farming community. Some farmers used these media to learn about no-tillage and continued using them to search for information when needed. However, farmers' networking transcended the internet, and farmers did private or collective farm visits, although they further used the internet to maintain those relationships.

"I suppose a combination of reading things on the internet, on forums and going to open days and just meeting people. So it was—there was no one thing; it was just a combination of a lot of things. […] Twitter, travelling, did a […] scholarship and that sort of thing as well. So yeah, just lots of small things pushing in that direction." (8NT)

Furthermore, the internet enabled farmers to widen the farming community and knowledge exchange internationally. Thus, it permitted no-tillage farmers to contact other farmers with similar ideas and concerns, while local communities had other experiences with conventional tillage, as has been pointed out by Skaalsveen et al. (2020). Nonetheless, these knowledge claims were produced in other spaces. Therefore, farmers approached knowledge from the internet as a source of ideas, not facts, to validate on their own farms.

> "Since the internet came along, farmers can all talk to each other and discuss ideas and help each other. It doesn't matter where you are. Rather than just talking given local neighbours, now we can talk to people anywhere… anywhere in the world really; and that's how we've learned and moved forward." (6NT)

Some farmers had benefited from a scholarship to develop a research project visiting other farms around the World. These scholarships also gave farmers the opportunity to share information internationally and gather experiences from countries where no-tillage was more extended and had a long history. Moreover, their condition as scholars and their travels increased their presence on social media.

> "Because I've just finished a [Trust] scholarship myself looking at herbicide-resistant weeds. And I visited United States, South America and Australia, all big no-till countries." (9NT)

Additionally, farmers received farm visits from other farmers, agronomists, and people interested in their farming practices. Those visits could be co-organised by agri-businesses, machinery manufacturers or governmental institutions and designed for national or international audiences. The objective of those farm visits was to showcase no-tillage farming practices and other practices related to environmental stewardship or conservation agriculture.

> "They're conventional farmers. Though they tend to be those that are looking very strongly at going down the conservation agriculture route. Whether disc-till or no-till. Or possibly just trying to incorporate cover crops into their conventional agriculture. […] It is a big step for a lot of people. They want to be able to speak to those who have done it already or are doing it. To try and speed their knowledge up so they can go more confidently." (10NT)

Social media was a major communication channel for farmers, particularly no-tillage farmers, to build their farming actor-networks and differentiate themselves from other farming practices. Farming forums and Twitter became farmer-to-farmer knowledge transfer platforms and increased the speed of interested farmers' learning of no-tillage and other conservation agriculture practices. Thus, social media became a necessary actor to build, maintain and differentiate no-tillage farming actor-networks.

> "No-tillage is social media kind of thing. There's a lot of farmers who are no-tillage who are on social media." (7CT)
> "There's a big farming community on Twitter. So just seeing what people are doing […] it's good to just keep tabs on things, and you just see what's happening. The farming forum has probably been one of the biggest influences on what I've done. […] There was

> another one a long time ago, and there was quite a community of people who were interested in no-till and that sort of farming system. You could meet or not meet, but you know, share ideas through that, which is something that I guess never existed before. So that helped me, and I think a lot of other people to accelerate and move faster into new things we wouldn't have done otherwise." (8NT)

In this process of no-tillage farming actor-network building, particular farmers acquired dominant roles, becoming influential farmers. Those farmers shared their farming experiences through engaging with the local community (farmers and non-farmers), wider audiences through farm visits and meetings (further away farmers, but also researchers, extensionists, agronomists, agri-business' representatives, etc.), and even publishing their work on social media where it was accessible to anyone. Those farmers easily made connections to other actors from farming actor-networks that shared similar configurations, widening and strengthening them. Despite their binding, their dominant roles and knowledge claims were contested by other influential farmers. Moreover, their encounters with actors from farming actor-networks that had different configurations, or even different roles for no-tillage, could result in repelling rather than binding, creating separation. Consequently, the existence of influential farmers contributed to the boundary building of multiple farming actor-networks, although their work and effort were, generally, directed towards the building, maintenance and spread of no-tillage as a system related to conservation agriculture.

4.10. Comparing farming actor-networks: Spain and the UK cases

In this section, I summarise and compare Spanish and British no-tillage adoption paths across their different farming actor-networks.

Both Spanish and British farmers adopted no-tillage because of economic reasons. Indeed, adoption followed an optimisation rationale to reduce production costs linked to petrol consumption of ploughing and related field operations. However, important factors in the financial equation were meteorological risks; in Spain, these were mainly droughts and irregular rain patterns, which compromised yields to the point of no harvest and consequent loss of investment. Flooding also occurred in both countries, but for some farmers in the UK, they were the major threats to their farms; with no economic compensations through insurances, there no-tillage could contribute to increasing resilience with quick re-seeding. However, the main goal of initially adopting no-tillage was to reduce production costs, taking distance from the productivist paradigm that maximises inputs to obtain higher yields. Additionally, in Spain, agronomists from farmers' cooperatives and extension services supported this optimisation approach in their recommendations to farmers. Moreover, it must not be forgotten that this adoption path happened in farming actor-networks in which grain prices were low, but farming was subsidised, ensuring farm economic continuity as long as fields were seeded.

Barriers to this economically driven no-tillage adoption path were high investment requirements in technology. Small farmers, hobby or part-time farmers and farmers close to retirement without business successor were especially hindered from adopting no-tillage under high investment conditions, particularly because the investment was not only in the no-tillage drill, which was extraordinarily expensive compared to conventional tools but also in powerful tractors capable of manoeuvring the weight of these drills. In the UK, the uncertainty following Brexit led to two reactions: quickly adopt no-tillage while subsidies were still secured or not investing in any innovation until the political situation was cleared. In any case, it has to be stressed that in these farming actor-network configurations, no-tillage was assessed positively for farmers' local agro-environmental conditions. That meant that no-tillage was understood as reducing production costs without compromising yields and could even improve yields during dry years. Moreover, some of the adopters had found lower investment options through smaller drills that did not require changing tractors or through second-hand markets.

In similar farming actor-network configurations, business farmers who were driven by economic growth and had bigger farms found juridical and economic tools to approach the investment requirements. Indeed, business farmers traditionally followed the productivist paradigm and tried to extend their farms and intensify their production. Nowadays, land access was restricted due to low availability and high land prices, caused in turn by subsidy policies, speculation with entitlements and in the UK, an increase in non-farming buyers. In addition, environmentalism was also driving the change from the intensification paradigm into an optimisation one. Due to this combination, business farmers who were connected to technological and research innovations and assessed no-tillage as the best practice for their farm would enrol in partnerships to approach the high machinery investments and other economic constraints in their farming actor-networks.

On the contrary, some farmers assessed no-tillage as not suitable for their local agro-environmental conditions or their farm structure. In Spain, this assessment was related to low surface dedicated to rain-fed agriculture under meteorologically riskier locations, a negative assessment of no-tillage due to infiltration decrease, or a negative assessment of no-tillage due to soil susceptibility to compaction under no-tillage management. In the UK, the negative assessment of no-tillage by business farmers was related to weed treatment costs, seeding times and limitations to crop sugar beet and potatoes. In other circumstances, farmers had not a formed opinion on no-tillage and required more evidence to build a clear role for no-tillage. If the latter happened in farming on rented land, some farmers could not afford the risk of investing in innovation. In any of these cases, in which no-tillage was not a solution to economic tensions in the farming actor-network, farmers in Spain adopted other roles different from the 'food producer'. In other words, farmers reacted to the farming actor-network economic constraints through other paths than changing their farm management. In Spain, farmers actively engaged with cooperatives, young farmers associations, farmers' unions, etc., to improve their negotiations with actors from the market or policymakers. In the UK, farmers' business role was more present in all farming actor-networks due to directly selling their products. Then, in response to price constraints, farmers searched for better prices by negotiating with grain merchants, 'gambling' with stocks, or searching for grain merchants or direct buyers offering better prices.

Furthermore, no-tillage was used in conventional tillage managed farms under specific conditions. In some cases, this was due to no-tillage drills being valued for their precision in placing seeds compared with conventional machines. Consequently, some conventional tillage farmers adopted no-tillage as a tool in conventionally or minimum-tillage systems. Conversely, in other farming actor-network configurations, no-tillage was assessed positively only for particular crops or specific field conditions. This links to 'the good farmers' assessing with care to use the most appropriate tool for each situation. Additionally, many farmers enjoyed and were used to have a variety of tools that they applied conveniently. However, there were also some no-tillage and conventional tillage farmers, especially in the UK, who preferred having one good machine and disengage from the constant bombardment of information and advertisements from the whole farming input businesses (machinery manufacturers and traders, and agri-businesses in general). Moreover, the use of many tools attending to crop and field needs required flexibility to make changes on a day to day basis. Business farmers generally planned their field operations ahead, sometimes in a routine manner, with little flexibility for last-minute decisions. Therefore, they were less likely to adopt no-tillage as a tool. The exception is if they assessed no-tillage as a better practice for a specific crop, then they either made the investment in a no-tillage drill or used a contractor, depending on the relative importance of that crop in the farm. Contrarily, even if no-tillage was assessed negatively in terms of production, it could be assessed as economically beneficial and used especially only on marginal, less productive land to obtain subsidies and eventually some yield benefits. As these marginal fields were often highly vulnerable to erosion and no-tillage beneficial impact on erosion, this might be a desirable practice. Cheap machinery options were crucial for no-tillage adoption as a tool.

In Spain, cooperatives and the internet played central roles for information circulation in all of these farming actor-network configurations. Additionally to their involvement in marketing grains and buying inputs to get better deals for farmers, many cooperatives offered consultancy regarding CAP requirements fulfilment and information or connections for insurances. Cooperatives also distributed magazines from agri-businesses and extension services. Moreover, cooperatives hired independent agronomists or, in the case of Navarre, host agronomists from the regional extension service. Farmers used and valued this service, especially if they trust the advisor due to long-lasting relationships and the institutional reputation from Navarre's extension service. Nonetheless, farmers always contrasted new information with their own traditional, local and experiential knowledge and, nowadays, also through the internet visiting well-known institutions' websites. Furthermore, cooperatives hosted events that promoted innovations from agri-businesses, extension services and research centres. However, farmers' mistrust the information coming from the agri-businesses because of the bias towards marketing their own products, although as it was free of cost, they maintain the relationships. In any case, cooperatives became spaces of community binding, in addition to village bars, where neighbour farmers exchanged experiential knowledge and built their community meaning and values around the symbol of the 'good farmer' and how fields should look like and been kept. Innovative farmers whose practices clashed with those local community symbols of 'good farmer' bond through the internet with other farmers with similar interests.

In the UK, farming actor-networks were more atomised due to the lack of cooperatives, and therefore, information flows less centralised. Some farmers were certified agronomists themselves, and others hired agronomists. The main role of the agronomist was to plan the use of agrochemicals: these were the fertilisers, herbicides and pesticides. Thus, the responsibility of complying with environmental regulations was in agronomists' hands. The relationship between the farmer and the agronomist was negotiated, although farmers, as employers, had a dominant role. Additionally, the lack of cooperatives and the demise of farming clubs, together with the reduction of the number of farmers, were changing and loosening the bonds of the local farming communities, which were holding through personal friendships or contract work. Still, farmers networked in meetings, fairs, workshops etc., with advisors and peers. Moreover, innovative farmers were able to build online farming communities, which eventually turned into field visits and farmers' groups.

The sustained adoption of no-tillage in time followed two approaches that, even if they seem contradictory, co-existed and merged in no-tillage farming actor-networks. In the first approach, farmers used no-tillage as a technological package. In those cases, no-tillage was adopted in the first instance as an assembled actor. However, in practice, non-human actors became dominant actors and threatened productivity. Indeed, in those cases, no-tillage farms were highly dependant on total herbicides to control weeds, applied before seeding. Glyphosate dominated the total herbicides availability in farming actor-networks due to its low price. However, glyphosate's potential toxicity and consequent banning threatened these no-tillage farming actor-network configurations. Actually, no-tillage reliance on herbicides was a barrier for no-tillage adoption for many traditional farmers who prefer a combination of fallow and tillage rather than applying toxic-agrochemicals or ineffective agri-businesses marketed products. These preferences were linked to environmentalism, tradition and the lack of effective herbicides for some weeds, such as *Bromo*, blackgrass or ligneous weeds. In the UK, besides weed and weed management, some high priced crops maintained dominant roles in the farming actor-networks even if farms had transitioned to no-tillage as a technological package. These were potatoes and sugar beets, and their soil disturbance requirements to grow and be harvested conditioned the rest of the farming actor-networks. These circumstances drove no-tillage technological package adopters to include strategic ploughing in their rotations. Here, strategic ploughing was preferred instead of other riskier and more innovative alternatives because it fitted better in the technological gear.

In the second approach, no-tillage became a system with strong relations to conservation agriculture. These were farms from innovative environmentalist farmers who, after the adoption of no-tillage due to economic reasons, established strong connections with conservation agriculture. To some extent, environmentalism and care for the natural entities in their farms also drove adoption, but still, the economic optimisation was the key factor. Additionally, those innovative no-tillage farmers started networking among all actors involved in innovation and conservation agriculture. These relationships were established due to farmers' initiative in searching for information about no-tillage outside their conventional tillage local communities. These new bonds and information flow impacted farmers in causing the development of a new role besides the 'food producer'. A role that involved networking, learning and innovating, possible thanks to time savings because performing fewer field operations and thanks to social media and the internet. In these cases, Spanish farmers experienced English language barriers, while British farmers had the opportunity to strengthen that role by conducting research with farming scholarships. In these cases, no-tillage was not a punctualised actor-network or a completed technological package; it was still in construction, which means that farming ideas, mainly related to conservation agriculture principles, were never understood as applicable without experimentation. Indeed, here no-tillage was a system involving many actors; the complexity and particularities of the interactions were both interesting but also frightening. Nonetheless, the farming experience was enriched due to the networking, learning and innovating roles, in addition to the 'food producer', leading to farmers sustaining their enrolment in the no-tillage farming actor-networks, sometimes as 'influential farmers' themselves.

4.11. Conclusions to no-tillage adoption potential in Spain and the UK

- The main reason to adopt no-tillage was cost reduction, to increase benefits while grain prices were low and to be able to manage meteorological risks (mainly droughts and flooding). Barriers to this adoption path were high investment requirements in machinery when no-tillage was assessed positively, which could be overcome with cheaper and more versatile no-tillage drills or by forming business partnerships.
- Alternatively, no-tillage could be negatively assessed, in terms of yield reduction or herbicide use, in which cases farmers reduced farming costs in other ways and adopted 'non-food producers' roles to negotiate higher benefits.
- No-tillage was adopted as a tool in conventional tillage systems for particular crops or field conditions. On the contrary, some no-tillage farmers did strategic tillage according to field needs. This adoption path required the time for individual field assessment and the flexibility of changing field operation plans, besides low machinery prices.
- No-tillage was adopted as a technological package together with other productivist practices. This role of no-tillage was reliant on glyphosate as a cheap total herbicide to combat weeds. Therefore, the barriers to adoption in these cases were environmental regulations increasingly banning herbicides, the changing role of herbicides from necessary phytosanitary treatment to toxic agrochemicals and agri-businesses marketed products, and some particularly dominant weeds (*Bromo*, black-grass and ligneous weeds) that did not respond to herbicides. Additionally, dominant crops (potatoes and sugar beet) representing high income but requiring soil disturbance also hindered this adoption path.
- No-tillage was adopted as a system together with other conservation agriculture practices. In these cases, farmers paid attention to interactions between non-human actors in their farming actor-networks to increase yields. The complexity of the interactions potentiated farmers' binding with non-human actors on-farm and other farmers through social media, which favoured the long-time adoption of this no-tillage path.
- On-farm experimentation, including testing external innovations in the form of crops, varieties, machinery, the management or simply ideas, co-creating knowledge and innovations, was part of all farming actor-networks.
- Overall, ANT proved to be a successful tool to distinguish adoption drivers and barriers in a complex and messy world by focusing on the adoption paths or material, information, etc., flows across different configurations of inter-connected actors, in which actors' and networks' roles and meanings shifted and co-constructed each other.

Chapter 5.

The multiple soils I: soils in the farming actor-networks

Figure 40. Chapter 5 cover photo: soil in the field, in Castille and Leon, Spain

5.1. Introduction to the multiple soils I: soils in the farming actor-networks

In this chapter, I first analyse the relations between farmers and soils, to then analyse how those relations co-construct tillage management. The chapter presents results from the analysis of the semi-structured interviews with no-tillage and conventional tillage farmers in Spain and the UK, informing and discussing:

- Soil paths to no-tillage adoption
- Farmers assessment of tillage management impact on soils

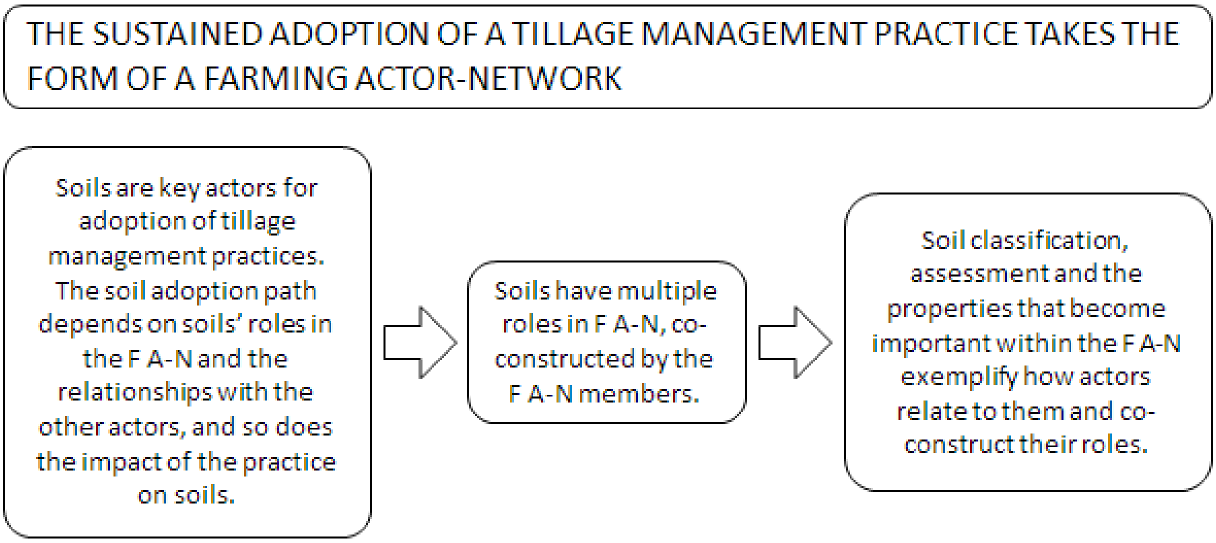


Figure 41. Main arguments to understand soils' role in no-tillage adoption and the 'insiders' account of impact on soils. F A-N: Farming Actor-Network.

The chapter is divided into five sections, plus the conclusions. The main arguments for the analysis are described in Figure 41. In 5.2 and 5.4, I provide farmers' account of soils; for the Spanish and the British cases, respectively. In those sections, acknowledging that the farmers were acting as spokespersons of soils and their wider farming actor-networks. The approach followed ANT and Hinchliffe (2007) understanding that the language and ideas used by farmers in identifying, describing and explaining soils were influenced by the farming actor-networks in which they are enrolled. For this analysis, I focused on the questions:

- Which roles did soils have in the farming actor-networks?
- Which soil properties were important in the farming actor-networks?
- Which soil knowledges sustained soils' roles in the farming actor-networks?

In those sections, I discuss how the interviewed farmers defined and referred to soils. Following the ANT approach, this is how the actor-networks enabled soils to exist, establishing their roles and defining who or what they were. As discussed in the literature review (see section: Actor-Network

Theory as a research ontology), this occurs in an interaction with the actor itself. Moreover, actor-networks are dynamic, with ever-changing actors and roles, and several actor-networks co-exist influencing each other. Therefore, the actors' identity is a layered outcome of the multiple networks in which they are enrolled. Thus, in these sections, I also explore soils' multiplicity.

In sections 5.3 and 5.5, the different paths that involve soils as a fundamental link in the farming actor-networks leading to tillage management adoption are presented and discussed for Spain and the UK. The sections build upon the previous sections in the way that they show how different farming actor-networks with multiple roles for soils and the properties that made them valuable, sustained by diverse actors and knowledges, led to different agricultural practices.

I further explore farmers' relation to soils by paying attention to how farmers relate to soils' chemical, biological and physical properties. Through this exercise, it was possible to identify how different farming actor-network configurations had different roles for soils and farmers, led to the adoption of different practices (conventional tillage vs no-tillage) and also to different adoption patterns (no-tillage as a tool, as a technological package and as a system).

I finish the chapter by comparing soils' roles and soil paths, leading to no-tillage adoption in Spain and the UK.

5.2. How Spanish farmers account for soils

In this section, I discuss soils' roles in Spanish farming actor-networks, as build through the relations with farmers. I start the section by revealing soils' multiplicity with the entanglement between soil and land, accentuated by language. Then, I present how the interaction between soils and farmers, but also with other actors, co-constructed soils' roles. These roles were embedded in how soils were described, classified and assessed in the farming actor-networks by enrolling relevant soil properties while others remained in the plasma (what remains in between actor-networks, as discussed in the literature review in section Actors in actor-networks). In Spain, soils' assessment was based on yielding capability, soils that did not fulfil this productive role were marginalised in agriculture, but precisely that neglect allowed soils to occupy other roles. I finish the section by following the circulation of soil knowledges across the farming actor-networks and how these further shaped soils' multiple roles through negotiation between diverse actors.

5.2.1. The entanglement between soil and land

Soils' multiplicity became clear as farmers referred to them in different ways during the interviews. Even the same person presented different meanings. In the farming actor-networks, a commonality identified across participant farmers was an entanglement between soils and land. This entanglement was partly due to how the Spanish language uses the words "soil" (*suelo*) and "earth" (*tierra*). The word *tierra* in Spanish means land, earth and soil. During the interviews, farmers used *tierra* interchangeably to mean land and soils.

Accordingly, across farming actor-networks, soils had two major roles: one as individual soils and the other one entangled with the land. The first role was similar to soil science's understanding of soils as discrete natural entities that develop and can be described and classified, which Rhoades referred to as 'soil taxonomy' level (Rhoades, 1994 cited in Talawar and Rhoades, 1998). In contrast, the second role was related to land. In the latter, farmers expressed connotations of farm extension, ownership and heritage. Rhoades referred to this as 'land classification' (Rhoades, 1994, cited in Talawar and Rhoades, 1998). Sometimes the reference to one of the roles was clear, but on many occasions, the limits between the roles and meanings of soils and land merged. The merging and fluctuating boundaries between the two roles suggest soils were multiple, in the sense that their diverse roles related to oneself with intricate relations between the versions (instead of a plurality of disconnected soils), the same as the sheep's versions analysed by Law and Mol (2008). In other words, the multiple soils were different but inter-connected.

5.2.2. Soil descriptions, classifications and the ideal soil

In this section, I further discuss how soils' roles were co-constructed through the assembling of soil properties. The analysis focused on how the power of some dominant soil properties manifested in the ways farmers described, classified and assessed the quality of soils. Acknowledging that this was a farmers' translation of soils' roles and their farming actor-network assessment of the compliance of these roles.

Soils were enrolled in the farming actor-networks in a subordinated role. Indeed, soils pertained to the farming actor-networks as long as they acted as expected by the other actors that had co-constructed their role. This was similar to how Eden, Tunstall and Tapsell (2000) defined the enrolment of the river Cole in a restoration plan. On the contrary, farmers, with a dominant role, became the *'spokespersons'* for soils. This meant that farmers had gained the authority to speak on behalf of their soils in the farming actor-networks. Nonetheless, soils or other actors could always contest these power relations.

Before analysing in-depth the relationship between farmers and soils, I wish to highlight farmers' acknowledgement of the existence of that bond. By doing so, the farmers lay the conduit, which enables the flow of entities (Turnbull, 2008) and the translation of knowledge, power and action. Indeed, soils were part of their farms, such as the climate, the crops and their management operations (see 5NT comment). Additionally, as discussed in chapter 4 (see: Values of freedom, naturalness and pride of growing food), farmers had a sense of nature and land stewardship. This relates to farmers' relation to nature more broadly as a garden, maintained and brought to flourish by human intervention (Thompson, 1994). Finding the optimal balance between production and conservation translated into a need for soil knowledge that farmers acquired, among others, through *working*, *loving*, *living* and sensing/*feeling* their soils as 1NT expressed. This knowledge co-construction through living their land was also found by Kaljonen (2006) between Finnish farmers and their farms.

> "Okey, the farm is situated in a terrain with a semi-arid climate, more or less rainfall of about 400 - 450 mL. It is a loam soil. It has been under no-tillage for around 15 years. Without rotation, the only rotation that is done, well, if it can be called rotation, is wheat, barley, barley, wheat. In principle, that's all I can tell you about this farm." (5NT)
> "Working it, loving it, living it… It's like that; it's like that. You have to… feel it, that's what I tell my sons. That's how the land is; it is like that. You have to know what you lead. These are… my fixations; then my wife calls me crazy. Well, damn it." (1NT)

Soil classification was the local, traditional, and experiential translation of soil diversity. Indeed, personal experiences added to those shared in the farming community to build soil knowledges. Farmers recognised a diversity of soils in their regions and classified them based on soils' visible features, such as colour or gravel content, in discrete soil classes. Furthermore, in their classifications, the entanglement between soil and land was present, with criteria such as land units or location.

> "They are *Negral* [black], yes. They are more of the stronger ones. They are not floodplain, but they are close to the river, on the other side of the road. […]"(3CT)

Overall, Spanish farmers assessed soil quality in terms of yield production. In other words, in how far soils fulfilled their productive role. This assessment criteria did not come only from their own relationship with their soils and their productive purpose, but it was sustained by other actors in the farming actor-networks, for example, the agri-business interest in local farm products as expressed by 4CT. For him, his and his neighbours' soils must have been *'good'* as their local food production had attracted many manufacturers and businesses to the region. On the contrary, soils containing salts, toxic for crops, were assessed as *'bad'* without considering how they fulfilled other roles (e.g. cultural) in the farming actor-networks.

> "There is everything here. Very clayey and sandy. What is close to the [river] river is very sandy soil and what is closer to the town is more clayey, and in the mountains, well, there are soils that are very… that have a lot of salt, other lands are *Cascajo* [gravel] soils, which we call, and other lands that are more clayey. Here we have all soils." (4NT)
> "[…] It is a very good area. Thus, all companies come here in order to us to put crops here, they know this land will produce and will give a profit. […]" (4CT)
> "Well, the soils that are here… there are good fields, and other soils are more like saltpetre." (1NT)

However, farmers acknowledged soils having productivity limitations regardless of human fertilisation input and distinguished soils accordingly. This, contrary to a view in which technology can tame and control everything, provided soils with an agency and power that impacted crops and farmers. In traditional farming soils' productive limitations were present in the conceptualisation of fallow, which in the farming actor-networks still carried the notion of *'letting the soils rest'* as 5NT mentioned.

Nonetheless, 'good' soils had a synergic response to management and inputs. In this case, production costs (fertilisers) translated into higher benefits in yields on 'good' soils, whereas 'bad' soils only slightly increased their productive capability when fertilisers were added, independently on the quantity, as 4CT explained. This showcases how the bond between farmers and their soils depended on soils' properties in general and yielding capability in particular. It is evidence of how non-human actors bring their abilities into social practices (Jones & Cloke, 2008), shaping farming possibilities. Consequently, more attention and investment was directed towards productive soils, whereas unproductive soils were translated into marginal land.

> "Well, let's see… not that I notice… as long as I live from the land. I am also not a person that… […] I mean, I see everyone has their own idea of land… One field that is bad, no matter how much good [fertilizer] you want to spread on it, it isn't going to be good. If you spread good [fertilizer] in a good field, it can become very good. I don't know if I explained myself. That is to say, for example, on a thing that you know does not generate a lot of profit, in a land that isn't [good], you can add manure and what you want… it won't be productive no matter how much you add, no matter how much you add, the land can't give more! In other words, the land has a limit, that soil has a limit. You can add grounded gold, but no! The land is not going to give you a yield that compensates the investment you had… that compensates your expenses. On the contrary, on a land that is good… spread [fertilizer]! If you add, it can give you not a good yield, but a very good yield. I mean, what you add, you take much more advantage of it." (4CT)

Additionally, in farming actor-networks, soil quality had a dynamic character and changed between different agricultural land uses. Not only due to the particular crops that were grown and their specific nutrient requirements but also crops' interaction with water through soils. Thus, soils' interaction with other non-human actors influenced the value system to assess soils. Moreover, quality assessment became highly localised as it depended not only on intrinsic soil properties but also on relational properties such as land use, microclimate, vegetation, etc. (Talawar & Rhoades, 1998). Soils, as dynamic actors, challenged farmers' knowledges. Farmers' experience with irrigation modernisation processes made them witnesses of how traditional and local soil quality classification criteria were contested by highly productive soils turning into less productive and vice versa, as 4NT explained.

> "Let's see, I'll explain it to you. Here it has been proven that, with irrigation, with flood irrigation and sprinkle irrigation, before they yielded… I mean, there came better yields in loose, loose soils which were close to the [river]. Nonetheless, nowadays, with sprinkle irrigation on soils that are stronger, more clayey, the same or more than at the other [soils] is harvested. I don't know if it is because it drains more, because the other compacts more if it is sprinkle irrigated, I don't know why… I mean, there was a change there…. Because, when they made us the land consolidation, we all wanted to go to that soil there, nonetheless, now it has been proven that with sprinkle irrigation this kind of soils are yielding the same or more." (4NT)

Figure 42. Flooded fields in Navarre in 2018.

Indeed, soils' dynamism in their interaction with water further characterised soil quality assessment concerning the capability to provide water to crops and determining the adequacy of entering the fields to work. The interaction with water depended on soil features like *'strength'*, linked to clay content, and *'stoniness'*. Moreover, it depended also on the weather as a dominant actor of the Spanish farming actor-networks, characterised by irregularities that in the case of water availability ranged from droughts to floodings. During flooding events, soils' topographical location, soils' depth, water assimilation and drainage became very important. Moreover, soils' interaction with water provided farmers with inferred information about the inaccessible subsoil. Because of the dynamism of the weather and the interaction with soils and crop development, soils quality was again a dynamic and challenging concept that changed from year to year, as 4NT explained. Soils' dynamism mirrors the broader importance to recognise nature as dynamic rather than static, operating in its own rhythms, to be able to understand social flows and change (Jones & Cloke, 2008). This, in turn, supports the importance of taking into account farmers' knowledges generated on their own land and in relation to a dynamic nature (Burgess, Clark & Harrison, 2000; Murdoch & Clark, 1994).

> "It really depends a lot because there are soils… if it rains a lot, the strong soils are better. Because it retains moisture, and then it has a higher potential to produce yields. Nonetheless, when it rains little, there are soils that if we see them now, the barley would appear worse than… However, when it doesn't rain, those soils keep more freshness, more moisture, those are the gravely soils, and you can harvest and maybe on the strong soils you don't harvest. The soil type here… depends on the year." (4NT)

Indeed, soils' interaction with water was important for farmers as it determined soils' workability and the restrictions to perform field operations. The relation between soil and water determined the appropriateness to work, to farm, and thus, it determined farmers' livelihood. The perfect balance of water content in soil was known by Spanish conventional tillage farmers as '*tempero*', or friability. This condition was the most appropriate to do fieldwork with the best results and the lowest negative impact on soils physical quality. Farmers' attentiveness to dynamic soil properties, such as workability, has been pointed out by Stoate *et al.* (2019) when referring to abstract soils, while when referring to their own soils at their farms, they mentioned more static, inherent characteristics such as texture. Farmers interviewed in this research also mentioned these soil properties, but in regulating the dynamic relationships with, for example, water and nutrients.

> "Yes, they are different. For example, if you go down there, to the pond, as we say here, there it is very calcareous. And this here, is *Buro* [clayey], as we call it here, clay. It is bad, bad, bad. And, well, if the year comes good, awesome! This year, now you can enter the fields until now you couldn't because you sunk until here… there was nothing more than water! And at the *Baldanía* [flanks], it is the contrary, spread water! And the crops [grow] until here, and you don't sink in the soil. If you go over here…" (5CT)

Thus, clay and sand contents had dominant roles in determining how the interaction between soils and water developed, and therefore, soils' workability. While clayey soils were not highly valued due to more problems related to water stagnation, sand had many more disadvantages. As 3NT explained, sand did not retain water, had no organic matter content, nor structure, and therefore it restricted crop development. However, even these bad soils had a good side, as they were favourable for crop emergence.

> "Because sand… it is more… it doesn't retain, it has no organic matter, it dries more, it hasn't so much structure… And well, [crop] emergence is easier, but when it is time to harvest, it hasn't had the sustain it needed to finish, clearly. And here, the organic part is the problem. We haven't talked about it, but well… it is…" (3NT)

Some farmers described their ideal soils based on the discussed local, experiential criteria. So, farmers valued local soils based on what they were able to grow on them and the ease of working with them. This included soil and land properties, such as stoniness, slope and interaction with water. As farming communities, they had identified soils' locations and their most appropriate agricultural use, as well as the most valued soils, which often were those situated at river plains, due to their fertility, acquired through repeated flooding in the past, as 1NT explained.

Ultimately, these relationships between farmers and soils were based on soils enrolment in the farming actor-network in a subjugated role, to be tamed. The easier the soils were to work with and responded to the networks' needs in terms of crop production, the more a specific soil was valued as 1CT expressed. As seen, that relates to the 'myth of the garden' (Thompson, 1994) and a common version of understanding nature as an object to be governed in Western cultures (Hinchliffe, 2007).

> "Well, of course! **** if I have it [ideal soil]… It is a soil that is not very hard, and that is well… that hasn't any problems of drainage. That absorbs all water it gets. That is the ideal! The lands that were classified as first-class at the land consolidation, those are the good ones! Easy to tame because there are hard soils that are good as well, but they are more difficult; they require more runs to make more powder to put the crop in. But a land like that, with three runs… they always have entry even if the soil is a bit soft, it gets a bit more concealed. But a stronger soil, compacter, you enter [the field] a bit soft, and you are done! The yield, for any reason, it is really noticeable. They become yellow; they don't get on, the soil gets tighten, it doesn't drain too good… those are the soils, those are the different soils…" (1CT)

However, for some no-tillage environmentalist farmers, the ideal soil transcended the local and experiential. These were environmentalist farmers who followed conservation agriculture principles and had integrated the ideal soil that this paradigm promotes.

According to the conservationist paradigm, nature achieves a flourishing climax following ecological succession while human intervention deteriorates nature. Here, the ideal soils are in ecological balance, have better quality, and need fewer human intervention to produce food, as 5NT expressed. The criteria that became important were those that differ degraded soils from the natural ideal. Thus, farmers in these farming actor-networks, in addition to the local and experiential criteria, valued soils according to organic matter content and biological activity. Endowed with life, soils' agency is even greater and more challenging (Swidler, 2009).

Nonetheless, no-tillage environmentalist farmers following the conservation paradigm had, like all the other farmers, remnants from a productivist paradigm and a sense of stewardship of their land as from the garden myth. Thus, from the latter, they inherited the responsibility to lead soils to their 'natural' balance, or as close as possible, by enhancing their properties, with a particular focus on organic matter and microorganisms. While from the productivist paradigm, these farmers inherited the aim of improving yields, although this time it was through ‘letting the soils work for us’ as put by Elliott (1988), which had a great influence on management decisions, as I show in following sections.

> “My ideal soil would be one with a good quantity of organic matter, of two and a half or more, which is very low. It would have adequate microbiology. A good porous structure, a good bulk density, isn’t it? I would like to manage it the least as possible. I mean, not having to act much on that soil, because every time I act, I think I am harming the soil, even if I want to improve it! I mean machinery runs… And… that’s all! That would be my soil.
> It would have a good balance. For me, a good soil is a soil that is in balance, and agriculture… what we are doing is to disrupt that balance of the soil, no? Thus, that rupture… the minimum as possible, right? That would be my ideal.
> I know there are soils… You can not ask here for, maybe yields as they have in [location] of 7 or 8.000 because it isn’t the same rainfall and maybe it isn’t the same quality of soils. But to respect the soil we really have here in this area, and not disrupt the balance! It would be that…” (5NT)

5.2.3. Soil knowledges circulation

In this section, I discuss soil knowledges circulating through the farming actor-network, their different sources and how they sustained different soil roles and wider farming actor-networks. Sources of these knowledges can be identified as farmers’ own interaction with soils and the communities’ local traditional knowledges shared between members, which I have both discussed in the previous section. In this section, I focus on technical and scientific information and the internet. In contrast, knowledges that permeate from policies and legal norms are included in the next section. All those knowledges co-existed and circulated in the studied farming actor-networks.

In the previous section, I have discussed farmers’ experiential knowledge acquired from the direct relationship between them and the soil and the shared local value systems that manifested in descriptions, classifications and assessments. I have also discussed how farmers’ empirical experiences with soils were strongly influenced by their roles in the farming actor-networks. In other words, properties that aligned or contested the fulfilment of soils’ expected roles were brought into existence, enrolled in the farming actor-network, whereas other soil properties remained unknown, in the plasma not belonging to a particular farming actor-network. In this section, I introduce the link to other sources of soil knowledges and how they sustain some of the already mentioned roles or might have added more layers to the multiplicity of soils.

Land classification and consolidation processes left farmers with a technoscientific experience of assessing soils. The great impact these processes had on how farmers understood innovation has been explained in chapter 4 (see: Spanish farming innovation characteristics). Farmers’ interaction with the field-technicians in charge of the classification build trust in these processes. First, because technoscientific knowledge became contextualised through the local interaction with the farming actor-network. Second, because farmers felt their authority to talk on behalf of their soils as spokesmen was taken into account by acting as guides and accompanying technicians during fieldwork. Under these circumstances, in which knowledges are locally validated, knowledge exchange is likely to happen instead of farmers mistrusting external information (Riley, 2016). The latter contrasted with current administrative practices, such as regional monitoring of CAP compliance or rural policy development, which were seen as alienated to farmers' context because they were carried out in far-away offices, with little fieldwork nor contact with farmers.

Furthermore, land classification and land consolidation brought a value system to assess soils as natural resources, to which farmers had to adhere. The processes required farmers to choose between quality and quantity. Quality was defined in terms of soils' agricultural productive capacity. So, 'good' quality land was equivalent to a greater extension of poorer land, in productive terms. Thus, ultimately farmers chose between intensification or extensification while soils became exchangeable based on yield potential, an economic value. Farmers who attached soils and land to other values, for example, social values of inherited land and chose to maintain ownership of little fields and not enrol in land consolidation, were criticised as unprofessional.

> "The chap who was coming… stepped on them and said 'this one is third class!' and we said 'Nooo! Here there is a bit of sixth, here a bit of second…' and the chap did draw them… No, the chap knew, more or less, the one who came… at least he stepped on them! Nowadays everything is done over satellites and well…" (3CT)

Besides their interest in soils and soils' productivity, when it came to paying for soil tests or consultancies, there was a general reluctance. Farmers justified the lack of soil testing due to little variability of soil characteristics in the region, which contradicted their acknowledgement of different soils even in their own farms. On the contrary, they relied on local, traditional and experiential knowledge to select the most appropriate crops and varieties for each field and to plan their fertilisation. Additionally, farmers got access to soil tests' information through their farming actor-networks. For example, cooperatives or neighbours shared soil test information in informal meetings at bars and cafes.

> "I haven't done. More or less, because [5NT] is doing, I got to find out about the story. No, here, more or less, the analysis (…) over there it is saltpetre, here it is more *Buro*, as it's called, more clayey, more *Cascajo*. If we have to spread so much of this, this much of that, this from here… and more or less you have it under control." (5CT)

Moreover, soil analysis was limited to productive soils. First, because of the high costs, farmers performed soil tests only on those fields that were intended for the major income crops to adjust their fertilisation plans while marginal land was not being tested. The actors involved in soil testing differed across the farming actor-networks. Some farmers took the samples and sent them to independent laboratories or to universities. Others relied on the extension service technician who took the samples and, with the results, provided advice on the fertilization plan to enhance crop production. Second, if farmers had contracts with agri-businesses that sold them seeds and bought their yield, these sometimes asked for soil tests or performed them without an extra cost for the farmer. Third, in locations where investment in fertilisers was high (because they have high production, up to three harvests in a year), some agri-businesses technicians/salespersons arranged free soil tests as a marketing strategy to recommend and sell their products.

Nonetheless, these differences led to very different access to soil test and expert knowledge. Highly productive fields, especially on irrigated land, were tested more frequently because they were farmed more intensively, the crops produced higher economic revenue, worthy of investment, and farmers were more likely to have direct contracts with agri-businesses. Whereas rainfed land, which was less intensively cultivated and had lower commercial weight in the mixed land use farms, was rarely tested.

> "No. No. On the irrigated land now, they are starting to do some soil analysis. The seed companies they tell you to do, that we should do, for the fertilising… […] We… They have done… where you will be growing maize, obviously, if you buy the seed from them, they tell you 'Listen, I will do a soil analysis for you'. […]" (4NT)

In a different situation, farmers who had adopted no-tillage as a system were interested in soil properties that were not the generally tested nutrient content. However, their willingness to widen soil analysis did not necessarily translate into action due to tests' and consultancies' high cost.

> "[…] I don't know, maybe we have to change our mentality into that it is a good investment doing soil analytics, to know how we have this soil! But I… I compare it with other areas, and I see that for the same cost they give much more services in other countries rather than here. We should change that!
> […] Yes. I don't care because I see that it is becoming something… It is good to know about it, but I need to know more. I need to know how the soil is, not only nitrogen, phosphorous and potassium. There are more things…" (5NT)

Moreover, these farmers were taking a system, relational approach to farm management and trying to find the underlying causes of farming problems (pests, diseases, etc.) at the interactions between system components. Therefore, they were eager to have a better understanding of soils' relational role in the system and improving soils' relational capabilities, to proactively avoid farming problems and enhance yields. Nonetheless, this system approach was, in many cases, an overwhelming knowledge demanding approach that required a learning process, as Ingram found with English reduced tillage farmers (2010). Therefore, farmers sought soil expert advice or, as a cost-free alternative, online *'gurus'*, as 5NT referred to them.

Following outreach publications of scientists, agronomists and influential peers, all farmers increased knowledge, got ideas to experiment with at their farms and expanded and reinforced their particular farming actor-networks. In the case of the farmers adopting no-tillage as a system, the latter referred to positive feedbacks obtained and created at accessing (and sharing) information that also took (eco)-systemic approaches to farming. Farmers were interested in obtaining information about recovering soils' lost natural balance through the enhancement of soils' relational capabilities and particularly through soils' life. Knowledge exchange, as much as it was a learning process, was also a co-construction of meanings, and as Krzywoszynska (2019b) identified in the relationship between English farmers and so-called soil experts, a way to be inspired, legitimise and justify their practices. Thus, the circulation of these knowledges helped to co-construct soils role as natural, relational, life entities in these farming actor-networks.

Figure 43. Earthworm casts as evidence of soils' life. Fieldwork 2018.

> "I would like, above all, I would like to meet people who are specialized in soils. It is my heritage. Thus, I want to meet people who knows about soils and what to do to improve my soils, ok? And forget about the factors, […] and see it more like a system. A researcher, for me, should let me know what balances have to be in the soil, in my soil, in my own soil. Because not all soils are the same. What should I apply to the soil to maintain the soil as similar as possible to a soil that has never been agricultural. I think that a soil that has never been managed in agriculture has a natural balance *per se*." (5NT)
> (5NT)

In the preceding section, I have explored soils' multiple roles and how they were co-constructed by different farming actor-network configurations. Across the farms, *'tierra'* entangled soils and land, enabling soils to become discrete entities and at the same time carrying meanings of ownership, stewardship and heritage. Furthermore, soils were classified based on visual properties, while their quality was assessed based on yield productivity. However, soils' dynamism, or, in other words, their changing properties in response to fluctuating relations with other actors (particularly weather), challenged soil knowledges. Notwithstanding these challenges, yielding soil assessment criteria was supported by other relations in the farming actor-networks, such as the agri-businesses and the food industry; and led to distinguishing productive soils from marginal land. While more attention and higher investment were directed to productive soils, which reacted in synergy with farmers' efforts to produce high yields, marginal land was where other soil roles had the opportunity to develop. Concurrently, in farming actor-networks in which no-tillage had been adopted as a system in relation to conservation agriculture, soils' were becoming natural, relational and life entities. This role was not sustained by existing knowledge circulation conduits (e.g. soil biological analysis had a high cost), but the internet allowed to build new relations to ensure its enrolment in the farming actor-networks.

5.3. Spanish soils' role in no-tillage adoption paths

In this section, I present Spanish no-tillage adoption paths in which soils were a fundamental link. First, I discuss the notion of agriculture's impact on soils in relation to land stewardship and the tensions regarding soils' roles as resources. Then, I focus on the different chains of actors and their bonds in relation to chemical, biological and physical soil management and how these co-construct farming actor-networks and eventually led to no-tillage adoption.

5.3.1. Agriculture's impact on soils and land stewardship

To start the discussion about soil management, first, it is important to establish that farmers acknowledged that their agricultural practices had an impact on soils. First, compared to urban and industrial land uses, farmers saw rural activities as preserving nature. If farmers were damaging nature, it would have disappeared (Burgess, Clark & Harrison, 2000). Second, farmers acknowledged that different agricultural practices could damage or enhance soil quality. As seen above, soil quality was primarily assessed regarding soils' productive role, although ecological roles were becoming more important. While across the studied cases, soils were entangled with land, and farmers had a moral duty of stewardship.

> "[…] And the soil's need to care for it. I mean, I think soils are… fundamental! […]" (3NT)

> "[…] I know that with the other [conventional tillage] I would lose my heritage, which is the soil, and with this one [no-tillage] at least, although it hasn't resulted so good so far, I have tried to maintain my heritage." (5NT)

How land stewardship translates into practices that enhance soils has shifted in time. Maybe nowadays, there is a greater awareness of soils importance in eco-systems and productive systems, but in agriculture, focusing on soils is nothing new. In the interviews, traditional fallow was still seen as letting the soils rest from their productive role, to recover. While adding chemical fertilisers was seen as replenishing the nutrients extracted by harvesting, giving back to the soil what had been taken from it. Today, these strategies that somehow manifest farmers' soil stewardship co-exist with others that focus on different soil properties and/or their related actors.

When it comes to the responsibility to provide stewardship or repair damage, soils' multiple roles were in conflict with land ownership. As seen, soils in the farming actor-networks could take the role of a natural resource with its value becoming exchangeable in economic terms. This role had been emphasised by the land classification and consolidation processes. Moreover, it was also sustained by CAP subsidies schemes, through which higher-yielding areas and bigger size farms obtained the highest payments (Cong & Brady, 2012). Taking this role, the farming actor-network agreed on understanding soils as an economic good, used by farmers for their own economic benefit. Therefore, farmers had the responsibility of repairing the damage caused by agriculture following the principle of 'the polluter pays'. At the same time, because farmers were the primary beneficiaries of soils' productiveness, farmers carried the responsibility of soils' improvement.

On land owned by the farmer, soils' role as an economic resource did not clash with land stewardship because farming was planned for the long term. Then, farmers adopted practices that, according to their farming actor-networks, aligned with both of these roles of soils as productive entities, and at the same time, part of their land that with a need to be taken care of. Nonetheless, different land ownership forms such as communal or rented land, created tension in the farming actor-networks due to soils' role as a resource and the expectations from the whole farming actor-network about soils' role and the kind of relationships that are built with resources, which are to make economic profit from them.

On communal land shared between farmers and shepherds, even though the right to use the land was shared, the stewardship responsibility lied on farmers. Communal land norms determined limiting soil moisture conditions (in terms of rainfall) that restricted field access to shepherds and their livestock to avoid soil compaction by animal trampling. Besides the city council taking some kind of stewardship role in producing those regulations, in practice, it was the farmers who took the stewardship role, even monitoring the compliance of communal land norms, as 4CT explains.

> "[…] there are norms for the days that he [shepherd] can enter, and those he can't. I mean, if the seven days he is allowed to enter it is raining, here in the City Council there is a norm that if it reaches a certain quantity of litres, the livestock can't enter the field because it can harm the field. Thus, he has to respect that. There are times that he respects that, and times he doesn't. Then you have to keep an eye on it and tell him, 'Listen, leave, you are harming me.' […]" (4CT)

On rented land and communal land that rotated between neighbours, the tension between resource and stewardship was even higher. Stewardship aimed to ensure and improve soils' long term productive role and entailed an investment of time, money and knowledge. Farmers were reluctant to pass on their investments translated into an improved soil quality to other resource users. Moreover, different land users could base their soil quality assessment on diverse soil roles and criteria, as 2NT referred to when talking about his no-tillage management. Thus, there was a difficulty in translating soils' values into economic terms. Robinson et al. (2014), when talking about soils as resources, suggested the valuation of soils according to the fulfilment state of their multiple functions with special attention to soils' ecological ones. In other words, how soils' fulfil their multiple roles. However, how soils were enrolled in the land property market was not as multifunctional dynamic entities whose value changes with management, but rather as static resources that had an inherent economic value based on its productive capability assessed during land classification.

> "Now it would bother me… I don't know the improvements I think I am doing… now starting everything from null. So, you have been improving, changing everything, if they tell me now 'No, the fields are going to be consolidated… […]' Then, why am I doing all of this? Moreover, there is another issue, all the land I am managing is rented, I don't own anything, this means that the person who is renting it to me, maybe in 4 years, can rent it to someone else. And the improvements I am doing, someone else would take them. Of course, maybe for me, they are improvements, and for someone else, they are damages. Do you know? He says, 'You are filling [the field] with weeds…' I don't know… Well, that can happen… and it is another barrier to this kind of things [conservation agriculture practices]. That you are investing money, resources or time and then, clearly, it is not yours, and they can take it from you." (2NT)

5.3.2. Soil chemical fertility management

Not all fields received the same fertilisation ratio; marginal land received less attention. As discussed before, marginal land could be designated as such due to properties related to land (e.g. location, field size, etc.) or soils' intrinsic properties (e.g. stoniness, depth, etc.). In relation to management decisions, marginal land and poorer soils led to reduced investment in the form of fertilisers, time or knowledge (e.g. soil tests). As 3CT explained, 'good' soils paid off the investment in fertilisers with higher yields, while 'poorer' soils had greater risks to suffer hydrological droughts, and this increased the risk of not getting an economic return from the investment.

> "No, no, no. Depending on the soil, I do… What I know is strong land, I spread more fertilizer, what is thinner, I spread a bit less. But in the end, seeds I spread the same.
> […] Because the land that you know is good, that you know… there the plough leaves it good. Soil (…) that admits… that has good germination, that is fresh… So, there I spread more fertilizer because it produces more. The other, if you load it and the drought pushes a bit more, it knocks the crop off! […]" (3CT)

Nonetheless, in the farming actor-networks, it was on marginal land that the dominant role among soils' multiplicity could be taken by other roles than the productive one. Boardman et al. (2003) relate farmers' lower economic dependence on marginal land's production to a greater willingness to adopt conservation practices in exchange for an economic subsidy. However, in the analysed farming actor-networks, other soil roles, still related to agricultural land use, also found their space to exist on marginal land. These were the cases of soils' social roles related to soils embodying family bonds and inheritance, or soils' cultural roles such as maintaining agricultural practices in the Bardenas Reales as a symbol of traditional communal farming, or even soils' experimental roles.

Indeed, classification as marginal land made those soils more appropriate to test different practices. These included those conservation practices incentivised by CAP regulations to obtain subsidies without compromising productive soils' benefits. However, some farmers went beyond the requirements and experimented with other practices or a combination of practices such as cover crops. Additionally, for conventional tillage farmers, marginal land could be a soil to experiment with no-tillage.

Nutrient management was one of the purposes to introduce crop rotations. As seen in chapter 4 (see: Rotation and greening areas), rotations were one of CAP's requirements to access subsidies. Moreover, all farmers acknowledged the benefit of growing legumes, which fixate nitrogen, that could be used by the following crop reducing fertilisers costs. However, it was farmers adopting no-tillage as a system that had stronger bonds with the practice because, in their relational and systemic approach, rotation also sustained no-tillage (and vice versa).

Nonetheless, this improvement to soil chemical fertility with rotations was still dependant on other networks' actors, such as rainfall. If legumes did not germinate and grow, then they did not provide the benefits, and farmers lost the economic investment of the seeds and other field operations. In places where this loss was predictable due to recurrent droughts, it had ended in the abandonment of rotations or secluded it to marginal land.

> "Yes, not lately, but around two years… three or four years ago, I was doing a rotation that worked quite well. I grew peas and barley, and I was exchanging peas for barley or wheat. Then, it showed a lot. What happened was that… the problem these years back, that it didn't rain seeding the peas, and if they didn't emerge… they didn't improve they didn't know anything! So I stopped doing it because the years they emerged, it showed

> in the following year, it showed a lot because they fix a lot of nitrogen, the soil improved a lot… what happened is that I stopped doing it because if they didn't emerge… I was losing…" (4NT)

To fulfil soils' productive role highlighting the nutritious aspect of food, relevant chemicals in the soil properties were not only nutrients but also agrochemical products and other soil components that were toxic to the plant. Those chemical components also related to tillage management decisions.

For some farmers, soils' ecological roles and farmers' land stewardship role maintaining soils' capability to produce nutritious food conflicted with herbicide dependence in no-tillage farming. Glyphosate, in particular, was used extensively in no-tillage management as a total herbicide before seeding. Nonetheless, as seen in chapter 4 (see: The multiple roles of herbicides), the controversy about its negative impact on human health and the different roles of the herbicides in the farming actor-networks (phytosanitary treatments, toxic agrochemicals and marketed products) led to questioning the appropriateness for its use, preventing some farmers from adopting no-tillage.

> "Glyphosate? I will shoot rockets [celebrate] the day it gets banned! I am the first one… because I am against it. Because I think it is bad and we have to care. If you seed the land in 200 years, the least is that it is not infected, isn't it? Because if it infects the wheat, to the soil, something will go as well, isn't it? I mean, I don't understand much, but I think so… and I think it has to…" (3CT)

On the contrary, no-tillage farmers perceived an improvement in chemical fertility and a reduction of the toxicity of certain components. These experiences in which soil improvement was connected to no-tillage, as 1NT suggested with salt content, contributed to sustain no-tillage adoption in the long term and reinforce those farming actor-networks.

> "On those soils that are bad to plough because they have saltpetre and clays and so… that is bad, then soils improve a lot with no-tillage. You leave crop residues, you leave everything, and it will be showing… […] you go on improving… […] You make a fertile layer on that soil…" (1NT)

5.3.3. Soil biological fertility management

The only farmers who expressed an interest in enhancing biological fertility were no-tillage farmers, to the extent that it became the main focus of soil fertility for those farmers adopting no-tillage as a system. Vankeerberghen (2016) identified the life soil role as the differentiating factor between conventional tillage and conservation tillage farming in Belgium and as the tipping point to adopt other conservation practices. However, in this research in Spain, I found that farming actor-networks in which no-tillage was enrolled as a technological package also enrolled soils as life, natural and relational entities, but that did not become central to management and farmers hold control over the farm and the soils by applying normalised practices. In contrast, farming actor-networks following the systemic approach managed biological fertility by implementing no-tillage, rotations, and leaving crop residues on the surface. Thus, when no-tillage was adopted as a system, all these practices sustained each other in the farming actor-networks.

> "[…] The biota has diminished, and I think that if I continue to do this, my soils will be more… they are in the direction, as I am managing it now, to become just that: a sustain for plants. I would have to do something like hydroponics on soils. Yes, that is what I am doing. But what I really want is that my soils improve and that that improvement positively impacts yield. Because now I see I am doing bad. I'm doing bad. Yes, yes." (5NT)

Nonetheless, those other management practices also broke relations and introduced tensions in their farming actor-networks. For example, leaving crop residues on the surface represented a disruption of normalised practices. Commonly, farmers had contracts so that straw was bailed and collected after harvest. Those relations helped to sustain the conventional tillage farming actor-networks in which crop residues were seen as problematic actors. Therefore, farmers who changed these established farming methods confronted a great level of criticism and uncertainty. Building new relations to sustain those new practices and overcome isolation, enabling the farming actor-networks to change, was crucial for long term adoption, as previously noted by Krzywoszynska (2019b) for sustainable soil management practices in England.

> "Yes, before I sold it [straw] and now it has been years that I removed from the contract. They always told me, 'don't worry, if you have any problem you can enter again, it doesn't matter.' Of course, you don't know where you are heading! Really… […] there is a lot of straw on the surface.
> Thus, working and under those conditions, in which nobody has done it when everybody tells you that there will be pest problems, diseases… it is a bit risky!
> […] It is difficult that in an environment where everybody does things a particular way, to opt-out and do something that in the beginning is not going to provide you with an evident economic return… and that will be a complicated bet… It isn't easy! It isn't easy! […]" (2NT)

Some of the newly generated relations that sustained the adoption of new practices were the positive feedbacks from other farmers in the community. So, no-tillage farmers had seen the benefits of no-tillage from their peers. For example, during land classification for land consolidation, 1NT neighbour who had been doing no-tillage for 20 years had the best soil, with earthworms and organic matter.

> "Indeed, [farmer], when they did the sampling for the irrigation, it turned out he had the best soil from the area, and he had been doing no-tillage for 20 years. He had done, like this, a layer… Very good… They took a shovel and made a pit… and you could see a layer of fertile soil, the straw, the earthworms…everything. It really showed. It really showed." (1NT)

Nonetheless, many farmers saw the practice of leaving crop residues on the surface as a source of pests. Not denying the agronomic benefits from organic matter, the related problems counteracted them because of the need for controlling the problems through pesticides, which were both expensive and harmful for the environment and human health. Soil life, in those farming actor-networks, was a dangerous actor that was best to control by keeping it suppressed.

> "[…] because of that you tell him 'No, there is a mulching cover…", "There will be bugs… there will be lots of bugs!", 'No, this way it gets fertilized when it breaks down!', 'Yes, yes, everything you want! Everything you want but there are bugs, slugs, aphids, what's out…. There is no list of bugs that you can't find there; there are all there! And then, you know what you have to do afterwards, isn't it? Treatment against all bugs!" (5CT)

On the contrary, in no-tillage systems, farmers made their soil management decisions not to suppress soil life but to enhance it. In those farming actor-networks, soil life and organic matter were considered the actors that could recover soils' natural balance, in which soils' ecological and productive role aligned. Indeed, the management aim was to improve soils' natural, life, and relational properties so that soils could act with minimal machinery and product additions. How far these farmers believed in enhancing the natural soil life without artificial products was shown by their refusal of using biofertilisers. However, soil life enrolment was challenging and taming it into their expected role required farmers' guidance. This usually came in the form of enhancing life with no-tillage, crop residue maintainance, rotations, and sometimes cover crops, while the pests were supposed to reduce naturally with these practices and, if they appeared, were treated in conventional ways with pesticides.

> "Me, with the ones from the fertilisers, well […] they come to sell mycorrhizae, biostimulators and so on. I have tried something sometime, from those who come. And I tell them, 'Let's see, I am sure your product works, I am convinced, and that it has what you say, etcetera and it does… But, but I, my idea is first to potentiate what you have. I mean, I don't want to live on a medication basis; I have to live based on a diet, on normal health, isn't it? Listen! I get ill, and then I have to take medication to get better. But not base my diet on taking this, and then I am going all crazy, […] it's a similar example. So the idea is that you sell me this, 'that does that.. that potentiates I don't know what, that solubilizes I don't know…' And I say 'yes, ok, I agree' There is where I say, why you don't first improve what you have, and then if you need something more you compensate it with something? […]" (2NT)

5.3.4. Soil physical fertility management

Securing a good soil structure at the upper 5 or 10 cm was vital for all farmers to provide an appropriate bed for seed germination and settlement. To achieve that, conventional farmers did field preparation operations, including tillage, aiming for a good till, whereas no-tillage farmers concentrated on obtaining a good soil structure through increasing organic matter and promoting biological activity to enhance soils' natural aggregation processes.

> "Structure of that part [soil surface], at the time of seed positioning, when doing no-tillage, etcetera. I do think it is important to maintain a good soil structure in the first 10 cm. Because below, it will be improving slowly, isn't it? But in the beginning, the top… Differences can be seen there regarding that management of leaving soil covered with lots of residues, compared with that what is with fewer residues and what is ploughed." (2NT)

Conventional farmers paid attention to soils' moisture conditions to determine the most appropriate tillage method. Indeed, farmers had a range of tools for field preparation at different depths. Primarily they wanted to avoid creating clods, artificial aggregates or clumps of hard soil that were difficult to break afterwards. Moreover, the assessment of which particular tool to use was done in a flexible manner, evaluating each fields conditions and the crop requirements. In that flexible approach, no-tillage was also a tool that provided predictable results, for example, better seed placement or being able to seed with huge crop residues on surface.

> "[…] That depends a bit on the '*tempero'*. This is how more or less… but well if there is good '*tempero'*: the plough. If the '*tempero'* is passing, that it is drying: chisel plough because that one doesn't bring out clods. The *'tempero'* passes even more: the power harrow. It is like that, you always leave it without clods, because later it is easier to prepare.
> Because later you have to prepare, with the '*preparador'*, which is a small cultivator. Or how we did it traditionally, with the '*rastro'*, which is a table with nails and the *molón* behind. And that's it! The seeding machine! and plough! and this way life goes on in the countryside, bouncing [on the tractor]." (5CT)

On the contrary, for farmers who adopted no-tillage as a system, conventional tillage disrupted soils' natural capability to structure itself. Moreover, as 3NT said, tillage could leave soils in a very unsuitable state for field operations leading to other problems. Whereas letting soils structure develop for itself, had some benefits such as a reduction of soil crusting and consequently an improvement of crop emergence as 5NT mentioned. The reduction of soil crusting is a generalised benefit claimed by conservation agriculture advocates (see: Kassam, Friedrich & Derpsch, 2019). For these reasons, in these farming actor-networks, the connection to the plough was almost broken.

> "Because the land hasn't been turned. The land at the moment that you turn it, especially when it is dry, some people pass the harrow [*grada rapida*], those with discs… and they leave it… buff very like that. That become very soggy; I mean, it has a sponge effect and does not release [water]. And even if you don't sink, you can't work it because it is very plastic, very… do you know?
> And with this, you seed, and it is more natural. I mean, it is more… and above all, because turning [the soil]… this is more natural. More… and because it has the residues on the top, I don't know, it makes a different effect. Do you understand? And there are more

> bugs than turn it. For the roots, I think it does not have that effect of compaction of 'S***! I have crushed it, and…' It [no-tillage] does work. It does work. […]" (3NT)
>
> "[…] Around here there were any problems of soil crusting when we did traditional ploughing, and with this [no-tillage] you reduce it a lot. Thus, emergence is much better and so on." (5NT)

The adoption of no-tillage as a technological package was an intermediate approach between adopting it very flexibly as a tool or with fervent believes in soils life, natural and relational capabilities. So, farmers who adopted no-tillage as a technological package had some links to soils' life role, wanting to benefit from it economically and ecologically. Nonetheless, they approached the management decisions without decreasing their control over the farm by using machinery and agrochemical products. Moreover, in their farming actor-networks, not all soils were appropriate for no-tillage. Contrasting with the adoption of no-tillage as a system in which all soils could reach their maximal potential through no-tillage together with other conservation practices. So, 1NT, for example, commented that on silty soils, no-tillage worked good and improved overall soil fertility, whereas on '*tierra Sarda'*, a red soil with gravel, shallow soil preparation worked better.

> "[…] They have some salts, and they are silty. Thus, there are lands where no-tillage works better; with this one, it works very well. In areas with the *Sarda* soil, as we call the red soil with gravel, there no-tillage goes a bit worse because it is drier. So there, maybe ploughing or semi-ploughing or a chisel or semi-chisel works better." (1NT)

Figure 44. Field borders at the Bardenas Reales dangerously close to a gully.

Soil erosion is often the main cause to promote no-tillage. In Spain it was a big problem, but not in all studied locations. It was particularly dangerous in the arid region of Bardenas Reales. Not only due to soil loss but also due to the erosive features that increased farmers' accident risks during field operation. Indeed, in this region, gully erosion was common and was favoured by loose sandy soils, as 4CT explained. In these conditions, 4NT sustained that no-tillage decreased erosion, especially wind erosion, because no-tillage did not loose soils further, and it protected the soil surface.

> "Of course, there is a lot of erosion! Because that is all hills, the water can't be collected, and it goes on pouring, and because it purs on the same point, to the lowest site, so it arrives at an area, and it drags and drags and goes on carving and carving! Me, for example, my field, I have lost one field because the gully has carved it. A little field, but the gully slowly goes carving it. And the soil goes on falling because it is a sandy soil, very strange, loose… And you can't come close, I mean you can't go to the border, because there are slopes where you have three or four meters. I mean, you always leave… Chasms are created… I don't like it! *La Bardena*…" (4CT)
> "It is a very arid soil with a lot of salt. When we go, you will see, I also think that with no-tillage you improve the soil. Because we, me, with all the straw and everything, I spread it and leave it. So I think it improves a lot. Because there is a lot of salt, saline soil, and it improves a lot by doing no-tillage, there is less erosion… because here, I don't know if you know this place, but there is a lot of wind, so if you have turned the soil, it takes it all!" (4NT)

Additionally, in this more arid region, water was crucial. No-tillage is often related to higher water retention capabilities. Consequently, no-tillage farmers saw their practice as increasing water retention and having more control over seed placement, resulting in being able to secure crop establishment with low rainfall, while their conventional tillage neighbours did not. On the contrary, conventional farmers saw their own practice as increasing infiltration.

> "I think so, yes. I go from the basis of: if you turn the soil and takes out the moisture, then the moisture, if you haven't turned it, will still be there, isn't it? Moreover, no-tillage has the advantage of, because you place much better the seed in the soil, me with no-tillage, if it rains 15 litres, it is enough for [crop] emergence. Whereas, with conventional ploughing, because the soil has no moisture, it takes it itself. […] it has to rain 30 litres or more. […]" (4NT)

When adopting no-tillage, relationships between actors in the farming actor-network transitioned and changed. For example, by maintaining crop residues, surface soil temperature, compared to conventional tillage, changed. Specifically, no-tillage regulated soil temperature avoiding abrupt variations. This involved slower heating of the soil after winter. This, in turn, had an impact on germination. In response to these new tensions, 5NT explained that farmers had to adapt the seeding times when adopting no-tillage.

> "[…] With traditional plough, it gets cold and warm very quickly, and with conservation agriculture, so to say it, regulates a bit more the abrupt changes that there are. I think that is good, but you also have to understand the crops, don't you? For example, if you are going to grow a maize with no-tillage, because it [the soil] is a bit colder coming from winter and because it takes longer to warm up, then the logical thing to do would be to

> wait a bit the maize seeding so that the land, the soil, takes the right temperature and the crop can germinate. I mean, compared with conventional tillage, it takes a bit longer to warm up. And some people didn't know that, and had crop emergence problems, because of that, because the soil hadn't enough temperature for the seeds to germinate well." (5NT)

A major tension in all farming actor-networks was soil compaction. The fear of soil compaction restrained farmers from entering the field on moist soil conditions. A symbol of good stewardship was being patient. Nonetheless, that was not an easy exercise, as farmers always had the uncertainty of future weather and field conditions plus the need to perform field operations to secure enough time for crop development and obtaining a yield even if it would not be the highest.

No-tillage farmers might have had a narrower window in the fields' moisture conditions to enter and do the field operations. This was because their wheel marks stayed longer (were not ploughed out) and had long term negative consequences on crop development. Indeed, soil compaction was the major farm problem for some of the no-tillage farmers.

> "The major problems… For me, I think it's compaction. […] I would say, maybe in my case, soil compaction. In the end, you work with heavy machinery. This is an area where sometimes you have to enter the field when it is moist. That can be a problem that I see it is more difficult to control, isn't it? To manage… Because the other, in terms of weeds, diseases, pests, I don't have anything that the others don't." (2NT)

The ways this compaction tension was alleviated in no-tillage fields differed across farming actor-networks. On fields where no-tillage was adopted as a tool or as a technological package, their flexibility included strategic tillage, which also solved issues related to weed management. Strategic tillage could be applied as a tool, when assessed appropriate according to soil conditions, or could be directly integrated into farm long-term rotation plans as 4NT was doing. The latter was seen on those farms that adopted no-tillage as a technological package, and other technological solutions (e.g. herbicides, strategic tillage) were applied to maintain farmers' domain over other actors roles.

> "[…] By doing this kind of rotation, every five years I break them, I mean, I do conventional tillage on the field, on each field, I mean with the vertical system, not with the plough but with a subsoiler.[…] With the vertical system, I mean a chisel or a subsoiler." (4NT)

However, as seen before, those farmers who had adopted no-tillage as a system were reluctant to use 'external' inputs and focused on enhancing soils' 'natural' structuring capabilities. For them, soils had a natural structure, favourable to soils productive and ecological roles, that could be recovered from agricultural impact through conservation agriculture practices.

> "But it isn't easy; it is easier to enter with the subsoiler. Clearly, you pass the subsoiler, and that's it! […] No, but you have temptations sometimes to try, isn't it? I am going to try… but I don't want to. I don't know why, I mean, I refuse! I don't think it is a solution

> either. Maybe it would create a placebo effect, an effect that at that moment, the problem might get solved, but then, after a year or two, the same happens again. If I had to start with a system, maybe I would start with that one, and then I would plan the crops and so on. But now… I don't see it; I compare it with my peers, isn't it?" (2NT)

Consequently, those farmers were more likely to experiment with rotations and cover crops to improve, among others, soil compaction. The idea of cover crops was to include a variety of crops with different behaviour and root systems that helped to alleviate soil compaction. Having live roots in the soil became very important to improve overall soil fertility. For some farmers, those relations led to change other actors' roles in the farming actor-network such as 'weed' into 'spontaneous vegetation'. However, these roles were still dependent on the relationships with crop development. Cover crops overall involved more investment (in the form of time, money, knowledge), and therefore often seen as a higher risk than rotations. Therefore, farmers enrolled CAP's benefits from greening areas and used marginal land to experiment with those new practices to gain knowledge and reduce risks before implementing the practice on their whole farm (which was not the case yet in any of the farms at the moment of the interviews).

> "Well, types of roots, I would say, even more: types of plants with different behaviour. Thus, in winter, the idea is to rotate with crops, like rapeseed, vetch, beans, cereals… and then in summer, then I try to leave spontaneous herbs. In a lot of places, people… my fields are easily recognisable! And then, most of all, when September comes, that people start to plough, my fields are full of vegetation, of any kind! But you have to know if that vegetation is going to affect you or not, on the crop you are going to grow. If it is going to die by itself, or if you have to kill it… it is different! And the idea is maybe not so much rotating between different species that have different root systems, and then that there should be roots the majority of the year, that the soil isn't nacked, well, not nacked but without living vegetation, functional, isn't it?" (2NT)

On the contrary, conventional tillage farmers saw ploughing or even subsoiling as a tool, among others. Subsoiling was not a routine practice for some farmers, not even the plough and tended to do minimum-tillage. Moreover, also conventional farmers felt proud of having deep roots in their fields as a symbol of good stewardship.

> "Subsoiling, well I have done it very few times, normally [it is] more [about] the pride of roots being there… […] I haven't done, no, I haven't. Maybe I should, in some of them [fields], I was thinking to do it this year, […] on very hard soils. […]". (2CT)

In this section, by applying ANT, I examined in detail the roles that soils play in farming actor-networks, co-constructing paths leading to no-tillage adoption. First, I discussed agriculture's impact on soils and its relationship with soils' as resources and farmers' land stewardship, which created tensions when land ownership was shared or rotated. Then, I focused on soils chemical management, which distinguished productive from marginal land, the latter being less worked and fertilised but where experimental practices took place, such as rotation and cover crops. Furthermore, I discussed the importance of toxic chemicals in the adoption of no-tillage, particularly how glyphosate residues could be a barrier and salt content improved through no-tillage. Then, I discussed soil biological properties management, which was central for farmers who had adopted no-tillage as a system. To boost soil biology, they applied crop residues, whereas in conventional tillage farming actor-networks crop residues were sources of pests and diseases. I finished the section discussing physical soil properties management, in particular the examination of field conditions for the timing of field operations and selection of tools, including no-tillage as a tool. I also approach the controversies around water relation with tillage management in semi-arid conditions. Finally, I discuss the self-structuring capability of life soils, which was boosted through cover crops and rotations by farmers who had adopted no-tillage as a system, whereas those who had adopted no-tillage as a technological package recurred to strategic tillage to quickly alleviate soil compaction.

5.4. How British farmers account for soils

In this section, I discuss soils' roles in British farming actor-networks, as build through their relations with human and non-human actors, particularly farmers. I start the section by discussing how soils were classified and assessed by enrolling relevant soil properties. In the UK, soils' classification and assessment were based on texture and workability, distinguishing 'light' and 'heavy' soils. Moreover, workability was greatly influenced by soils' dynamism and relation with the weather. Then, I highlight soils' role as a historical product. I finish the section by following the circulation of soil knowledges and discussing how this further co-constructed soils' multiple roles.

5.4.1. Soil classification and assessment

Soils were enrolled in the British farming actor-networks as diverse and dynamic actors. Soils' properties, dynamism and variability determined field operations and their timing to not compromise crop development and yield. Therefore, farmers had to engage with soils and adjust the farming actor-network configurations to maintain soils' enrolment for productive purposes.

> "So you're going to have, with different soil types, you're going to have different conditions that you're dealing with. Sometimes, it might be extremely dry and hard on sandy land or on heavy land, and sometimes it might be extremely wet, sometimes it might be late in the season when you're working with. There are all sorts of permutations." (10CT)

Farmers classified and assessed soils according to the dominant soil properties, which were particle size (sand, silt, clay) and workability. By working their farms, farmers had experienced soil diversity based on the properties that mattered the most to them and their farming actor-networks. Soils' heterogeneity was high, with different soil *'patches'* in one field. Besides particle size, farmers identified organic materials to classify peat soils, whereas other soil properties, such as colour, enriched descriptions but were not classifiers. Some farmers referred to technoscientific soil classification systems, which were also based on soil texture and drainage, therefore supporting each other.

> "Yeah. So we have land, including here at home, we go from the lower sand through to quite heavy clay, clay loam with a little bit of silt in places. We cope with everything including in the same field quite often, blow away sand at one end or light sand at one end and clay at the other." (10NT)
> "There are Milton series. There are mostly sandy-loam in gravel, very, very free draining and a bit challenging on a dry year. But I mean we're on easy working soils." (8CT)

Soils' workability assessment was expressed in terms of *'light'* and *'heavy'* soils and related to soil texture. Workability has previously been identified as an important property for local soil classifications and assessments internationally (Talawar & Rhoades, 1998) and in the UK (Stoate *et al.*, 2019). Usually, 'light' soils were related to coarser textures and ease to work to prepare a seedbed, while 'heavy' soils had high clay content, as Stoate et al. (2019) found as well. Interestingly, in this research, farmers also referred to 'heavy sands' that were difficult to farm (presumably with high clay content). Furthermore, 'heavy clays' associated with lower drainage and higher compaction, hampering the functioning of artificial drainage systems and favouring the expansion of the dreaded black grass and slugs. Being able to establish crops on those difficult 'heavy' soils was challenging but was often rewarded with high yields. Importantly, accomplishing crop establishment on 'heavy' soils was a symbol of being a good farmer, able to overcome the challenges.

> "Every field varies. There is strong heavy work in some parts of the field. And the silt wopp in another. The variation is… it does really, really vary […]." (9CT)
> "Just because it is quite heavy clay and is wet, so it's more difficult to use no-till on this soil. That's the problem we have; more black-grass as well; more slugs; it's just more difficult in general." (8NT)

Clays were further classified as having magnesium or calcium, properties that could increase their difficulty or ease to be worked. Indeed, '*magnesium clay'* decreased workability by increasing soils' stickiness when moist and hardness when dry, while calcium acted the opposite way, loosening soils and improving workability.

Figure 45. Soil surface during winter.

Moreover, in the British farming actor-networks, soils' dynamism was strongly related to climate and seasonality. Thus, lighter soils were easier to work but faced drought problems during the summer. Soils' dynamism was defined by soils' relation with the weather (temperature and rain). Consequently, soil properties that interfered in that relation, such as sand and stone fractions increasing drainage, became important.

> "[…] We have the southern half, which is lighter sand, lighter land and most years we run out of water on this land. So, we're severely limited by the water, but you know it's quite easy to work land; so, it's easy to no-till. And then we have the northern half of the farm, which gets progressively more clay, and so we tend to get higher yields from that; […]. But in a wack year, we can get higher yields on the lighter land. It's all chalk subsoil, so the lowest pH we have—I think is 7.9 going to 8 and a half very high calcium soils; so even the clays are relatively easy to work because of the high calcium." (8NT)

5.4.2. Soils as historical products and agriculture's impact

A common notion across British farming actor-networks was that soils had a history based on soil formation processes and land use. Sometimes farmers' understanding of soils' formation was informed by technoscientific knowledge; others were based on experiential knowledge (e.g. 9CT comment). Additionally, and importantly, farmers related human history of land use to soils' agency. For example, 7CT explained how 'light' soils at the slopes had been farmed for a long time, while 'heavy' soil at the top of the hills had not, because their heavier characteristics made them more difficult to work, especially in the past with horsepower. In this sense, farmers acknowledged soils had a historical agency that, if not determining, at least co-constructed human fate (Foltz, 2003).

> "[…] when you look across the field surface, you'll see some lower surfaces; they're only low by very, very, marginal, but […] let the water in from the river carrying the silt. And it built it up, from the silt from the river over the top of the peat […]. These lower places, where the water stood longer, and it deposited the smaller particles making it to heavier land" (9CT)
> "It's on the right side, and it's got a right aspect for the Sun, and it's actually a little bit lighter than the land at the very top of the hill, which is a much heavier clay. It is a much more… I was going to say clay from glaciation. It is much heavier soil and, traditionally, much more difficult to work. Our soils would have been able to be worked by horses. The soil above is too heavy for that. So it hasn't been in cultivation as long as ours." (7CT)

British farmers had a great awareness of the historical alteration of nature through land use, and thus, human impact on soils. The combination of non-human and human formation and transformation of soils made them historical products. Moreover, due to the relationship between soils and the rest of the farms, farmers also recognised that the impact on soils had wider repercussions on the farm, yield and the environment. However, farmers endorsed that different farming practices had different effects on soils and that it was possible to create positive impacts. Certainly, in these farming actor-networks soils acquired a role as historical products, the result of the geological history from which they stemmed, but this was not static but constantly reshaped by many human impacts (Swidler, 2009). Because soils had this role as historical products and were not given nor static, improving their family farms was a motivation for many farmers to do their job.

> "We've got a largely unnatural landscape in the UK. There's very little of it that hasn't had human impact. So human impact has modified the catchments […]. " (10CT)
> "The things that are attracted to me to no-till, soil health. Because of sustainability going forward. I want to leave my farm in a better condition than I inherited it if my boys want to farm. […]" (9NT)

The British farmers I interviewed accused modern agriculture of losing bonds with soils and climate. Instead, modern agriculture followed a productivist paradigm, relying on inputs from farming industries (agri-businesses, machinery manufacturers, etc.). Because of those inputs, soils and climate had lost their traditional dominant roles, which had determined farming practices in the past. Thus, farmers linked modern agriculture to the idea of reason (and technology) being able to solve all problems, but its disconnection from nature and its local characteristics leads to environmental crisis (Foltz, 2003). Indeed, modern agricultures' dominance over farming practices was at the cost of breaking the bonds with those non-human actors, compromising the environment and farms' productivity.

> “Yeah, basically ignore what the world is saying. Basically, farming is ruled by your soils and the weather. Not by the calendar, which conventional farming is. They are only marching spring barely, no matter what the soil moisture or soil temperature are. Trying to establish spring barely. No soil is too cold, too wet.” (10NT)

On the contrary, the interviewed farmers constantly re-build their ties with soils. In some cases, the bond was related to the traditional attentiveness of field conditions and knowledge about soils’ responses to practices. However, this attentiveness was sometimes lost when working with contractors because they did not have the time nor the interest to change their plans according to field needs (e.g. soil ‘patches’ requiring more field operations, but contractors would limit their work to the previously agreed terms). In other cases, the bond between soils and farmers was strengthened due to soil biology and soil health. Indeed, some farmers developed an interest in those soil properties that motivated their farming and ensured soils’ enrolment in the farming actor-networks.

> “Well, I think the soil biology side of it I find pretty fascinating. Yeah, I do. I do enjoy that. Yeah, I mean, it’s a very tiny little world. I mean, how many people in the world can [01:34:00 Inaudible] soils? I mean, very, very few people do. You know you can’t talk about soil to your friends. They’ll just suddenly go completely mad. That’s a bit of what I do enjoy. I do very much enjoy that. Growing the crops, I don’t enjoy as much as the stuff I do with the soil. Growing a crop and getting a good result I do like.” (7NT)

5.4.3. Soil knowledges circulation

UK farmers based their soils’ knowledge mainly on their experience working their land, but some also examined their soils in more detail. Working the land provided a spatial knowledge about soils’ distribution, but also a temporal variability according to which soils responded differently to particular weather conditions. In addition to working their lands, many farmers monitored their soils with a spade. They took advantage of the close proximity to the soils to use their senses to assess soil health by looking at it and smelling it. The properties that they paid attention to were general soil structure and some evidence of soil life.

> “Just experience, really. We have had some testing done, but it’s… Since we have been farming here for a long time, we know what soils do well in what years. It’s pretty obvious when you go and spend time in [the fields] what type of soil they are. […] When you spend the whole year with a field, you can see… If it’s a dry year: this area is bad, or this area is good or whatever. So, you get ideas like that as well. I’m just saying over the course of years; you can see the trends as to what happens in a particular area in a particular year.” (8NT)

Farmers drew on different knowledge sources to assess their soils and build their abstract ideal soils. Thus, farmers who had travelled to visit other farms around the World took those experiences to develop their ideal soils. Many farmers had visited and learned about soils internationally, sometimes as part of a research project, as a consequence of their relationship with an agri-business or machinery manufacturer, or as a private initiative. With the farmers, these knowledges and ideas migrated, being translated as they encountered different local representations (Livingstone, 2003). Additionally, to develop their ideal soils, farmers drew from their soil tests and other technoscientific knowledge inputs by comparing standards or thresholds with their own soils' properties and identifying their deficiencies.

> "My ideal soil will be, if I could go anywhere in the world, it would either be a black soil from Ukraine…. or some soils in Iowa were quite beautiful, […] Not too much clay, not too much sand. Yeah, just a nice balance, all high organic matter, really. That's another thing, that was always nice to have, potash releasing clay, that would be better than magnesium clay" (9NT)

Farmers added to the various sources of soil knowledges the external technoscientific information about soil properties and soil formation. Indeed, in farming actor-networks, those soil knowledges supported different practices as long as the bonds with the farmers were maintained. In other words, external information co-constructed meanings of soils, practices and impact in farming actor-networks while this knowledge proved to be true locally, adding bits of information to complete the farming experiences.

Soil tests were mainly used to monitor nutrient content and plan fertilisation accordingly, although some farmers were developing an interest in precision farming. When hiring agronomists, they were responsible for designing the fertilisation plans based on those occasional soil tests and other information such as straw and manure additions and did the calculations assisted by computer programs. Moreover, some farmers were getting interested in the spatial distribution of soil properties to adapt farming operations to them. Thus, some farmers had maps of their soils per field, with the intention to adjust automated machinery with integrated GPS to perform fertilisation or tillage according to the soil properties.

> "We're always digging and smelling. We have to test every three to five years. We've only basics on our system. But just experience, I guess, a lot of it. We soil test to know our nutrition requirements. That's simple as it is." (9NT)

Some farmers were interested in monitoring their soil health but were critical of the suitability of the available tests. Particularly, farmers questioned the adequacy of tests performed in one moment in time and how that related to nutrient cycles, organic matter breakdown, and overall soil dynamism and crop growing cycles.

> "[…] a lot of the soil tests are not very good, we know that. […]. Yeah, the organic matter test doesn't give you the difference between, you know, labile and stable organic matter content, the environmental content that is recycling through the soil biology and the

organic matter content that's to be recycled. […]. And you know the test on phosphates and potassium levels and things; I mean they're just measuring the available phosphate; they were not measuring all of it. […] I mean, I'm just guessing, but 95 per cent of it is completely stable, and you're not going to get it. […] I mean, we're more interested in how do you get […] to that stuff that isn't available? […] what's the mechanism that releases that to us?" (7NT)

Some farmers were interested in organic matter and biological indexes in soil tests to assess soil health. Nonetheless, these tests were not done systematically to account for soil health on the farm, but anecdotally to assess the impact of particular practices or products they were experimenting with due to the high costs of these tests.

> "It's just being brave enough to experiment. […] soil biology assessment is quite expensive, and I've only had this one done. But if you look [he shows soil tests results]: this is the active bacteria, this level high; active fungi, it's just into the high; […] that's the ratio, nematodes… I mean, it gets more and more complicated. I have seen tests from other farms, and there are no fungi at all; it's just all bacteria." (6NT)

Indeed, farmers had some experience with some experiments focusing on soils, either personally developed or as part of on-farm research trials. When experimenting on their own, farmers assessed the impact on soils with a 'learning by doing' approach, and the criterion was if *'it worked'*. Therefore, even if not recorded quantitatively nor distinguishing all factors, those experiments validated practices within particular farming actor-network configurations, included farmers' satisfaction and enhanced farmers' relationships with soils. On the contrary, participation in on-farm research trials could not always have the same beneficial results. Through their bonds with agri-businesses, machinery manufacturers or research centres, farmers would participate in on-farm field trials with a focus on soils or soil health. The scientific design, and its consequences on field operations and the amount of data produced, could become unrealistic and overwhelming.

> "Yeah, it's just everything that's going on in the soil is just so complicated. We couldn't begin to understand it all, but as farmers, we just observe what happens, and if something works, it works, and we don't question too much." (6NT)
> "At first, we've got the only long term cover crop zero-till trial going on at the moment, which is a five-year trial, and it's basically focused on soil health, soil biology. So it's not scientifically done; it's a kind of farmer trial, but it's quite involved. […] there's so much data that you hardly know what to do with it all. […]." (7NT)

However, farmers recognised the need to continue investigating soils. Indeed, farmers acknowledged the need to better understand soils because these were dominant actors in their farming actor-networks. Farmers were eager to obtain information about soils beyond nutrient content and based on long-term experiments that could inform about changes in soils due to farming practices.

> "We don't know enough about soils. It's a completely… Even farmers are aware… We recognize how ignorant we are about soils. There's so much more investigation that

> needs to be done into soil… because the soil is the very thing we need to produce crops. So we need to know more about it. […]" (7CT)

In the preceding section, I have presented and discussed soils' multiple roles in the British farming actor-networks and how they were co-constructed through their relations. In the UK, soils had a historical agency that had influenced land use, but they were also seen as historical products themselves, in constant change due to land use. Consequently, having a positive impact on soils to improve their farms was important for farmers. Furthermore, soils were classified based on particle size, while their quality was assessed based on workability. Farmers distinguished easy workable 'light' soils from difficult 'heavy' soils, which moreover were related to water excess, compaction, weed and pest proliferation. Soil knowledges were mainly acquired by farmers through working and, sometimes, examining their soils. In addition, on-farm field trial research and international travel experiences co-constructed soils in the farming actor-networks.

5.5. British soils' role in no-tillage adoption paths

In this section, I present British no-tillage adoption paths in which soils were a fundamental link. I do this by identifying chains of actors and analysing their bonds in relation to chemical, biological and physical soil management to discern how they co-construct farming actor-networks and might lead to or prevent no-tillage adoption.

5.5.1. Soil chemical fertility management

Farmers acknowledged that farming mined soils' nutrients. Soils developed from lithological materials, from which they inherited some of their chemical properties. However, soils could show nutrient deficiencies due to their long history of land use and particularly farming, which had mined soils' nutrients through harvesting crops where the nutrients accumulated. To avoid continuing mining soils, some farmers did soil tests to inform their fertilisation plans and return to the soils the nutrients required to sustainably grow crops without exhausting nutrient stocks. Furthermore, some farmers added amendments to correct magnesium levels or acid pH.

> "Some of [the nutrients] are naturally deficient because of the rock from which the soil came from. That's the problem. But it may also be that we in the past have drawn out those nutrients which were… and now we've got a deficiency in developing. And we have to add them back. That's acceptable. I've realized I can recognize that. But that's what the soil test is trying to tell me… if we haven't got them. That's right." (7CT)

However, soil nutrient deficiencies did not directly cause a nutrient deficit in crops. More specifically, crops requirement for nutrients varied through their growing cycles, and soil deficiencies were only noticeable or in need to be fixed when they occurred at the timings when crops required those nutrients.

> "You can see deficiencies in soil, but when they actually ever become deficiencies in plants is another matter because […], it's all whether it's deficient at a particular time when the plant needs it. That's when deficiency is… That's when you see it. […]" (7CT)

On the contrary, some farmers followed a strategy of decreasing interventions. Farmers who had adopted no-tillage as a system believed in soils self-improving properties and their natural capability of sustaining plants. Therefore, for those farmers, the strategy to improve soils' productive role was decreasing intervention. Experiencing positive results following their practices (e.g. a balanced pH) supported their long-term adoption of no-tillage as a system.

Furthermore, soils' self-improving capabilities were based on complex nutrient cycles. Indeed, in addition to the nutrient calculations based on outputs through harvest and inputs through fertilisers (including organic), attention was paid to the unavailable nutrient stocks in soils. Those were made plant available through the action of soil biology. Certainly, nutrient cycles were even more complicated by the enrolment of cover crops (also referred to as '*catch crops'*), which should be catching nitrogen excess and releasing it slowly with organic matter decay. Nonetheless, some no-tillage farmers were experiencing nutrient deficiencies due to the competition of cover crops and the decrease in artificial aeration inducing organic matter decay and nutrient release. The difficulties experienced through applying some conservation practices forced farmers to continue negotiating the enrolment of these conservation actors (e.g. cover crops, soils life, etc.) by changing the farming actor-network configurations.

> "The bacteria that feed on the organic matter actually release the nitrogen, phosphate and all the rest of it. Those group of bacteria, which are working in that oxidised environment on top of the surface […]. So, the more cultivations you do, the more organic matter you […] oxidize. […] So, the more tillage you do, the more nutrients you release and the better your crop does. If you don't do any tillage, you don't release the nutrients. So, you are allegedly in a bad place, which is why zero-till crops can look so poor. So, we have to adjust our nutrients to take that into account. Then, if you use a cover crop as well, you make the situation even worse because the cover crop sucks our nutrients." (7NT)

5.5.2. Soil biological fertility management

Farmers who had adopted no-tillage as a system together with other conservation agriculture principles had enrolled soils in their farming actor-networks as living entities. Indeed, their soil improvement efforts were focused on enhancing soil biology that, in turn, would increase yields.

Rarely, farmers used soil biological tests to assess the farming practices that they were testing on their land.

> "I've always had an interest in soil biology and learning and understanding how that works and using that to get the soil to work even better for me.
> […] I'm quite interested in mycorrhiza fungi and getting them to perform and increase.
> […] I've managed to increase the mycorrhiza levels to really quite large amounts. I get my roots tested to observe how much association we've got with the crops and positions in the rotations, or you know… how it affects it. Just to give me a good understanding of how it operates, really. […] If the soil is better and more alive and feeding the plant, then the plant should be healthier." (6NT)

The tension of soil biology not being enrolled successfully in the farming actor-networks had its causes in the depletion of organic matter. Indeed, organic matter was the actor needed to increase soil biology and obtain higher yields, but because of productivist ways of farming, soils had been denuded of their organic matter. In those farming actor-networks, the efforts were focused on increasing organic matter to boost soil biology.

> "Because the soil biology is not functioning like it used to […] If you look at our organic matter levels, our soil loss and our loss of soil biology, it's just been straight down. You know bigger tractors, more cultivation, more wheat, more oilseed rape… […] The whole thing just been down, straight down, you know? It has transferred soil from being a living, active medium to something that is more akin to hydroponic. […] you just have dirt instead of water.[…] But it can't be the right way, can it?
> […] carbon is the key to what we're trying to do. I'd been very much focussed on sort of the mechanical side of it and not focused enough on the biology sides of it. I started to realise that, actually, the system is driven by carbon. That's what drives it, and the more carbon that we can push into our systems, the better results we had.[…]" (7NT)

Nonetheless, soil organic matter was a relevant actor in both no-tillage and conventional tillage farming actor-networks. Farmers were particularly interested in increasing organic matter contents because it related to soil biology, nutrients, and workability. Organic matter importance showed in farmers' ideal soils. Moreover, it was a soil property that farmers could modify easily and that had a quick response. Therefore, farmers developed strategies to increase organic matter and monitored if the practices were achieving the desired effects.

> "Increasing organic matter is our main thing. […] That's our main driver, and that helps infiltration and workability, so yeah. That's our main thing. There are probably a few things that you can affect easiest, quickest possibly" (9NT)

Figure 46. Straw on the soil surface.

With the increasing importance of the organic matter and further transformations of farming actor-network configurations, the roles of straw had also changed. In a study of the adoption of organic inputs across different agro-ecological zones in Europe, legal prohibition of burning straw in Italy was considered a driver, whereas the management costs of straw incorporation and the loss of income from selling straw were considered as barriers (Hijbeek *et al.*, 2019). Nonetheless, focusing on farming actor-networks and straw roles enables a deeper understanding. Thus, traditionally, British farmers had burned straw. After straw burning was banned, farmers adapted by changing farming actor-network configurations and bailed straw for their own cattle or sold it for different purposes. Therefore, straw had changed its role from waste to a by-product. In some farming actor-networks, this was still the case; straw was a resource that could be sold. However, with the increasing importance of organic matter, many farming actor-networks, whether no-tillage or conventional tillage, straw was not extracted from the field. In those cases, straw was fresh organic matter and was recycled and incorporated into the soil, although the ways to do this varied between farmers. Incorporating straw caused further tensions, such as creating anaerobic or acid soil conditions and decreasing soils' productivity. Nonetheless, farming actor-networks were arranging new configurations to enrol this organic matter source, either with practices based on technology and machiner (such as straw chopping and spreading, with or without ploughing), or practices based on soil life (leaving straw on the surface to be broken down and integrated into the soil by micro and macro-fauna).

"We took the spring barley because I do a lot of straw, and so the spring barley straw is with more money. […] Probably over 100 pounds, 100 pounds an acre straw off of it, as well. […] But I feel it's everybody, if everybody chopped all the straw, there would be nothing for livestock." (9CT)

"And then I was also cultivating after the wheat. The idea was to try to incorporate the straw at that time after they stopped us burning the straw, but mixing the straw in the soil didn't work very well because once it got wet, it all started breaking down, and you get all acids produced from the breakdown of the straw, which affects the next crop. So someday, I thought it would be much better if we left the straw on the surface and then just put the seed in the soil underneath." (6NT)

In some conventional farming actor-networks, the potential of no-tillage to increase soil organic matter was questioned. More specifically, there were doubts about no-tillage being more capable of increasing organic matter contents compared to conventional tillage with straw incorporation, the location of organic matter in the soil profile under no-tillage, and overall benefits of organic matter, soil biology, and soil health in relation to growing crops.

"What is interesting about the no-till system is this discussion about soil organic matter. Are we losing muscle, and can we build soil organic matter? I'm not sure whether you can build soil organic matter with no-till farming. You may be able to stop it disappearing away, but I'm not convinced that actually, you can't build soil organic matter in a conventional system if you're all incorporating the straw all the time because you're putting organic matter back in.

We also have to ask what good organic matter is doing and where is the organic matter in the soil? Is the organic matter at the top or […] where is it?

[…] What is a healthy soil, and what is the best soil to grow, the media… and how can we improve our soils? Is no-till farming improving the soils, or is it just improving the top section, and nothing's happening underneath? […]" (7CT)

In contrast, farmers who had adopted no-tillage as a system in relation to conservation agriculture wanted to enhance soil biology under the premise that this would support farming. This belief was sustained by theories of ecological succession, in which soil biology (monitored by the fungi: bacteria ratio) developed in harmony with the above growing vegetation towards the climax system, which was a forest whose soil biology was predominantly fungi. However, all farming impacts were leading to more bacterial soils. With this knowledge, those no-tillage farmers wanted to create a fungi: bacteria ratio that benefited the plants they were growing. The strategy to achieve that was to decrease farming impact by reducing field operations and external inputs. Nonetheless, some farmers experimented with biofertilisers to boost soil biological activity and nutrient release.

"It is trying to get the soil working better and get the system work better. And behind it all, do you understand ecological succession? So we start off down here, and gradually nature keeps moving that way. […] So down here, this is all bacteria in the soil; and up in a forest, it's all fungal and hardly any bacteria. All the different levels of plant species are associated with a different percentage of bacteria to fungi. So […] here are the crops we

> grow; peas and beans, linseed over here, wheat, barley and oats, rape, and then the wheat are over here. So these are the ratio; it is about 95% bacteria and very little fungi. […] Up here, where there are no bacteria, if you got some wheat seeds, they would just not grow in woodland. […] So, ideally, we want our soil to be half and half to suit the crops that we're growing. The trouble with everything farmers do, whether it's cultivations, fertilizers, all the chemicals that we put on, are killing the fungi and making it more bacterial all the time. So it's making the soil reverse of what nature would do." (6NT)

5.5.3. Soil physical fertility management

In contrast with the ploughed fields, no-tillage fields could be perceived as messy. Even farmers who had adopted no-tillage had those bonds to the symbolism of the aesthetics of a neat field representing good farming as occurred to Swiss farmers (Schneider *et al.*, 2010). Certainly, it required a big mindset shift as ploughed land showed farmers' hard work and was the farming community accepted aesthetic. Notwithstanding the criticism and the peer pressure, no-tillage farmers continued their practices, challenging traditional farming symbolism.

> "[…] Because it's a messy way of farming, and my grandfather hates it! If you're a traditional farmer, where you've done things, everything looks nice, and that's what farming… when it was aesthetics. It's hard; it's a very big mind, it's a big mindset, it's a big shift." (9NT)

In farming actor-networks where conventional tillage was used, farmers had to assess field conditions and adapt seedbed preparation operations accordingly. That meant using different tools depending on soil moisture, weed presence, etc. Ingram (2008), based on advisors views, found that in the UK, conventional farmers were performing operations through habits having lost their connection to the land. However, in the present study, conventional farmers examined and responded to field conditions. Additionally, farmers knew the field 'patches' of soils requiring particular work. On the contrary, in farming actor-networks where no-tillage had been adopted as a technological package, the same seeding machine was used in one field operation, equal to all other fields in a 'one solution fits all' approach.

> "No. We used to do it when we were cultivating. We had to do it. Some fields you can plough and press, other fields you can plough and press, but then after that, you have to go back and power harrow it once or twice. In other fields, you have to plough and then power harrow several times. But now, no, it's just all treated just the same. You just drill it with a [machinery manufacturer], and that's it." (10NT)

Moreover, in farming actor-networks in which conventional tillage was used, attention had to be paid to not overwork the soil. Indeed, overworking the soil had opposite results than those aimed to obtain with tillage in that, instead of obtaining a loose till, tillage could create a compacted seedbed. Some machinery designs were more likely to produce these undesirable effects. Thus, farmers had to know their soils and their machines to achieve adequate seedbed.

Figure 47. Ploughed field.

Furthermore, farmers had to adjust their field operations to the right timing. Moist and cold soil conditions, late in the seeding season (November or December) or too early in the Spring, were more susceptible to being overworked, compacted or not providing the right seedbed conditions for crop establishment. Climate and weather influenced soil properties, the possibility to enter the field with heavy machinery or which field operations had to be done. Nonetheless, many conventional tillage farmers were able to adapt to a variety of field conditions through their tools. For example, by performing at once the seedbed preparation and seeding when field conditions allowed it, or by using the plough to '*lift'* the soil, and a few days later, the soil would have dried and warmed up, providing a good seedbed.

> "[…] Because I've watched the weather, it's going to be dry all this week, it's going to be lovely next week. It would be nice for the powerer to be going on Friday and work Saturday, Sunday, right through. So it's three days in front of the drill because it would work the land, it would lift it a bit, we aren't sure if it's dry enough yet, but it would have done it. It would have worked the land, it lifted it a bit, and 3 or 4 days of drying would have warmed the soil up. It would have taken the moisture out of the soil, and it would have warmed the soil up. So I'm going to put the seed in; it will be going better. If the soil is dry, the drill actually runs easier, better. […] You feel you've done a better job putting the seed into that. But if we follow the drill, follow the powerer with the drill, it may well be a little bit on the wet side yet. It all depends […]." (9CT)

Farmers had several strategies to avoid and reduce compaction, besides field operations timing and adaptation to weather. One strategy was to control issues around traffic, such as tire pressure and using guidelines to follow always the same tram lines. Other farmers would periodically use sub-soilers to alleviate compaction when the weather allowed the operation.

> "[…] you also have to be sure of tire pressures, but you're going to get much more problems with compaction if the soils are wet. […] Clay soils get wet later on in the year, and then they're very difficult to deal with. […] where the tram lines are, they always get compacted. […] So you have to have a strategy to be able to break up where the compaction happened from the previous year or to keep your tram lines in the same place, and that's why we use things like guidelines to try and have the tram lines and the track in the same place." (7CT)

On the contrary, in farming actor-networks in which soils were enrolled as life and self-structuring entities, compacted soils and plough pans would disappear with no-tillage. Plough pans were not a consequence of the compaction caused by machinery weight or the force transmitted through the plough, but a consequence of the small particles produced by soil aggregates being disrupted by tillage, which would eluviate through the soil profile and settle at the horizontal line where resistance (structured soil) was found.

> "The problem that we were having was a problem that had to do with soil compaction. I always thought that soil compaction was caused by weight. Just the weight of the machinery or, if not the weight of the machinery, the weight to the tyne operating; you know, sort of the force below the tyne as it went through the ground. […] it was only when I was talking to [soil scientist, consultant] that I sort of realised that the issue is not the weight; it's the fact that you're putting this line of horizontal weakness through the soil. […] So, all the soil aggregates, as they're coming out, they're all settling down the soil profile, and they get to this line of horizontal weakness, and then they all settle out on this line. So, you start to get this hard pan in there; and if you come along the same depth and you do it at the same depth twice, like I used to do […]. So when the zero-till came along, and we started experimenting with not doing any cultivation at all, we found that those problems went away. […]" (7NT)

Having lighter soils, which were easier to work, had a direct relationship with the costs of seedbed preparation. As Jones (2019) found through interviewing farmers from East Midlands, 'light' soils required fewer field operations and, therefore, less petrol consumption. Moreover, 'light' soils had fewer constraints to be worked when compared with 'heavy' soils, as they responded to rain with low water retention, enabling fieldwork in the first place. Thus, where the high investment in machinery constituted an economic barrier to adopt no-tillage, the low costs of seedbed preparation due to having 'light' soils further supported the conventional tillage actor-networks. On the contrary, farming actor-networks with difficult 'heavy' soils had always suffered to create an adequate seedbed. In those cases, no-tillage represented a bigger cost saver, and eventually, an improvement of soils' physical properties by not overworking them or working them in adverse conditions.

> "[…] the soil is very heavy clay and a lot of is quite low lime, below sea level and needs really good drainage to get it to be farmed at all. Because it's heavy clay, it was always very difficult to get a seedbed and get crops established. For Clay, it was always that when it was dry, it dried, baked out, really hard and couldn't break it up or if it was wet, it was just too wet to work, and I just realised that the less I did to the soil, the better it was really. So, over a few years, I evolved a system of direct tilling or no-till system where I've just drill crops straight into the soil undisturbed; and that's just been the best thing I've ever done, really. It just works so much better than the cultivation." (6NT)

Sugar beets and potatoes were important crops financially, co-constructing farming actor-network configurations that enabled growing them. However, growing sugar beets and potatoes had consequences on soil physical quality. Field preparations and harvesting those crops deteriorated soil structure, as 8CT explained.

> "[…] The only compaction we get is soil damages after the sugar beet, depending on when they're lifted out, what soil conditions they are like. That's the only soil damage we get. I mean, we have suffered in the past. We used to let some potato ground, and we found that they did so much damage to the soil structure that it really wasn't worth it. It would take 3 or 4 years to get the soil back into a good soil structure. It's a very stony soil, and when they used to grow these potatoes, I used to destone it, and it used to just lose all its structure […]." (8CT)

In summary, in this section, I applied ANT to deepen into the roles and relations between soils, farmers and the wider farming actor-networks to understand how these co-constructed soil management. I started by exploring soil chemical properties, particularly soil nutrients and how their stocks had to be replenished through fertilisation or unlocked and made plant available by soil biology. Then, I continued the debate around how no-tillage farmers intended to boost soil biology through less disruption, cover crops and organic matter additions. However, I highlighted that in the UK, organic matter had become a relevant actor in both conventional and no-tillage farming actor-networks, and this influenced the changing roles of straw. However, some critiques and knowledge gaps about the complex relationships remained, questioning no-tillage superior capability to increase soil organic carbon. I finished the section by focusing on soil physical management, including the role of compaction, the strategies to handle it, and how 'heavy clays' management involved a high economic cost that could be alleviated through no-tillage. Moreover, I presented conventional tillage farmers' connection to soils and their assessment to perform field operations with the right tools, which was not present in the 'one solution fits all' approach taken when no-tillage was adopted as a technological package.

5.6. Comparison of the multiple soils in farming actor-networks: Spanish and British cases

Using the frame of ANT, Law and Mol (2008) proposed an understanding of a sheep as multiple, characterised by different agencies resulting from different practices (actor-networks) in which the sheep was involved in a particular place and time (Cumbria 2001). I argue that because farming is constituted of multiple practices, in addition to the dynamic character of actor-networks and the knowledge circulation between co-existing actor-networks, soils in the farming actor-networks can be understood as multiple, and their multiplicity, on some occasions, created tensions and change in farm management.

Through the analysis of soils' roles in farming actor-networks, it was possible to follow how soils themselves became actor-networks co-constructed by human and non-human actors, a hybrid between human and non-human, an actor-network itself. This is similar to how Jones and Cloke (2008) describe trees, Law and Mol (2008) describe sheep, or Kortelainen (1999) explains the co-construction of a river in Finland as the outcome of physical processes articulated by non-human actors and human influence on the river properties and in constructing cultural meanings for the river.

General trends across farming actor-networks were the entanglement between soils and land, which underpinned farmers' land stewardship and extended it to soils as part of their farms. Previous findings linked farm legacy with the adoption of pro-environmental practices (Marr & Howley, 2019), and in this study, it appeared in both no-tillage and conventional tillage farms and in both countries, although in Spain, it was more accentuated because of language and the use of the word '*tierra*' blurring the boundaries between soils and land.

Farmers' soil knowledges were co-constructed by their lived experience of the soil and sharing information in the farming community. Those relations with soils and community developed in local soil descriptions, classifications and soil quality assessments. In Spain, soil quality assessment was based mainly on yield and workability, whereas in the UK, it was based almost entirely on workability. In Spain, embedded in soils' productivity, there was a notion of soils' intrinsic yielding limitations, which could not be overruled by technological solutions. In the UK, there was an interest to re-connect with soils after modern agriculture overruled the dominance of soils and climate at high environmental and economic costs. Moreover, in both countries, soils were dynamic entities and, as such, presented changing agencies according to their relations with other human and non-human actors, which challenged traditional, local and experiential knowledges by adopting non-expected roles when farming actor-network configurations varied.

Soils in the farming actor-networks were enrolled in a subordinated role, and farmers were their spokespersons, having the authority to speak on behalf of them. To trust other sources of information, for example, technoscientific knowledges, actors representing those first had to build bonds with local farm actors, human and non-human, which contextualised their knowledges and enabled knowledge exchange.

In Spain, besides farmers' interest in soils' productive role and their acknowledgement of different soils with distinguishing and limiting properties, farmers were reluctant to pay for soil tests. Investment in the form of money, knowledge and time was only worth it for soils that successfully enrolled in their productive role, while the other soils were classified as marginal land and received less attention from farmers and the broader farming actor-networks.

Nonetheless, it was on those marginalised soils where other soil roles dominated. Examples were: soils' cultural roles in the Bardenas Reales as a symbolism of community farming. Or social roles of inherited land from farming families which was not enrolled in land classification and consolidation, maintaining small and ill-shaped fields that did not align with the 'professional farming' landscape. Interestingly, in Spain, marginal land was also the place for soils' experimental roles, where different practices could be tested without endangering the economic sustainability of the farm by not risking the high yield potentials from the 'good' productive soils. Those practices were partly motivated to obtain CAP subsidies, but not only, for example, farmers who adopted no-tillage as a system experimented with cover crops on marginal land or conventional tillage farmers also experimented with no-tillage as a tool.

In the UK, soils' role as a historical product, formed by geomorphological processes but also shaped by land use, translated into a greater concern of modern agriculture as damaging soils and a willingness to reverse the impact. Soil tests, even if not systematically taken, were an extended practice to monitor available nutrients and other chemical properties and inform agronomists and farmers to plan fertilisation and amendments accordingly. However, farmers had an interest beyond those chemical soil properties, particularly in organic matter, and increasingly in soil biology. Nonetheless, testing those soil properties was too expensive, and the enrolment of those actors, together with cover crops, further increased complexity in the relations to the point that existing soil knowledge was either overwhelming or not satisfactory.

In the UK, the bond with soils was made and re-made by farmers. Conventional tillage farmers applied traditional attentiveness to soils and fields in order to select adequate tools and perform field operations without overworking the soil nor creating compaction. Farmers who had adopted no-tillage as a system experimented with different conservation practices to add organic matter and boost soil biology, finding in those actors a new motivation for farming. On the contrary, farmers who had adopted no-tillage as a technological practice, while interested in soils and soil improvement to sustain productivity, were using the same technological solution (no-tillage drill) equally on all fields, stunting their connection with soils.

Regarding how different farming actor-networks enacted different soil roles in both countries, it was possible to discern soils as lively, relational and natural entities in the networks that also enacted no-tillage as a system, aligned with the conservation agriculture paradigm. Soils were endowed with life which became essential to recover a theoretical natural balance in which soils productive and ecological roles aligned. Therefore, farmers abandoned practices that were contrary to enabling soils, and particularly soils' life, to recover their natural balanced state. By doing this, farmers broke some bonds and received considerable criticism, both increasing the tension and destabilising pre-existing farming actor-networks.

At the same time, newly emerged roles for soils and no-tillage had to build new bonds to sustain their existence. These came in the form of the adoption of several conservation practices that related and co-constructed each other. Indeed, in Spain, these farmers were the ones adopting crop residue retention on the surface, rotation, or cover crops. Whereas in the UK, the co-existence of farming actor-network and their constant interaction led to some conventional tillage farmers adopting cover crops, rotations and crop residue retention, mainly to increase organic matter, which was highly valued due to increasing nutrient contents, biological activity and workability. Nonetheless, in the no-tillage farming actor-networks, new bonds were also built through knowledge circulation between wider farming community neighbours and other knowledge sources, including technoscientific knowledge sources and the internet.

Another tension between opposite interests appeared in relation to soils enacted as resources. Specifically, the tension was between farmers as resource users when soils were enacted as an economic resource, opposite to farmers as stewards when soils were enacted as land. Consequently, in forms of land ownership in which soil use was shared or rotated (such as communal land in Spain or rented land in both countries), the tension could end in negligence of soil stewardship in favour of short term productivity. Furthermore, in the UK, this tension also related to growing high income, namely sugar beet and potato, either grown by the farmers themselves or farmers renting their land out for those purposes. In the latter case, of sugar beet and potato growing, it implied that at least when those crops were grown in rotation, some form of tillage was performed.

Tensions regarding soils' successful enrolment as yield producers or easy working media could appear due to non-human actors. For example, in Spain, crop rotation was widely enacted as improving soils' yielding role by enhancing soil chemical properties, particularly their nitrogen content. Nonetheless, in practice, rotation depended on non-human actors such as suitable weather for legume growth, and in the cases in which those were not successfully enrolled in the farming actor-networks rotation was abandoned.

Additionally, other actors, human and non-human, also presented multiple, dynamic and shifting roles, which in relation to soils and farmers shaped different network configurations. For example, no-tillage dependence on total herbicide use (glyphosate) was widely accepted. Nonetheless, this became a barrier for no-tillage adoption in Spain, mainly by conventional tillage environmentalist farmers when herbicides were enacted as toxic-agrochemicals compromising soils' productive (as producing nutritious food) and ecological roles, while herbicide reliance was a bond that sustained no-tillage when herbicides were enrolled as necessary phytosanitary treatments. Other examples were crop residues, or fresh organic matter, which in Spanish conventional tillage farming actor-networks had the dominant role as a source of pests and diseases, whereas, in no-tillage as a system, they were enrolled as actors that contributed to soils' capabilities to produce yields and protect ecosystems. Straw in the UK also had multiple roles depending on farming actor-network configurations, mainly as by-products that could be bailed and sold or as fresh organic matter, which in the UK was enacted in both no-tillage and conventional tillage farming actor-networks.

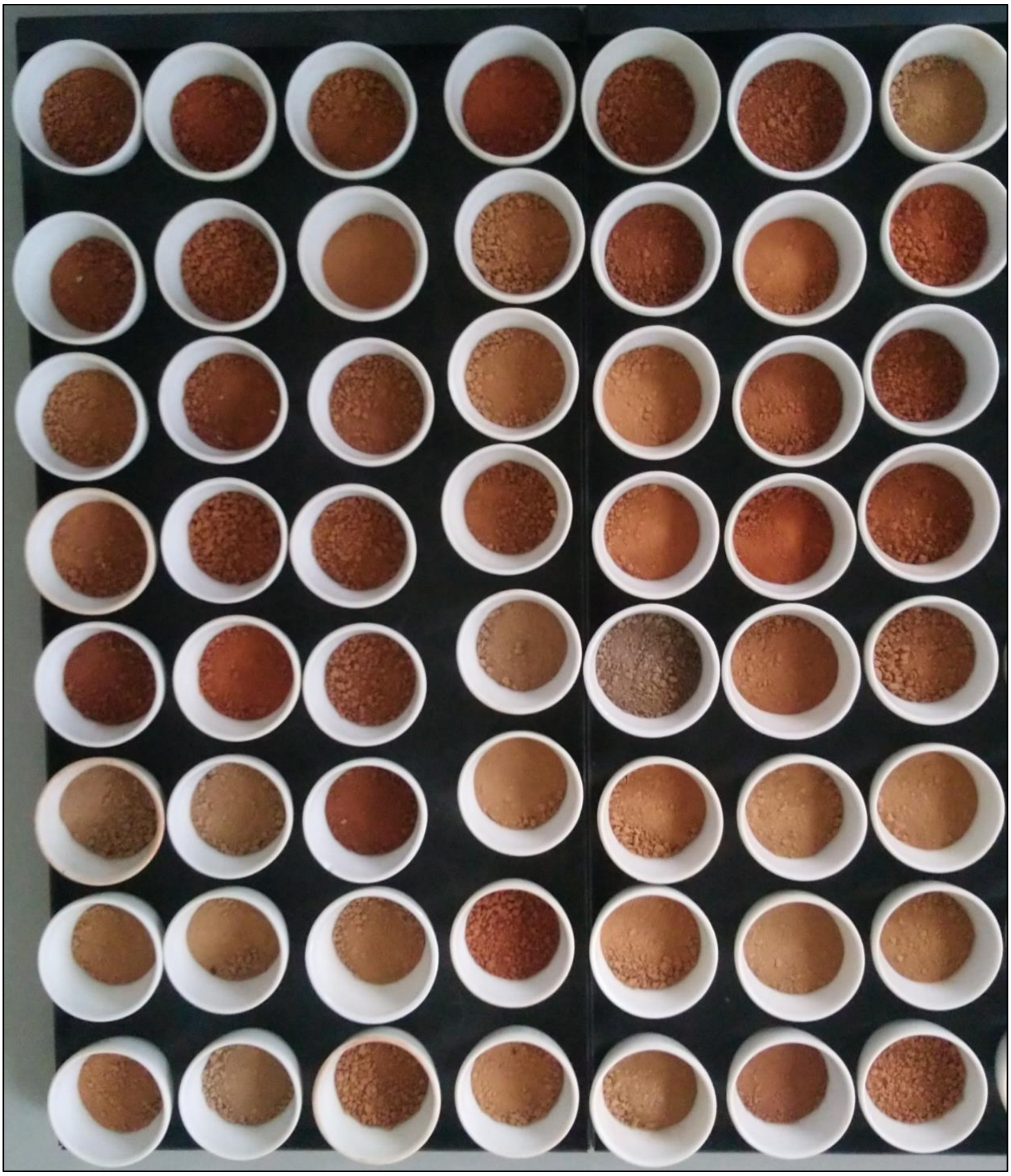
Soil physical conditions on the surface to ensure seed germination and crop establishment, same as non compacted soils to enable crop development, were crucial in all farming actor-networks. The use of the plough or other equipment followed the same patterns in the different farming actor-networks. In conventional tillage farming, actor-networks soils were always in a role in which they were dominated and tamed. Thus, the way to obtain good structure was through selecting the most appropriate tools, including the plough, depending on soils' changing state of workability. Similarly, in no-tillage farming actor-networks in which no-tillage was a tool, the no-tillage drill was only that, a tool that was appropriate for soils' state of workability. Differently, in farming actor-networks in which no-tillage was a system, soils were capable of self-structuring when appropriate conditions were given, and farmers were providing those conditions through no-tillage seeding and other practices. Furthermore, conventional tillage was restricting soils capabilities to self-structure. As an intermediate situation, when no-tillage was adopted as a technological package, soils had the self-structuring capability, but farmers had a stronger need to control the process, which was easier by using tools, agro-chemicals and other technologies.

5.7. Conclusions to the multiple soils and soil paths for no-tillage adoption

- ANT enables an understanding of actors as enacted through relationships and as multiple and made up of human and non-human agencies. ANT made it possible to analyse conventional tillage and no-tillage farming as actor-networks build around farmers and their practices. This has made it possible to draw attention to the co-construction of soils (their roles, values and meanings) and farming practices.
- Soils' role as discrete entities was entangled with soils' role as land, particularly in Spain, by the use of the word *'tierra'*.
- Soils' role as a historical product was dominant in the UK and related to an acknowledgement of modern farming disconnection from soils but jeopardising their existence, which turned into farmers' willingness to re-connect with soils and improve them.
- Soils were diverse and dynamic in both countries. Diverse in the sense that farmers identified different soils spatially, dynamic in the sense that their properties – or even their roles – shifted with farming actor-network configurations, meaning the shifting relations with other human or non-human actors (e.g. weather).
- Soils in Spain were classified according to visual features, while in the UK, the classification was based on particle size and organic materials.
- Soils in Spain were assessed based on their yielding capability, distinguishing 'good' productive from 'bad' marginal land. Nonetheless, soils had productivity limits that could not be overruled by technology nor other inputs. While productive soils were intensively farmed, on marginal land soils adopted other roles, including experimentation with no-tillage and other conservation agriculture practices.
- Soils in the UK were assessed based on workability, distinguishing 'light' from 'heavy' soils, which related to coarse texture and clays, respectively. While 'light' soils were easier to work to establish a seedbed, 'heavy' soils did not only require more work but also related to weed and pest proliferation, compaction, water excess, etc., although once established, produced higher yields. The costs associated with farming 'heavy clays' made it more cost-effective, adopting no-tillage on those soils but easier on 'light' soils.
- Soils became natural, relational living entities in the farming actor-networks that had adopted no-tillage as a system related to the conservation agriculture paradigm. Farmers' interest in soil knowledges that sustained this role was not fully fulfilled with their existing relationships (e.g. expensive soil biology analysis) but sustained through new connections built through the internet. Moreover, in this role, soils were self-improving, and therefore farmers followed a

strategy of decreasing interventions or, in any case, boost soil biology, which was the dominant soil property.

- Soil tests, while performed very rarely in Spain, were a normalised practice in the UK to inform fertilisation plans designed by agronomists or the farmers themselves.
- Crop residues were sources of pests and diseases in Spanish conventional tillage farming actor-networks; by-products in British conventional tillage farming actor-networks that bailed straw and sold it; and sources of valuable fresh organic matter to enrich soils in the rest of farming actor-networks; the latter favoured but not necessarily led to no-tillage adoption.
- Traditional farming included assessing fields conditions to select the most appropriate tool to prepare the seedbed. Occasionally, this included the adoption of no-tillage as a tool. In the UK, this was practised by conventional tillage farmers, while no-tillage farmers, particularly those who had adopted it as a technological package, had a 'one solution fits all' approach.
- Tensions between soils' roles as resources and soils' roles as land (linked to farmers' stewardship role) appeared on communal or rented land and, in the UK when growing potatoes or sugar beets.
- In spite of soils' agency, they were always enrolled in farming actor-networks to be dominated to be productive and workable.



Chapter 6.

The multiple soils II: soils' scientific assessment

Figure 48. Chapter 6 cover photo: soil samples in ceramic crucibles after loss on ignition

6.1. Introduction to the multiple soils II: soils' scientific assessment

In this chapter, I address the research question

- How does no-tillage impact soil physical quality?

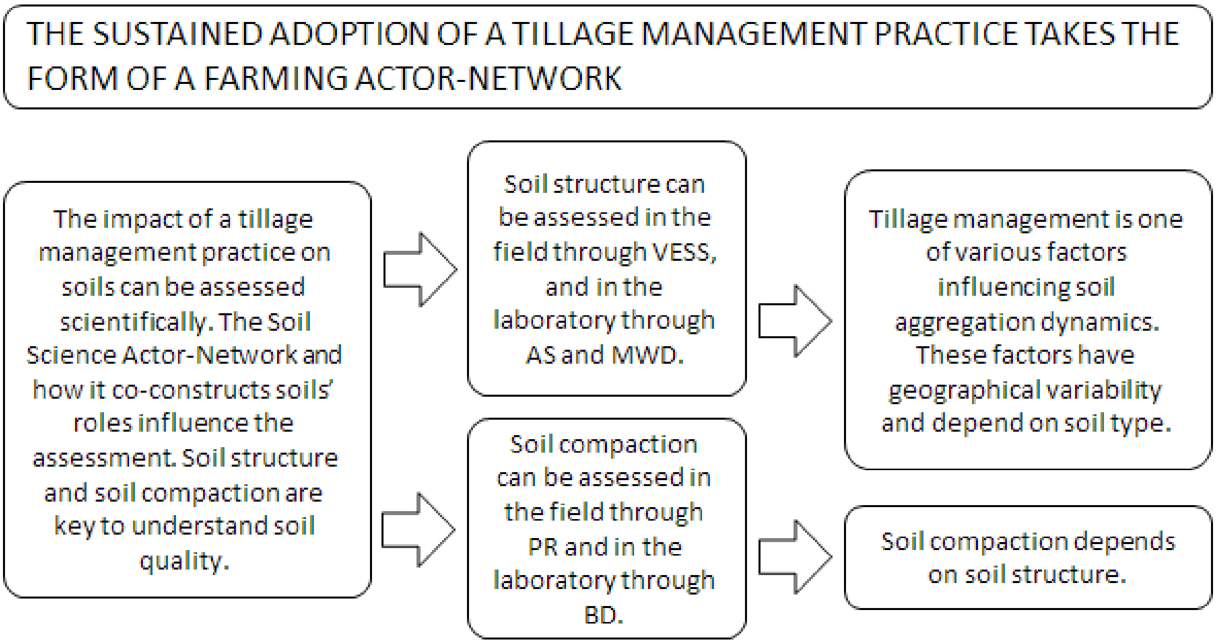


Figure 49. Main arguments to understand the scientific assessment of tillage management on soils. VESS: Visual Evaluation of Soil Structure. AS: Aggregate Stability. MWD: Mean Wide Diameter. PR: Penetration Resistance. BD: Bulk Density.

To answer this question, I have discussed farmers' assessment of tillage management impact on soils in the previous chapter, and now I focus on the scientific assessment of tillage management impact on physical soil properties. The main arguments for the scientific assessment are shown in Figure 49. This assessment is based on on-farm VESS and penetration resistance tests and laboratory results of bulk density, aggregate stability and aggregate size distribution (the latter transformed in mean wide diameter index). Additionally, I analysed other soil properties that act as aggregation or disaggregation agents to investigate how these interplay with tillage management.

Nonetheless, first I situate the researched soils in the wider biogeographical and regional context by describing general trends of Mediterranean and Atlantic soils and explain the expected soil characteristics of the researched farms as defined by soil surveys and classifications.

Next, I present and discuss the results of the scientific assessment of soil physical quality at the researched farms. Thus, the results of relevant soil properties influencing structure and compaction are given. Consecutively, results of the different on-farm and laboratory tests for soil structure and soil compaction are presented and discussed regarding coherence among tests and relation with aggregation agents. Finally, the influence of tillage management and its relevance among other soil agents is analysed and discussed. For the latter, due to unexpected variations in soils between neighbour farmers, the analysis shifted from the initial comparison between neighbour fields to re-grouping soils according to their aggregation agents and analysing the differences between and within each identified soil group.

6.2. Soils in bio-geographical regions

6.2.1. Soils in the Mediterranean region

This section reviews the soil formation factors and the principal soil characteristics in the Mediterranean biogeographical region. Starting with the climate, Mediterranean temperatures are characterised by hot summers and mild winters. While precipitation during the winter exceeds evapotranspiration, during the summer, there is a water deficit. Moreover, rainfall patterns are irregular and can occur in extreme events (cold front), which, combined with the land topography, leads to increased erosion risk for the whole region (Yaalon, 1997). Due to the erosive and sedimentary processes together with other surface and subsurface fluxes, soils' position in the landscape is also a vital soil formation factor.

Geologically, the Mediterranean region is a result of the collision of two tectonic plates with the consequent uplifts, basins and volcanic activity; in addition to erosive and sedimentary processes and an important contribution of eolic sediment deposition from the Sahara desert (Yaalon, 1997), resulting in high variability of parental materials.

The typical vegetation in the Mediterranean region is evergreen shrubs and sclerophyllous trees adapted to summer droughts and sporadic frosts (Roberts *et al.*, 2011). Vegetation growth occurs during spring and autumn, coinciding with precipitations and mild temperatures. Furthermore, fire is a regular part of the Mediterranean region, and vegetation has different strategies that enhance their resilience.

The Mediterranean region has the most prolonged continuous presence of human settlement and dense cultivation, extended to over 5,000 years (Yaalon, 1997). Accordingly, human presence has influenced soils and soil formation factors through land use change, for example, with conservation practices such as terracing. Regarding deforestation and its consequences for soil degradation, it is debatable how far climatic changes also influenced vegetation changes (Roberts *et al.*, 2011). Nonetheless, pollen data shows that forest cover during the Mid-Holocene was generally denser and extensive than nowadays (Collins, Davis & Kaplan, 2012).

The combination of these soil formation factors leads to a great variety of soils. Indeed, pedodiversity in the Mediterranean region is higher than in other biogeographical regions (Ibáñez, De Alba & Boixadera, 1995). Nonetheless, there are some general trends as relatively low SOM content, presence of calcium carbonate and soluble components, clay illuviation and coatings, and rubefication.

Lower biomass production in the Mediterranean vegetation in response to climatic conditions reduces organic inputs. Additionally, higher temperatures enhance microorganism activity, producing more significant organic matter mineralisation, contributing to lower soil organic matter contents in soils. In Spain, SOC under grassland and arable land uses are much lower than 2%, considered a threshold to classify degraded soils (Romanyà & Rovira, 2011).

Furthermore, a less percolating climate means that more soluble components remain in the soil. Depending on the parent material, soils contain calcium carbonate and salts. Additionally, dissolution of calcium carbonates and their precipitation result in a variety of secondary carbonates, including crusts, which are physical barriers that influence water flows, root growth and the overall land suitability for agricultural practices.

Nonetheless, precipitation is enough for clay illuviation to happen. Consequently, clays are eluviated from surface horizons and accumulated in-depth in the form of coatings and eventually forming argillic horizons. Moreover, through rubefication (iron oxyhydroxides mobilisation during weathering and precipitation as poorly crystalline ferrihydrites or very fine-grained hematite during dry summer periods), some soils acquired a distinctive red colour, which gave rise to early “Red Mediterranean” or “Terra Rossa” soil classifications, which eventually was discarded due to the lack of measurability (Yaalon, 1997).

6.2.2. Soils in the Atlantic region

This section reviews the soil formation factors and the principal soil characteristics in the Atlantic biogeographical region. Starting with the climate, this is highly influenced by the Atlantic Ocean and has moderate and mild temperatures that do not markedly differ between winter and summer; additionally, it has high precipitation and high humidity with a general water surplus (Condé *et al.*, 2008). Furthermore, mild climatic conditions with high biomass production lead to high organic matter contents in the soils of the Atlantic region.

The coasts have large tidal movements, and low-lying coasts present marshes and dunes. At these low-lying coasts, land reclamation from the sea has been practised for over 1,000 years (Condé *et al.*, 2008). Additionally, the North of the Atlantic region was covered by ice during the last ice age, and therefore highly influenced by glacial and postglacial processes. Indeed, soil parental materials in the Atlantic region include glacial deposits, among other sediments and sedimentary rocks, basalts and granites (Condé *et al.*, 2008).

The typical vegetation in the Atlantic region is deciduous forests, favoured by the climate. The dominant tree species are sessile oak (*Quercus petraea*) and the pedunculated oak (*Quercus robur*), and the beech (*Fagus sylvatica*) (Condé *et al.*, 2008). However, on wind-exposed sites or poor soils, scrubs predominate (Condé *et al.*, 2008).

The combination of soil formation factors also leads to high diversity in soils in the Atlantic region. Here, the high precipitation causes leaching of the more soluble components throughout the soil profiles and feeds the bogs and moors (Condé *et al.*, 2008). Consequently, salts from reclaimed land have been leached through the soil profile and do not represent problems for agriculture (if not flooded regularly) even if groundwater remains saline. Nonetheless, excess soil moisture also produces nutrient leaching and hampers soil workability. Therefore, it is considered to be the main bio-physical constraint for agriculture in this region, to the extent that drainage characteristics have become the dominant soil classifier (Coyle *et al.*, 2016).

6.3. Soil classification at research locations

6.3.1. Soil classification at Spanish research locations

The soil maps of the agricultural regions, shown in Figure 50, are based on the great group level of the Soil Taxonomy classification system. This information provides a general understanding of some of the characteristics of the soils that we find in the region and the influence of soil formation factors. For example, the prefix Xer- determines the Mediterranean climatological moisture regime, whereas the soils with the suffix –id are aridisol, developed under aridic conditions, same as torr- from torric.

Soils at locations 1, 2, 4-NT and 5 in Navarre and Aragon and 3-CT in Castille and Leon are classified as Xerocrept by the Spanish Soil map (1987). Xerochrept soils, per definition, are young soils (Inceptisols) developed under Mediterranean moisture regime. Here, the survey details indicate these Xerochrept have a deep effective root depth (100 - 150 cm), low organic matter content, sandy loam texture and slightly acid pH. Location 4-CT was located at a site classified as Torrifluvent, which are older soils (Entisol) developed under aridic/torric moisture regime and with the fluvent- character, meaning that organic matter is distributed irregularly throughout the soil profile as a consequence of having developed from different fluvial deposits. Again, the survey data describe the Torrifluvent as deep soils (100 – 150 cm), with organic matter that varies according to flooding frequency, base pH and loam texture. Location 3-NT was located at a soil classified in a map unit Xerorthent + Xerofluvent. The Xerorthent soils have medium organic matter content, are generally deep and moderately basic but occasionally slightly acid, and have loam or clayey texture. Xerofluvent soils are also deep, with medium organic matter content and slightly acid pH and sandy-loam texture. Those soils are older (Entisol), developed under the Mediterranean moisture regime and might or not present the fluventic character depending on the influence of river floodings.

At a second look at the soil maps, we can distinguish other major soil units in the agricultural regions in Navarre and Aragon, such as Calciorthid and Gypsiorthid, related to parental material containing calcareous rocks and gypsum, respectively.

6.3.2. Soil classification at British research locations

The soil maps shown in Figure 50 are based on a simplification of the English and Welsh classification system. This information is not intended for land planning nor detailed investigations (Cranfield University, 2021), but it provides a general overview of soil characteristics at the researched farms.

Sampled fields in the East of England were on a variety of soils. Both fields at location 6 were on 'Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils. Whereas at location 7, both fields were on 'Lime-rich loamy and clayey soils with impeded drainage' and at location 8 on 'Freely draining lime-rich loamy soils'.

Similarly, sampled fields from neighbour no-tillage and conventional tillage farms in Yorkshire and the Humber were on different soil types. 9-NT was on 'Loamy and clayey soils of coastal flats with naturally high groundwater" whereas 9-CT was on 'Slowly permeable seasonally wet slightly acid, but base-rich loamy and clayey soils' and both fields at location 10 are on 'Naturally wet very acid sandy and loamy soils.

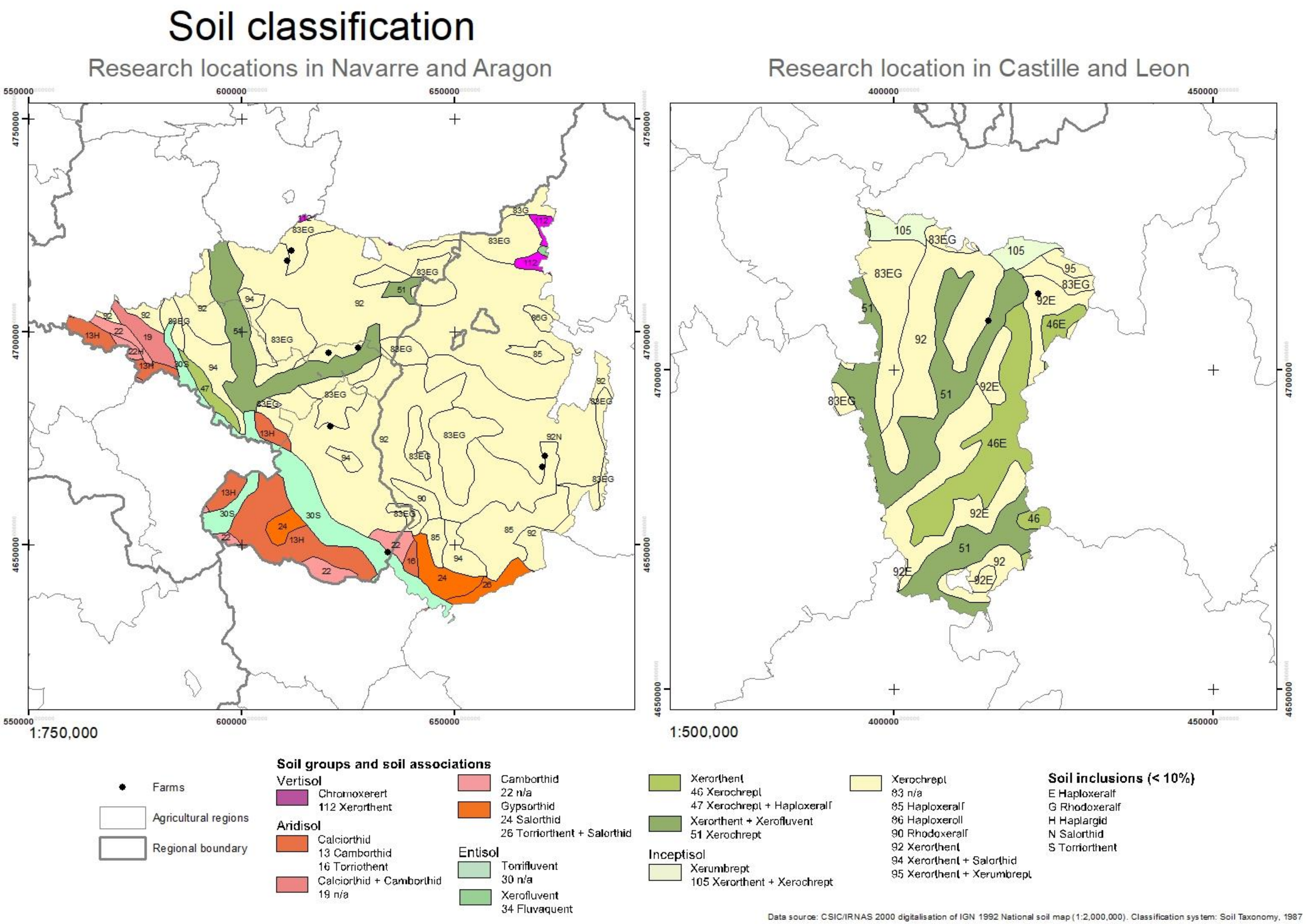


Figure 50. Spanish research locations soil classification maps (Soil Taxonomy, 1987)

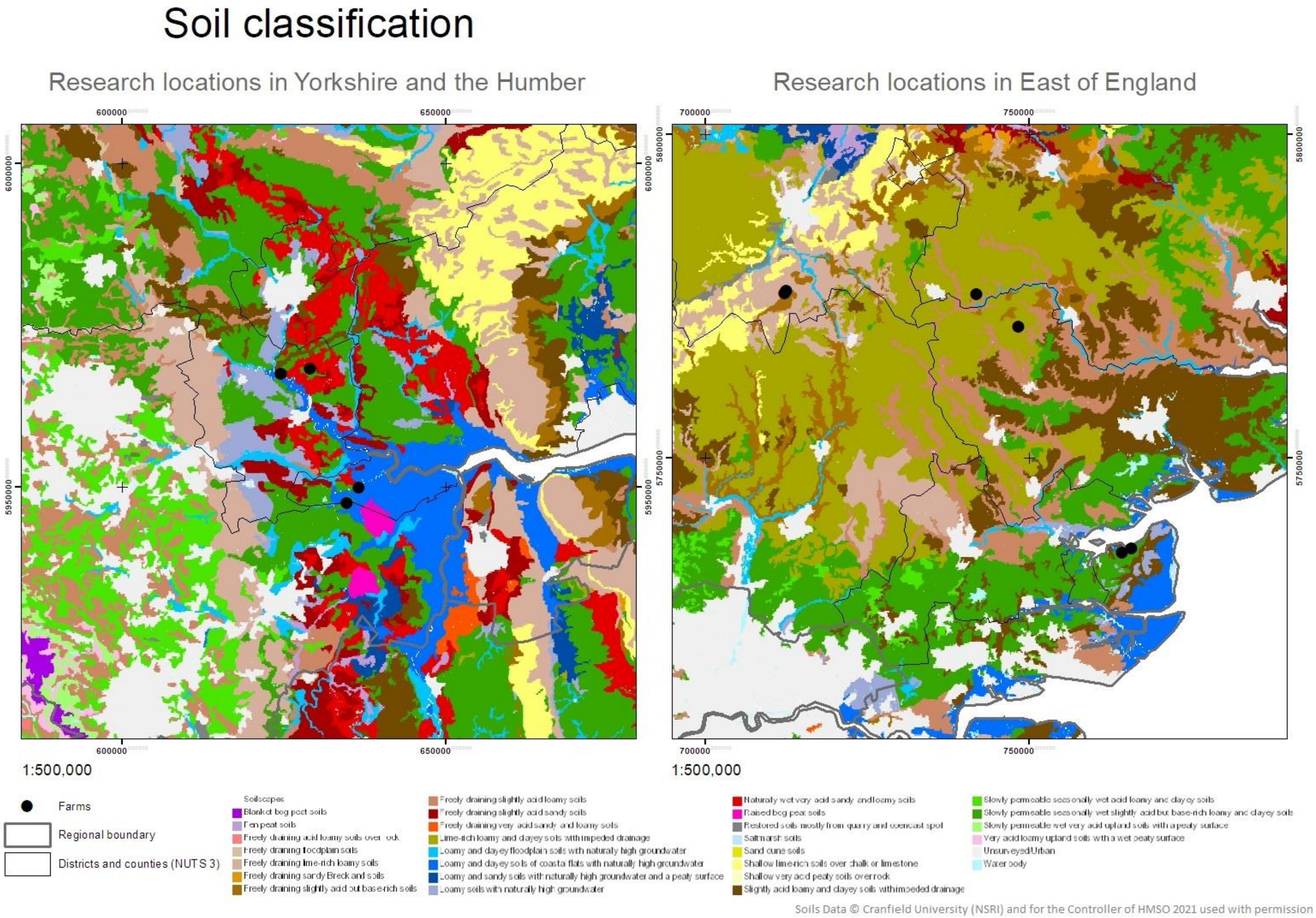


Figure 51. British research locations soil classification maps (soilscapes: simplified English and Welsh classification)

6.4. Relevant soil properties: aggregation agents

These complementary soil tests were chosen as they analyse factors that affect aggregation dynamics and, therefore, soil physical quality. The results of these tests are shown in this section, whereas their influence on soil structure and compaction is discussed later.

Particle size analysis and textural classification followed the English and Welsh system. Average clay, silt and sand contents, together with the soil texture classification, are shown in Table 11 for the Spanish soils and Table 12 for the British soils. General trends for the analysed Spanish soils are low clay, predominant silt and a range of sand contents. Spanish soils classified for Sandy silt Loam, except location 4, which classified for Silt Loam. Similarly, British soils had also low clay contents with different silt and sand proportions, classifying for diverse textures from Silt Loam to Loamy Sand.

pH was measured in deionised water (H_2O 1:5) to account for the protons in solution and in calcium chloride ($CaCl_2$ 1:5) to include exchangeable protons. In the same deionised water solution, electrical conductivity (EC) measurements were taken. Salinity was assessed through EC readings for Loam soil texture except for 10CT, which was assessed for Sand. Field average results of pH in water, EC and salinity classification are shown in Table 11 for Spanish soils and Table 12 for British soils.

For British soils, pH (H_2O 1:5) ranged from neutral to base and EC from non saline to moderate. While Spanish pH (H_2O 1:5) results were medium base to slightly alkaline soils at all sites except at 3-NT, which presented neutral soils. Additionally, soils presented none to low salinity conditions, except for 4-CT, which presented severe salinity. 4-CT and its neighbour field 4-NT were located at Bardenas Reales, with arid conditions where salinity issues are not rare. Indeed, the non saline conditions at 4-NT were surprising, especially after field visit during which surface saline efflorescence was spotted.

Soil Organic Carbon (SOC), nitrogen (N) and Carbon: Nitrogen ratio (C/N) were analysed with a CN analyser. The results averaged per field are presented in Table 11 for Spanish soils and Table 12 for British soils. Additionally, SOM was measured through loss on ignition as back-up data due to uncertainties regarding completion of SOC analysis in external laboratories during the Covid-19 pandemic and consequent lock-down in the UK.

Soil moisture was calculated from bulk density samples to provide information about field conditions at the moment of on-site assessments and soil sampling. Gravimetric Water Content (GWC) results are presented in Table 11 for the Spanish samples and Table 12 for the British samples.

Table 11. Spanish researched farms soil properties I

Field	Clay (%)	Silt (%)	Sand (%)	Texture classification	pH (H2O 1:5)	EC (H2O 1:5 dSm^{-2})	Salinity classification	SOC (%)	N (%)	C/N (ratio)	GWC (ratio)	CE (%v)
1-NT	6.16	67.33	26.51	Sandy silt Loam	8.16 ± 0.10	0.26 ± 0.06	Low	1.04 ± 0.17	0.11 ± 0.01	9.39 ± 0.77	0.21 ± 0.02	0.15 ± 0.19
1-CT	7.02	67.49	25.49		8.28 ± 0.13	0.22 ± 0.06		1.00 ± 0.12	0.12 ± 0.02	8.68 ± 0.34	0.26 ± 0.02	0.51 ± 0.65
2-NT	6.55	66.07	27.37		8.08 ± 0.10	0.24 ± 0.07		1.14 ± 0.17	0.12 ± 0.02	9.36 ± 1.08	0.26 ± 0.05	2.24 ± 1.92
2-CT	11.20	53.59	35.21		8.17 ± 0.07	0.16 ± 0.01	Non saline	1.51 ± 0.11	0.15 ± 0.02	10.15 ± 0.42	0.13 ± 0.02	10.43 ± 4.43
3-NT	9.29	47.51	43.20		6.86 ± 0.94	0.08 ± 0.04		1.19 ± 0.17	0.09 ± 0.02	13.73 ± 1.19	0.07 ± 0.01	1.51 ± 0.94
3-CT	15.21	59.43	25.36		8.28 ± 0.03	0.14 ± 0.01		1.25 ± 0.15	0.10 ± 0.01	13.39 ± 0.90	0.10 ± 0.02	3.62 ± 1.41
4-NT	0.99	88.65	10.37	Silt Loam	8.42 ± 0.12	0.13 ± 0.01		0.98 ± 0.04	0.09 ± 0.01	10.90 ± 0.36	0.09 ± 0.02	0.14 ± 0.19
4-CT	6.03	74.29	19.68		7.81 ± 0.13	2.31 ± 0.04	Severe	1.05 ± 0.13	0.10 ± 0.01	10.37 ± 1.21	0.14 ± 0.02	2.46 ± 2.31
5-NT	5.54	71.80	22.66	Sandy silt Loam	8.17 ± 0.18	0.20 ± 0.08	Low	1.18 ± 0.21	0.14 ± 0.02	8.59 ± 0.36	0.06 ± 0.01	0.63 ± 0.93
5-CT	6.73	69.04	24.23		8.53 ± 0.11	0.14 ± 0.02	Non saline	0.99 ± 0.08	0.12 ± 0.01	8.49 ± 0.25	0.09 ± 0.01	2.13 ± 3.46

*Results show average ± SD; NT: no-tillage; CT: conventional tillage

Table 12. British researched farms soil properties I

Field	Clay (%)	Silt (%)	Sand (%)	Texture classification	pH (H2O 1:5)	EC (H2O 1:5 dSm^{-2})	Salinity classification	SOC (%)	N (%)	C/N (ratio)	GSM (ratio)	CE (% v)
6-NT	12.07	73.38	14.55	Silt Loam	6.13 ± 0.66	0.37 ± 0.11	Moderate	2.98 ± 0.46	0.29 ± 0.04	10.28 ± 0.35	0.23 ± 0.06	1.52 ± 1.59
6-CT	9.98	73.08	16.94		7.23 ± 0.30	0.58 ± 0.28		2.47 ± 0.14	0.24 ± 0.02	10.17 ± 0.49	0.20 ± 0.01	1.10 ± 1.81
7-NT	14.01	59.50	26.50	Sandy silt Loam	7.15 ± 0.58	0.28 ± 0.08	Low	2.07 ± 0.16	0.20 ± 0.02	10.60 ± 0.62	0.21 ± 0.02	3.11 ± 4.20
7-CT	15.98	59.38	24.65		7.85 ± 0.07	0.27 ± 0.02		1.72 ± 0.07	0.17 ± 0.01	9.93 ± 0.32	0.17 ± 0.02	4.45 ± 4.79
8-NT	6.55	39.34	54.11	Sandy Loam	7.79 ± 0.17	0.33 ± 0.11		1.38 ± 0.21	0.15 ± 0.01	9.33 ± 0.72	0.11 ± 0.03	3.92 ± 3.44
8-CT	6.50	42.34	51.16		7.99 ± 0.06	0.22 ± 0.02		1.11 ± 0.30	0.11 ± 0.02	10.36 ± 1.02	0.13 ± 0.02	3.23 ± 2.06
9-NT	6.59	73.75	19.66	Silt Loam	7.67 ± 0.16	0.35 ± 0.09		2.55 ± 0.25	0.20 ± 0.03	12.64 ± 0.43	0.29 ± 0.06	0.23 ± 0.27
9-CT	7.36	62.20	30.44	Sandy silt Loam	6.00 ± 0.51	0.11 ± 0.01	Non saline	3.55 ± 0.44	0.28 ± 0.02	12.79 ± 0.84	0.24 ± 0.07	0.28 ± 0.49
10-NT	5.07	29.67	65.25	Sandy Loam	6.13 ± 0.30	0.23 ± 0.07	Low	1.60 ± 0.28	0.15 ± 0.03	10.61 ± 0.46	0.14 ± 0.04	0.57 ± 0.41
10-CT	4.20	20.75	75.06	Loamy sand	6.90 ± 0.32	0.14 ± 0.05	Non saline	1.56 ± 0.27	0.12 ± 0.01	12.57 ± 2.44	0.12 ± 0.02	1.36 ± 2.24

*Results show average ± SD; NT: no-tillage; CT: conventional tillage

Total calcium carbonates were analysed by titration and averaged per field, while iron, potassium, magnesium and chrome were analysed through XRF. Averaged results are shown in Table 13 and Table 14 for Spanish and British soils, respectively.

Table 13. Spanish researched farms soil properties II

Field	$CaCO_3$ (%)	Fe (ppm)	K (ppm)	Mn (ppm)
1-NT	40.46 ± 3.14	14,759 ± 1,807	15,583 ± 1,636	442 ± 43
1-CT	41.44 ± 0.86	16,484 ± 540	17,758 ± 411	425 ± 24
2-NT	36.18 ± 3.45	15,833 ± 596	16,633 ± 518	412 ± 35
2-CT	19.84 ± 2.66	23,016 ± 1,618	14,769 ± 360	828 ± 17
3-NT	1.58 ± 1.39	17,942 ± 2,890	21,611 ± 1,069	285 ± 34
3-CT	18.35 ± 5.41	23,918 ± 2,061	25,092 ± 1,086	315 ± 30
4-NT	47.91 ± 0.81	13,855 ± 755	16,730 ± 1,256	424 ± 7
4-CT	34.02 ± 2.53	17,588 ± 2,435	22,366 ± 2,947	320 ± 29
5-NT	36.29 ± 1.41	16,437 ± 1,485	19,459 ± 1,414	364 ± 28
5-CT	35.45 ± 1.48	17,332 ± 1,238	20,021 ± 1,287	382 ± 19

*Results show average ± SD for $CaCO_3$ and average ± SEM for Fe, K and Mn

Table 14. British researched farms soil properties II

Field	CaCO3 (%)	Fe (ppm)	K (ppm)	Mn (ppm)
6-NT	1.10 ± 0.50	33,909 ± 1,934	18,008 ± 583	434 ± 80
6-CT	1.93 ± 0.75	29,375 ± 2,932	18,885 ± 1,594	456 ± 38
7-NT	2.56 ± 1.72	27,598 ± 5,328	16,569 ± 818	562 ± 65
7-CT	4.75 ± 1.29	30,403 ± 1,192	18,715 ± 648	698 ± 96
8-NT	9.80 ± 2.66	20,679 ± 1,251	11,309 ± 801	770 ± 95
8-CT	17.26 ± 4.12	18,694 ± 2,564	10,955 ± 627	650 ± 86
9-NT	9.00 ± 0.45	29,494 ± 3,363	18,114 ± 1,502	804 ± 98
9-CT	0.83 ± 0.52	22,296 ± 2,791	12,971 ± 692	358 ± 14
10-NT	0.33 ± 0.41	13,095 ± 2,676	11,816 ± 756	315 ± 100
10-CT	0.58 ± 0.20	12,846 ± 1,275	9,388 ± 733	480 ± 72

*Results show average ± SD for $CaCO_3$ and average ± SEM for Fe, K and Mn

6.5. Soil structure assessment

This section presents the soil structure assessment through VESS on-farm and ASD and AS tests in the laboratory. The assessment follows Dexter's (1988) premise that a "Good soil structure is described as one where all the hierarchical orders are well-developed and stable".

First, the results of all tests are presented, and then the discussion focuses on the coherence between tests, the relationships with the analysed aggregation agents and the role of tillage management impact on soil structure.

6.5.1. VESS results

I performed an on-farm soil structure assessment applying VESS methodology at three sites in each field (4 sites at 7-NT). Results are shown per farm, averaging overall Sq scores in Table 15 and Table 16 for Spanish and British sampled fields, respectively. Results range from friable (Sq 1) to firm (Sq 3) and do not indicate a need for management change, although 3-NT with firm soils would require monitoring. Detailed VESS assessment examples for the Spanish soils with soil blocks' images can be found in Appendix C.

Table 15. Spanish soils VESS results

Field	VESS (overall Sq)
1-NT	1.93 ± 0.06
1-CT	2 ± 0
2-NT	1.93 ± 0.13
2-CT	2 ± 0
3-NT	3.33 ± 0.58
3-CT	2 ± 0
4-NT	2 ± 0
4-CT	2.87 ± 0.49
5-NT	2.63 ± 1.08
5-CT	2.49 ± 0.47

* Results show average ± SEM

Table 16. British soils VESS results

Field	VESS (overall Sq)
6-NT	1.98 ± 0.32
6-CT	1.33 ± 0.58
7-NT	1.78 ± 0.03
7-CT	1.65 ± 0.57
8-NT	2 ± 0
8-CT	2 ± 0
9-NT	1.86 ± 0.03
9-CT	1.86 ± 0.59
10-NT	2 ± 0
10-CT	2.21 ± 0.22

* Results show average ± SEM

6.5.2. Aggregate size distributions results

Aggregate size distributions after dry (ASD_d) and wet sieving (ASD_w) are shown in Figure 52 for Spanish samples and Figure 53. Aggregate size fractions included in the analysis were large macroaggregates (LMA > 2 mm), small macroaggregates (2 mm > SMA > 250 µm) and microaggregates (250 µm > MiA > 53 µm). Additional soil fractions included were the silt, and clay fraction (SC < 53 µm) and the sum of coarse elements (CE) subtracted from the aggregated soil at sand correction. Mean Wide Diameter after dry (MWD_d) and wet (MWD_w) sieving was calculated for all samples, and average results per field are shown in Table 17 and Table 18 for Spanish and British results, respectively.

In Spain, the soils at fields 1-NT, 1-CT and 2-NT were, after dry sieving, clearly dominated by the LMA_d soil fraction with corresponding higher MWD_d. At the other fields, proportions of LMA_d and SMA_d were more similar and higher than the other soil fractions after the dry sieving. In the UK, all soils' ASD_d were dominated by the LMA_d fraction, except 10-CT where LMA_d and SMA_d had more similar proportions and CE were high.

After wet sieving the Spanish samples, 2-NT maintained high LMA_w values, while for 2-CT and 3-CT SMA_w were dominant, 3-NT the CE was dominant and at 4-NT SC fraction dominated. 5-CT, 3-NT and 4-NT presented the lowest MWD_w. For British samples, 6-NT, 7-NT and 9-NT maintained high LMA_w, and farms from sites 8 and 10 presented high CE proportions. The other soils had more even distributions between the considered aggregate size fractions.

Table 17. Spanish soils' Mean Wide Diameter after dry and wet sieving per field

Field	MWD_d (mm)	MWD_w (mm)
1-NT	9.93 ± 0.37	3.31 ± 2.08
1-CT	10.12 ± 0.22	2.67 ± 1.95
2-NT	9.44 ± 0.44	4.22 ± 1.90
2-CT	4.01 ± 1.06	2.05 ± 0.36
3-NT	4.94 ± 1.23	1.33 ± 0.72
3-CT	4.98 ± 1.73	2.89 ± 1.69
4-NT	4.30 ± 1.16	1.43 ± 1.10
4-CT	5.77 ± 1.82	2.50 ± 0.95
5-NT	5.08 ± 1.01	2.08 ± 0.70
5-CT	5.03 ± 0.17	1.02 ± 0.55

*Results show average ± SD

Table 18. British soils' Mean Wide Diameter after dry and wet sieving per field

Field	MWD_d (mm)	MWD_w (mm)
6-NT	9.48 ± 0.94	8.27 ± 1.41
6-CT	9.00 ± 1.15	5.94 ± 2.13
7-NT	10.17 ± 0.32	7.71 ± 1.39
7-CT	9.60 ± 0.79	5.23 ± 2.46
8-NT	8.18 ± 0.60	3.23 ± 1.79
8-CT	8.30 ± 0.68	0.37 ± 0.06
9-NT	10.20 ± 0.73	8.37 ± 1.75
9-CT	8.23 ± 2.01	4.98 ± 1.30
10-NT	7.15 ± 0.46	3.19 ± 1.74
10-CT	3.17 ± 0.65	1.03 ± 0.54

*Results show average ± SD

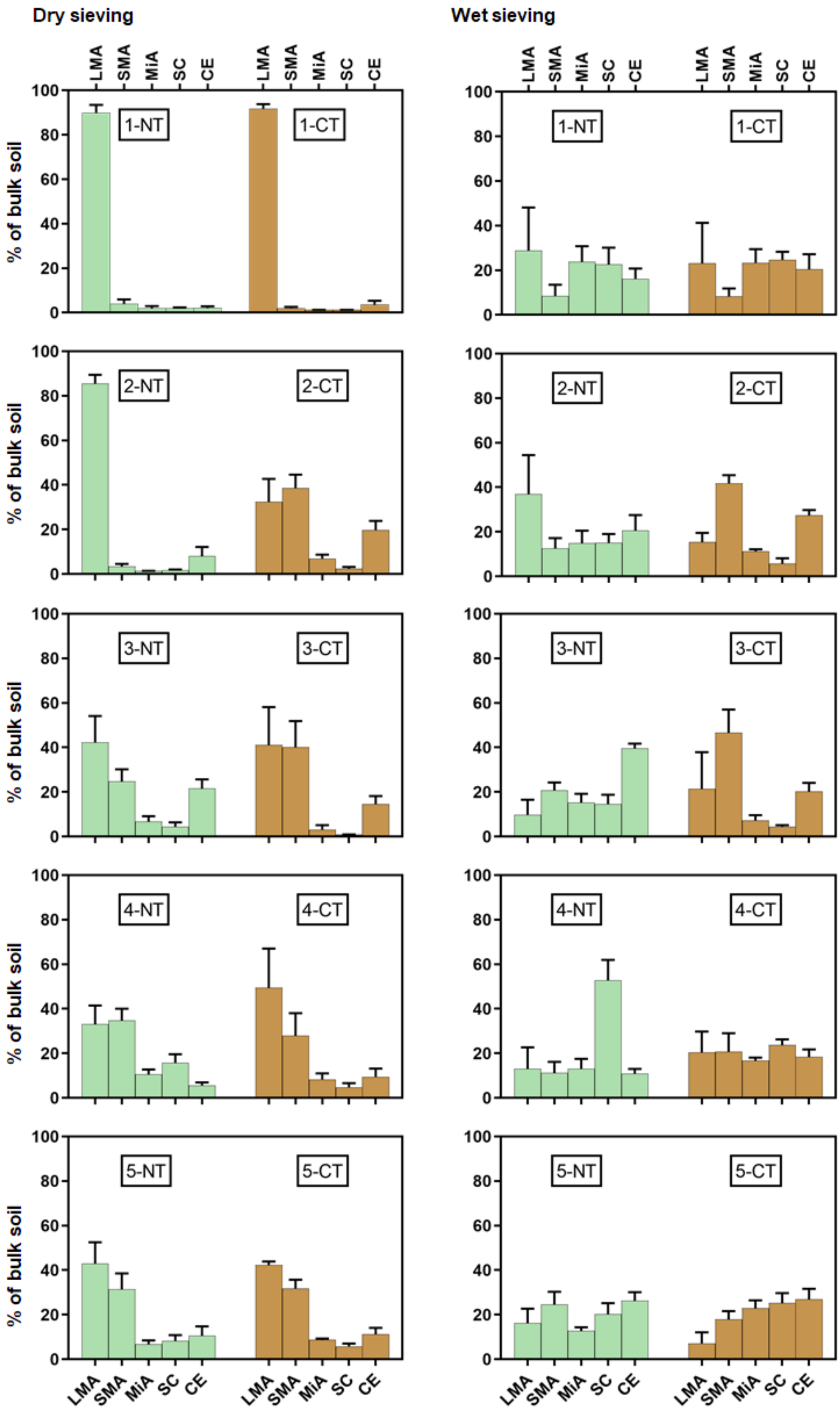


Figure 52. Spanish fields' Aggregate Size Distributions. Graphs show the average and SD of aggregate fractions per field. LMA: Large Macroaggregates; SMA: Small Macroaggregates; MiA: Microaggregates; SC: Silt and Clay; CE: Coarse elements and sand correction

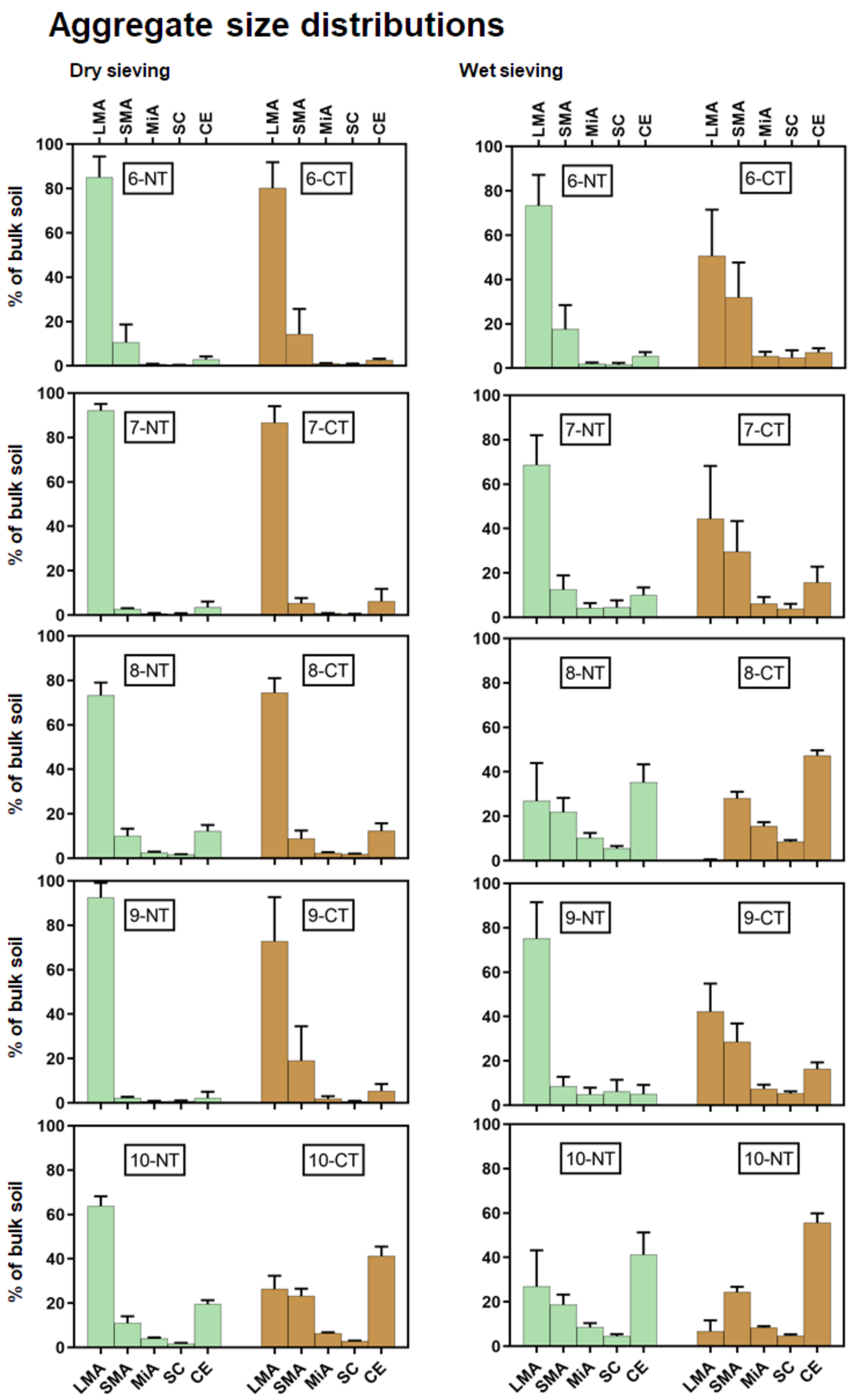


Figure 53. British fields' Aggregate Size Distributions. Graphs show the average and SD of aggregate fractions per field. LMA: Large Macroaggregates; SMA: Small Macroaggregates; MiA: Microaggregates; SC: Silt and Clay; CE: Coarse elements and sand correction

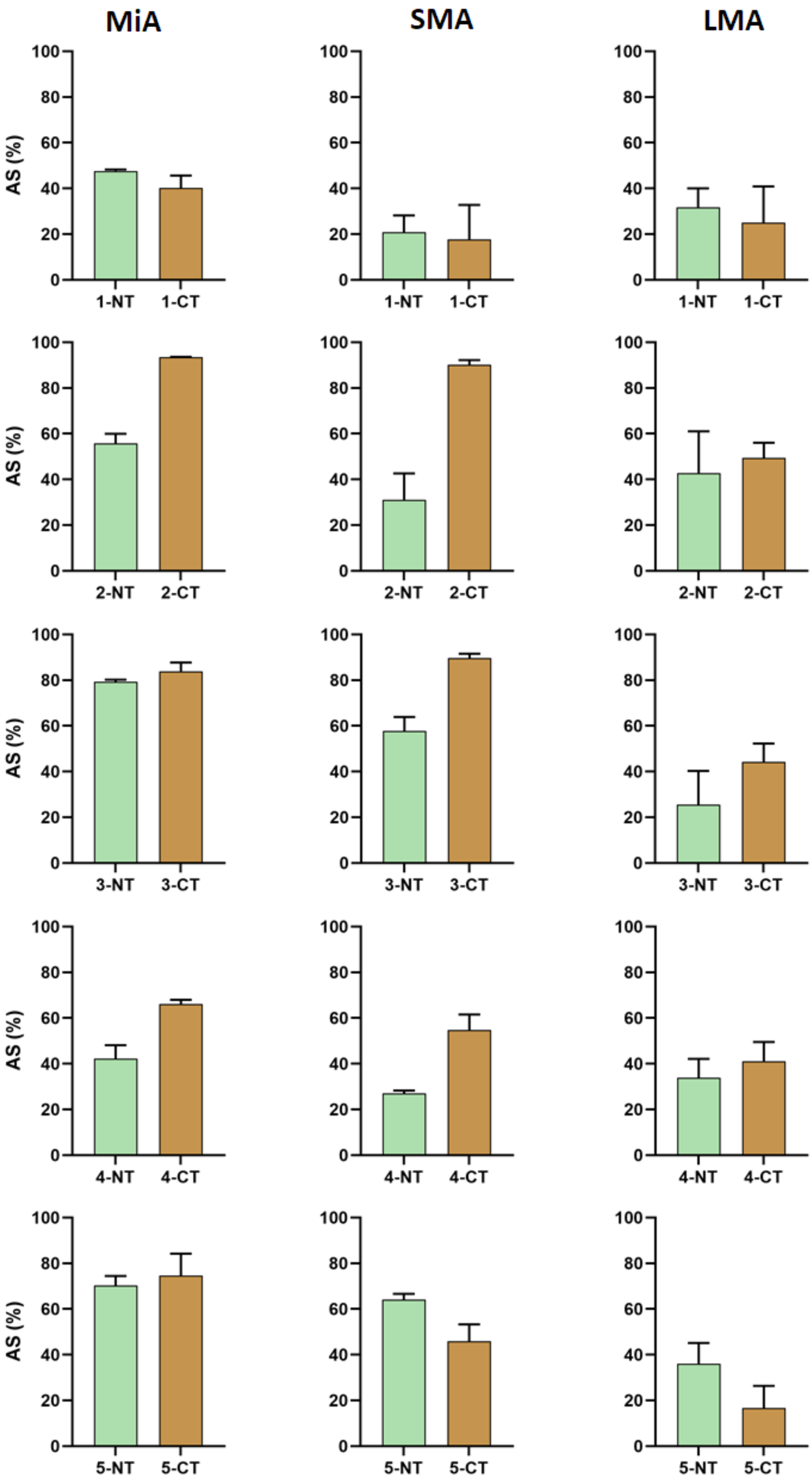


Figure 54. Spanish soils' Aggregate Stability (AS) representing the fraction of the aggregate size class that was resistant to wet sieving disruption. Graphs show the average and SD per aggregate size class and per field. LMA: Large macroaggregate; SMA: Small macroaggregate; MiA: Microaggregate.

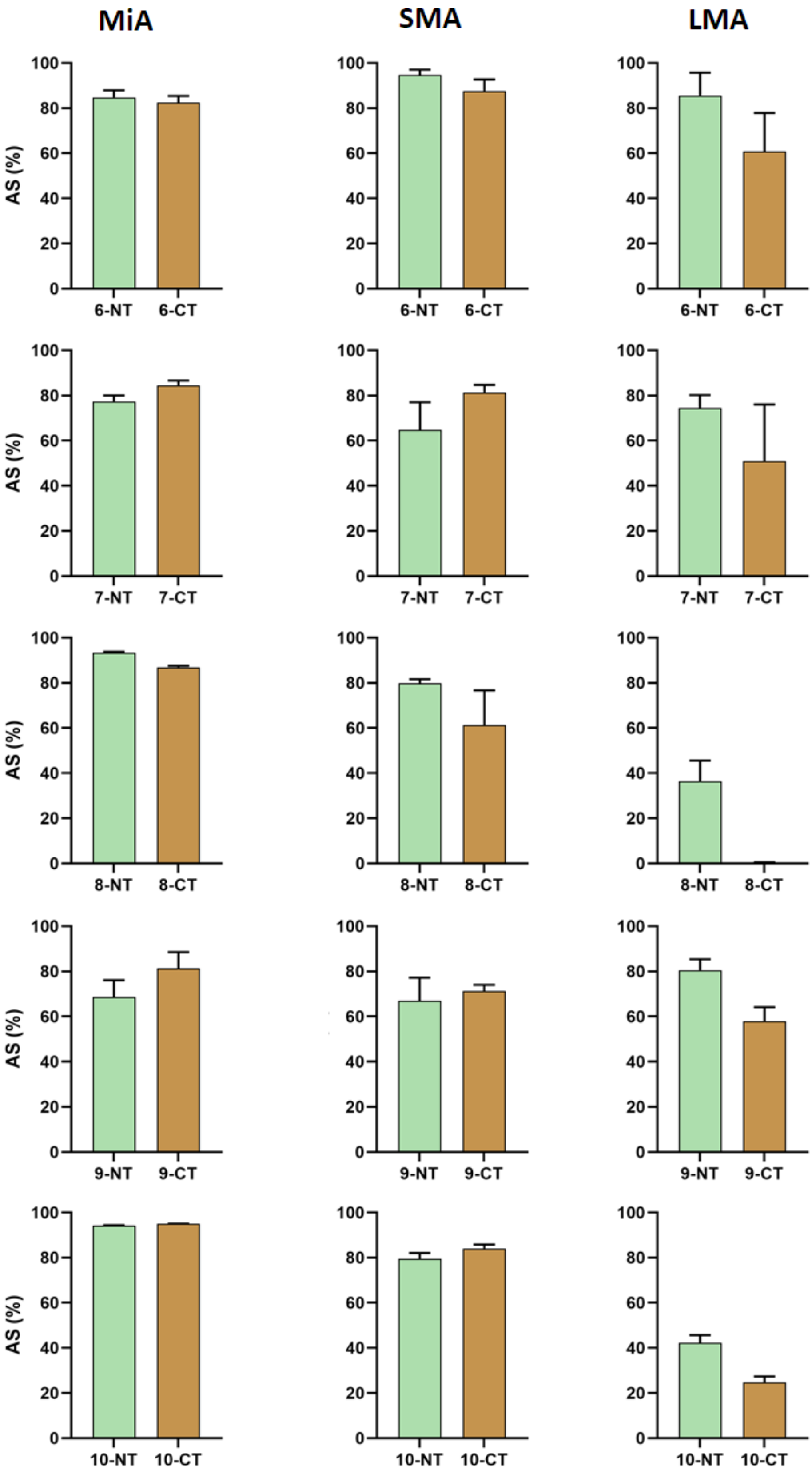


Figure 55. British soils' Aggregate Stability (AS) representing the fraction of the aggregate size class that was resistant to wet sieving disruption. Graphs show average and SD per aggregate size class and per field. LMA: Large macroaggregate; SMA: Small macroag

6.5.3. Aggregate stability tests results

Aggregate stability (AS) results are presented in Figure 54 for the Spanish soil samples and Figure 55 for the British soil samples.

Spanish soils presented higher AS for MiA than for SMA and LMA in that order except for both fields at location 1, 2-NT and 4-NT, which presented the order AS MiA > LMA > SMA and 3-CT, which presented the order AS SMA > MiA > LMA. Similarly, British soils also presented higher AS for MiA than for SMA and LMA, in that order, except for 7-NT, which presented higher AS for LMA than for SMA; 6-NT and 6-CT where SMA had the highest AS and 9-NT where LMA had the highest AS among the aggregate size fractions.

6.5.4. Coherence between soil structure tests

Different soil structure tests are expected to be related in the sense that better-structured soils in one test should show well-developed structures in the other tests. The expected relationships between the different structure tests performed are direct or positive in the case of the relations between the AS of the different aggregate sizes and their proportion in the bulk soil reflected in the ASD and MWD; whereas VESS is expected to relate inversely or negatively with AS and aggregate size in the ASD.

On-farm performed VESS did not appear to be particularly related to any of the other tests applied. Soils with better VESS scores (Sq 1 and 2) had a range of proportions of the different aggregate size fractions in both the dry and the wet sieving processes, and a range of aggregate stabilities for the different aggregate sizes considered. Soils (or sample sites within a field) with worse VESS scores (Sq 3 and 4) were less frequent among the analysed soils. The soils with those poorer scorings showed relatively low LMA, intermediate SMA, high MiA and low SC after both the dry and wet sieving. These results suggested a relation with the visual character of the analysis of soil structure. Specifically, in terms of macroaggregates being more likely to be identified by the naked eye whereas microaggregates (< 250 µm) might appear poorly developed soil matrix. Beherends Kraemer et al. (2017) found statistically significant inverse relationships between VESS and mean wide diameter (wet sieving), which is consistent with this idea. Nonetheless, it has to be noted that among the better scoring soils, similar proportions of the different aggregate sizes were found. A lack of meaningful relationships between VESS and other soil structure laboratory tests has been reported before (see: Askari, Cui and Holden, 2013).

On the contrary, AS and ASD_w showed a strong relationship. Soils with higher AS in any of the aggregate size classes had lower proportions of SC_w and MiA_w and remained aggregated in SMA_w and LMA_w after the wet sieving. These relationships were expected as the same aggregate disrupting forces are used in both tests, while when comparing AS and ASD_d, two different disruptive forces were compared: the mechanical disruption at the dry sieving and the mechanical plus the water disruption at the wet sieving. In this case, for the Spanish soils, AS LMA did not appear to be related to the ASD_d. Not even with LMA_d, suggesting that the aggregation agents of LMA of these soils responded differently to mechanical than to water disruptions or that the aggregation agents that regulate LMA_d were different from those aggregation agents that provided AS (wet) to LMA. Furthermore, a group of soils (1-CT, 1-NT, 2-NT) presented high LMA_d and low AS SMA and MiA. On the contrary, soils with higher AS SMA and AS MiA presented a higher proportion of MiA_d and SMA_d and lower SC_d, suggesting that AS had a greater influence on soils' aggregate distribution in smaller size aggregates (< 2 mm). Whereas for the British soils, AS LMA had an inverse relationship with smaller aggregate fractions and a direct relationship with LMA_d, suggesting that aggregation agents dominating LMA aggregation resist both dry and wet disruptions.

Additionally, soils presenting high AS of MiA also presented high AS SMA, whereas these relationships were not found with AS LMA. Meaning that MiA and SMA aggregate size aggregate stabilities were reacting in the same manner to water-induced breakdown while LMA had different behaviour. In turn, this similar reaction might suggest that in the analysed soils, the same aggregation agents regulated SMA and MiA aggregation and breakdown or that the different aggregation agents had similar behaviour regarding water breakdown forces, while LMA were regulated by different aggregation agents.

In terms of soil quality, a well developed hierarchical soil structure is made of MiA forming SMA and LMA. Additionally, those healthy soils would have low percentages of SC, which would show in stronger AS for all aggregate sizes. In this study, this relation was better shown after wet sieving, particularly with Spanish soils. From the Spanish analysed soils, better-structured 2-CT and 3-CT soils had higher AS and a range of LMA_w but high amounts of SMA_w (except for the 3 samples at 3-CT and their lower AS of LMA) and low amounts of MiA_w and SC_w. On the other end, 4-NT soils had lower AS and higher mounts of SC_w, meaning that those soil structures were poorer developed. In the middle ground, based on the discussed relations, it was possible to distinguish the group of 1-CT, 1-NT and 2-NT with low AS but very high LMA_d and the other soils (3-NT, 4-CT, 5-NT and 5-CT) with slightly higher AS but a similar proportion of SC_w. For the British soils, soils from locations 6, 7 and 9 (both no-tillage and conventional tillage fields) presented better-structured soils with high AS for LMA and high LMA_w.

6.6. Importance of tillage management among aggregation agents

Random forest was used to assess the relative importance of tillage management among analysed aggregation agents. Accordingly, I build one random forest model to predict each of the soil structure index (MWD_d, MWD_w, AS MiA, AS SMA and AS LMA) for the Spanish and the British soils separately. The variables included in the models were: tillage management (no-tillage or conventional tillage), sample depth (from 0 – 5 and 5 – 10 cm), clay, silt, sand, pH (H_2O), EC, SOC, N, CN, GWC, CE, $CaCO_3$, Fe, K and Mn. Details of the random forest models can be found in Appendix D, whereas in this section, the focus is on the relative importance of each aggregation/disaggregation agent in explaining each of the soil structure indexes.

Random forest models for Spanish results of MWD_d and MWD_w explained 67.98 % and 16.09 % of the variance from the training data, while for the British soils, it explained 77.52 % and 65.27 %, respectively. Variable importance to predict MWD_d and MWD_w in the Spanish and British soils is shown in Figure 56 and Figure 57. For the Spanish soils, tillage management increase in MSE in the MWD_d model was negative (-0.14 %) and in the 14th position from the 15 explanatory variables. On the contrary, tillage management in the MWD_w model had an increase in MSE of 2.34 % and was in 8th position among the chosen variables. In both models, GWC and K had high importance. For the British soils, tillage management increase in MSE in the MWD_d model was 3.93 % and in 11th position between the 15 variables. While for MWD_w, tillage management had a MSE increase of 7.10 % and was in the 6th position. In this case, sand, K and SOC were important.

For Spanish AS MiA, AS SMA and AS LMA, random forest models explained 62.71 %, 57.42 % and 27.22 % of the variance of the training data, whereas, for British results, they explained 62.76 %, 21.77 % and 57.81 %, respectively. Variables' importance to predict soils' AS MiA, AS SMA and AS LMA is shown in Figure 58 for Spanish and Figure 59 for British soils. In the Spanish cases, tillage management had an increase in MSE of 2.02 % for the AS MiA model, 2.33 % for the AS SMA model and 0.14 % for the AS LMA model being in the 13th position among the 15 chosen variables in all the models. As can be seen in Figure 58, the most important variables to predict AS MiA were $CaCO_3$, silt, and K, while for AS SMA, the most important variables were Fe, Mn and GWC; and for AS, LMA they were K, SOC and EC. For the British soils, tillage management had an increase in MSE of 1.23 %, 3.01 % and 5.45 % for the AS MiA, AS SMA and AS LMA models and was in 14th, 13th and 6th position among aggregation agents in the respective models.

These results show the relative importance of tillage management among aggregation agents. In other words, in the analysed farms, tillage management had a slight influence on soil structure but did not overpower the influence of other agents.

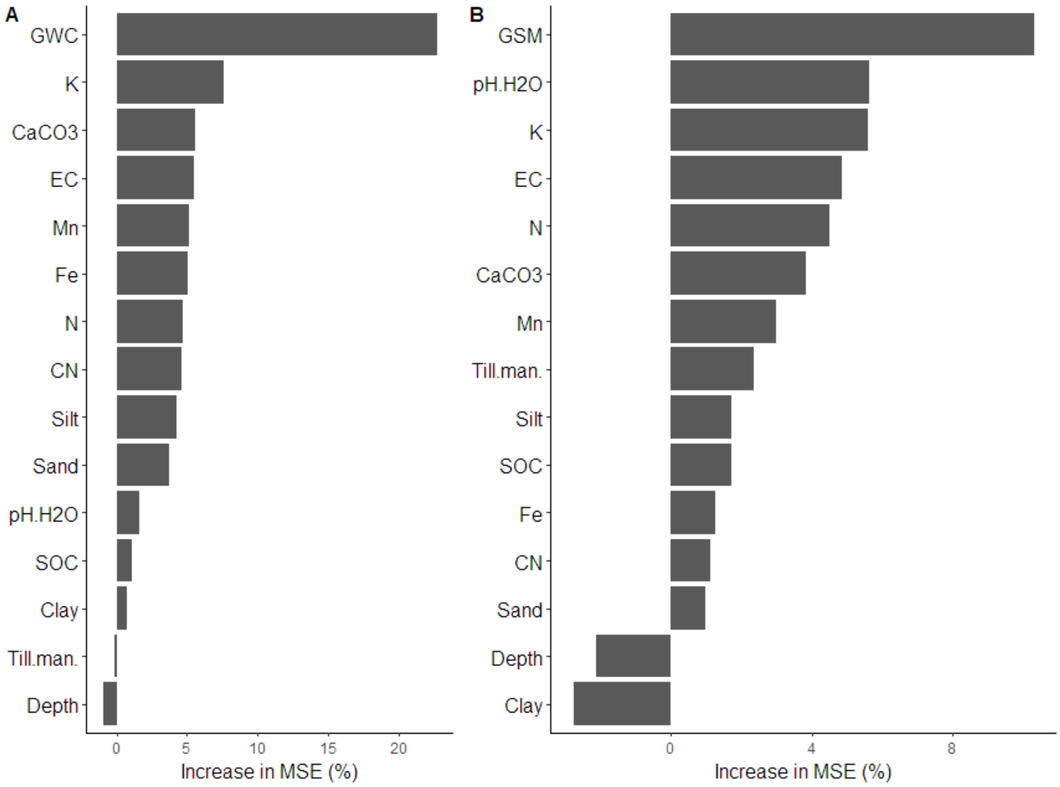


Figure 56. Variable importance in Spanish soils as the increase in mean square error. A: Random forest model for MWDd. B: Random forest model for MWDw

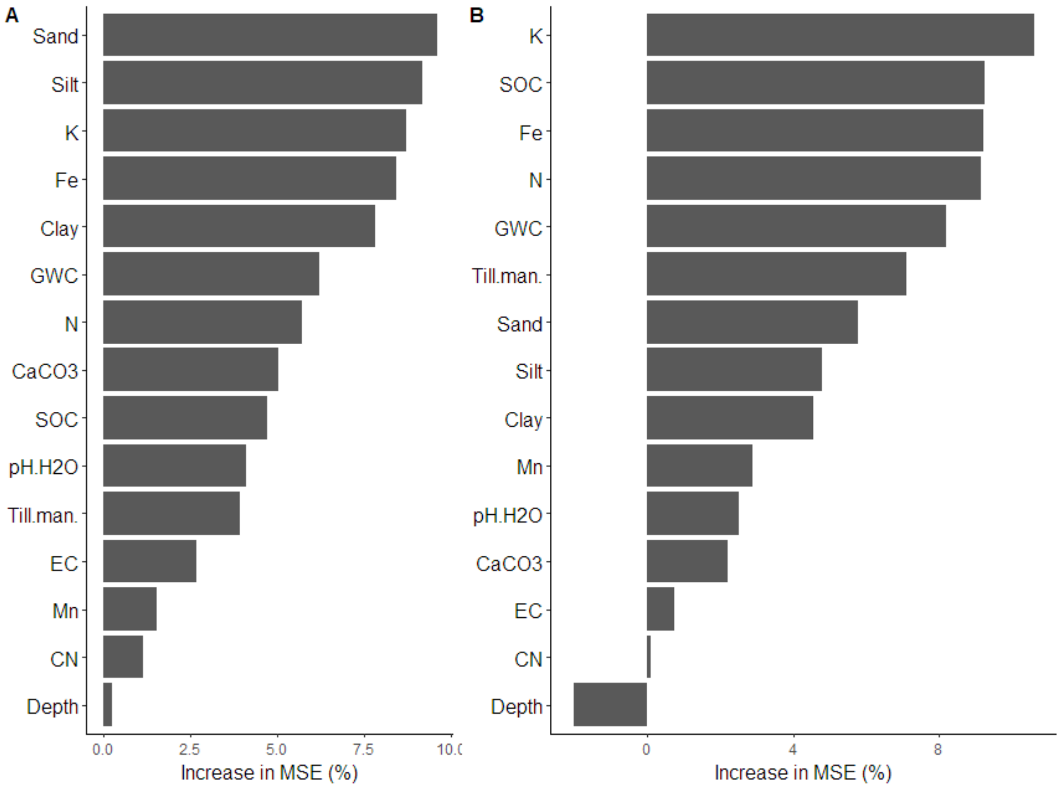


Figure 57. Variable importance in British soils as the increase in mean square error. A: Random forest model for MWDd. B: Random forest model for MWDw

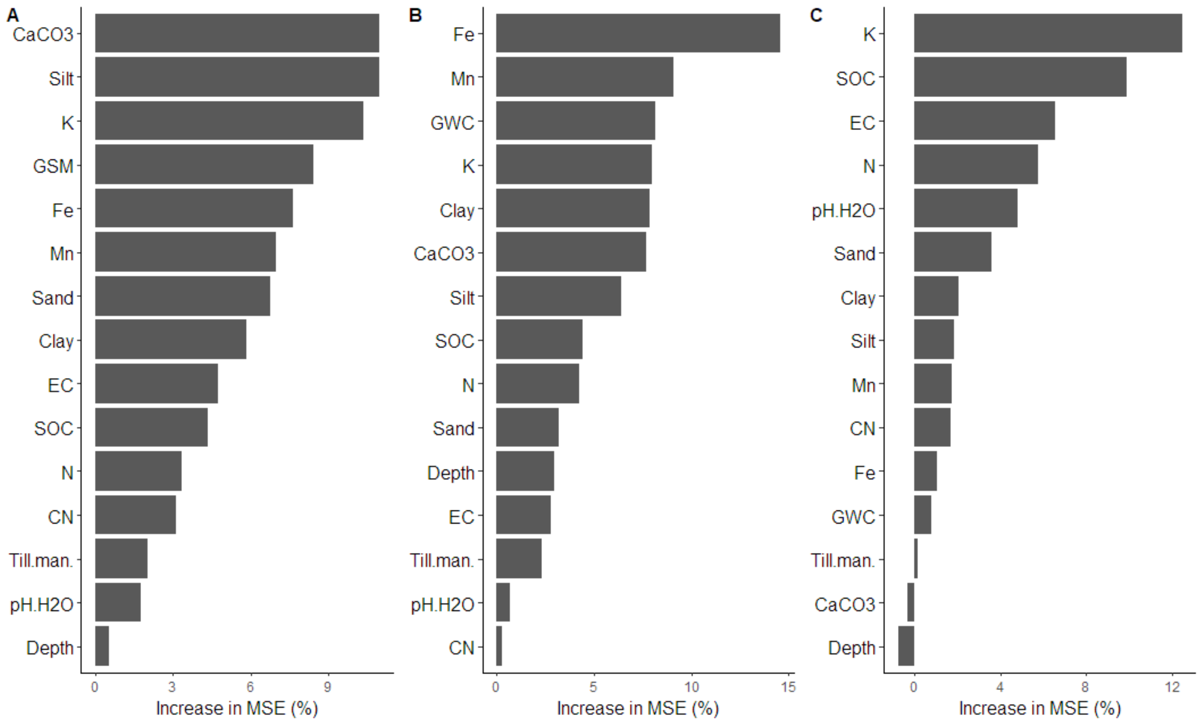


Figure 58. Variable importance in Spanish soils as the increase in mean square error. A: Random forest model for AS MiA; B: Random Forest model for AS SMA, C: Random forest model for AS LMA

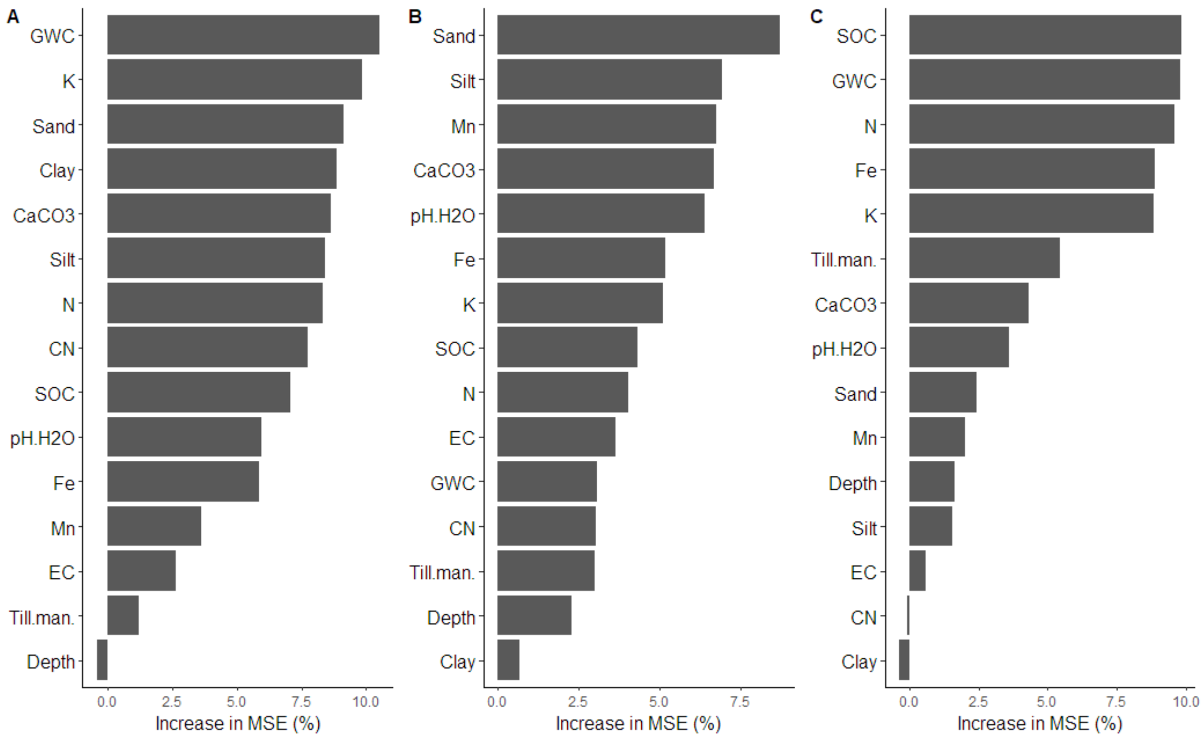


Figure 59. Variable importance in British soils as the increase in mean square error. A: Random forest model for AS MiA; B: Random Forest model for AS SMA, C: Random forest model for AS LMA

6.7. Relationships between soil structure and aggregation agents

This section includes the results of Pearson correlations performed between the different aggregation agents from section 6.4 and the soil structure indexes from section 6.5. Additionally, I discuss how these findings relate to previous research, particularly from the Mediterranean and Atlantic biogeographical regions.

6.7.1. Aggregation agents in the Spanish soils

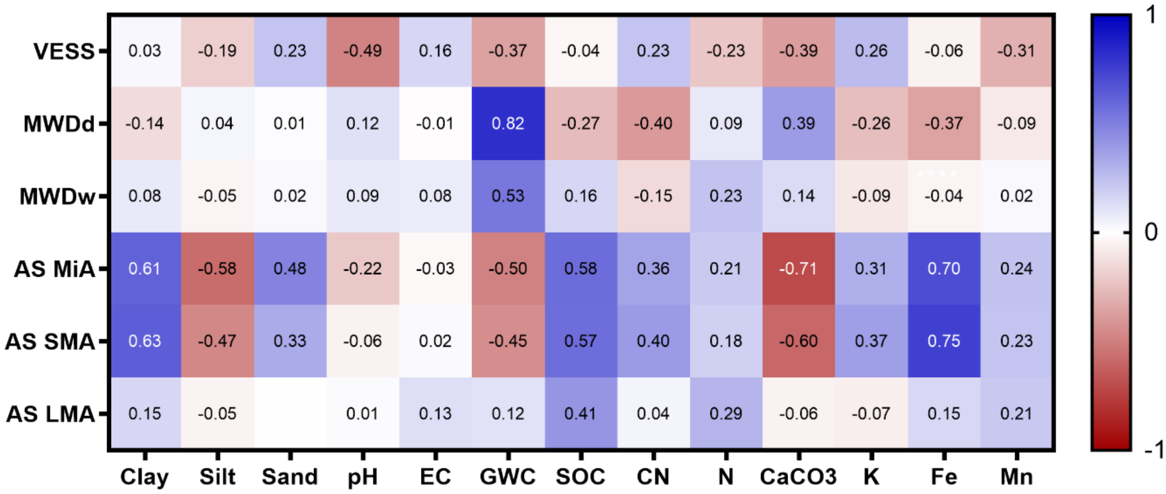


Figure 60. Heatmap of Pearson correlation coefficients between soil structure indexes and aggregation agents for Spanish soils

Pearson correlation coefficients between soil structure indexes and aggregation agents for Spanish soils are presented in Figure 60. VESS scores had significant correlation with pH (p-value <0.0001), GWC (p-value = 0.0037), CaCO3 (p-value = 0.0022), K (p-value = 0.0425) and Mn (p-value = 0.0147). The inverse relationship with GWC meant that soils with higher moisture scored better (lower score numbers), which aligns with Ball *et al.* (2007) suggestion that differences in VESS scoring between different fields assessed at different dates could be related to soil moisture, and particularly to lower soil moistures reducing cohesion among soil particles and lowering scores.

MWD indexes presented few significant correlations. Neither of the MWD indexes had a significant correlation with any of the soil particle sizes, despite clay being considered a major agent in aggregation dynamics. Indeed, in Serbia, MWD_d was directly related to clay and silt and inversely with sand (Ćirić *et al.*, 2012). On the contrary, MWD_d showed significant direct correlations with CaCO3 and inverse with K and Fe (p-values 0.0022, 0.0492 and 0.0040). When analysing the relationships between MWD with SOC, N and C/N, only MWD_d showed a significant correlation with SOC and C/N (p-values were 0.0388 and 0.0017), and surprisingly these were inverse relationships. This is opposite to organic matter being considered a major aggregation agent, particularly for macroaggregates; and findings from Falsone, Bonifacio and Zanini (2012) indicating that structural complexity increased with soil C/N ratio, and Haydu-Houdeshell et al. (2018) indicating that C/N ratio was highest in large macroaggregates suggesting less degraded organic matter in bigger aggregates. Furthermore, there were no significant relationships between pH nor EC and MWD, results that contrast with previous findings in soils from SE Spain where pH was positively correlated with larger aggregate sizes (Boix-Fayos *et al.*, 2001).

For AS, AS MiA and AS SMA presented more significant correlations with the aggregation agents than AS LMA. For instance, AS LMA had low coefficients with all of the particle size fractions, with no significant correlations. On the contrary, AS SMA and AS MiA had direct relationships with clay (p-values <0.0001) and sand (p-values 0.0103 and 0.0001 respectively) and inverse relationships with silt (p-values 0.0002 and < 0.00001). The direct relationship with clay was expected, as clay has a higher surface area and surface charge, providing more binding sites, whereas the direct relationship with sand is unexpected, as the contrary is true for sand (less binding capability). Nonetheless, this is explained in the fact that the same soils that had higher sand proportions also had higher clay quantities (and less silt). These results are consistent with previous findings in Italy, where higher AS MiA were correlated with sandy-clay textures while silty-loamy soils with low clay content were associated with low AS MiA (Spaccini & Piccolo, 2013). Additionally, Ramos, Nacci and Pla (2003) also found lower AS with increasing silt contents in NE Spain. Furthermore, none of the AS of the aggregate size fractions had significant relationships with pH nor EC, which contrast with the notion that salinity and monovalent cations increase clay dispersion and swelling, and therefore, reduce AS (Farahani *et al.*, 2018).

On the contrary, the analysis of the relationship between AS and SOC, N and C/N revealed that the AS of all three aggregate size classes was directly correlated with SOC (p-values 0.0010 with AS LMA and < 0.0001 with AS SMA and AS MiA). While only AS SMA and AS MiA had a significant correlation with C/N (p-values 0.0018 and 0.0047). Previously, in Mediterranean soils in California, AS did not show a statistically meaningful relationship with C/N (Haydu-Houdeshell *et al.*, 2018). significant correlation with Iron for SMA and AS SMA (p-values < 0.0001) was expected as iron acts as an aggregation agent. Not so the direct relationships between potassium and AS SMA and AS MiA (p-values 0.0032 and 0.0156), which are contrary to the notion of monovalent cations, such as Na and K, causing clay dispersion and therefore acting as disaggregation agents (Le Bissonnais, 1996). Potassium was even more dispersant than sodium in a study with Iranian soils, being clay dispersion and aggregate stability inversely related (Farahani *et al.*, 2018).

Importantly, AS SMA and AS MiA had a significant inverse correlation with GWC (p-values 0.0003 and <0.0001, respectively), which relate to the bias caused by sampling in different conditions. Moreover, it relates to the importance of understanding soils as dynamic entities, with characteristics that change in time with the influence of other dynamic parameters such as rainfall. Kemper and Rosenau (1986) associated the increased AS of dried soils to the soluble components such as silica, carbonates and organic molecules relocating and precipitating at the wedges of particles, acting as aggregation agents as soils dry; nonetheless, in this study, the relationship was inverse.

Surprisingly, calcium carbonate content had an inverse relationship with AS SMA and AS MiA (p-values < 0.0001). These results are contrary to a revision of the hierarchical aggregation model in the Mediterranean region after several studies found weak relationships between AS and SOC but strong correlations with $CaCO_3$. For example, Fernández-Ugalde et al. (2011) found positive results in their experiments that brought them to postulate that calcium carbonate helped to stabilise macroaggregates. Thus, in semi-arid regions, some of the aggregate stabilisation is attributed to calcium carbonate, which acts in two ways: first, calcium as polyvalent cation bonds with clays and SOC, and second, secondary carbonates precipitate forming bridges between existing soil aggregates or soil particles.

Accordingly, Boix-Fayos *et al.* (2001) suggested a threshold of 5 – 6% SOM to SOC becoming the major aggregation agent in soils from SE Spain, below that threshold carbonate content was strongly correlated with aggregate stability. However, they also found that SOM was inversely related to aggregates > 2mm while it was a direct relationship with aggregates < 1 mm. In this study, all aggregate sizes showed a direct relation with SOC, but soils did not exceed the specified threshold of 5 – 6 % SOM to SOM become the dominant aggregation agent (when multiplied per correlation factor 2.8 from Figure 61).

Nonetheless, my results do not indicate that $CaCO_3$ was a relevant aggregation agent for the researched soils. Nonetheless, MWD_d showed a direct correlation (p-value = 0.0022) with $CaCO_3$. All these findings might suggest that the aggregation capacity of $CaCO_3$ is brittle and dependant on the wet – drying cycle to be reestablished once broken, as described for cementing agents by Kemper and Rosenau (1986). Furthermore, Dimoyiannis *et al.* (1998) had described a destabilising potential of silt size calcium carbonates in soils developed from marl. In the current study, the relationship between $CaCO_3$ and particle size has not been studied, but it can be noted that the parental material in most of the farms were limestones, calcarenites, conglomerates and mudstones, and silt was the dominant fraction leading to sandy silt Loam texture classifications for the majority of the soils. Moreover, soils with higher silt content had also higher $CaCO_3$ contents (as did 4-NT).

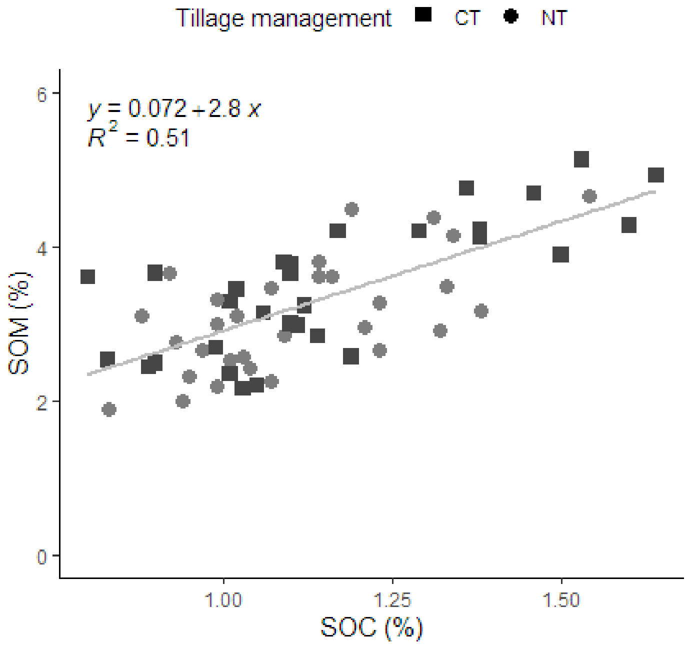


Figure 61. Linear regression between SOC and SOM

6.7.2. Aggregation agents in the British soils

Pearson correlation coefficients between soil structure indexes and aggregation agents for British soils are presented in Figure 62. VESS scores had significant direct correlation with CaCO3 (p-value = 0.0055), whereas surprisingly it presented significant inverse correlation with SOC (p-value = 0.0231), N (p-value = 0.0104), K (p-value = 0.0124) and Fe (p-value = 0.0424).

MWD indexes for British soils presented more significant correlations with aggregation agents than in the Spanish soils. Both MWD_d and MWD_w were directly correlated with clay and silt and inversely with sand (p-values < 0.0001 except for MWD_w and clay where the p-value was 0.0052). Moreover, both were directly correlated with GWC (p-values 0.0003 and < 0.0001 for MWD_d and MWD_w, respectively), SOC (p-values 0.0056 and < 0.0001), EC (p-value 0.0102 with MWD_d and 0.0052 with MWD_w) and N (p-values 0.0002 and < 0.0001, for MWD_d and MWD_w in that order). Additionally, both were directly correlated with K and Fe (p-values < 0.0001). Furthermore, MWD_d was positively correlated with Mn (p-value = 0.0206).

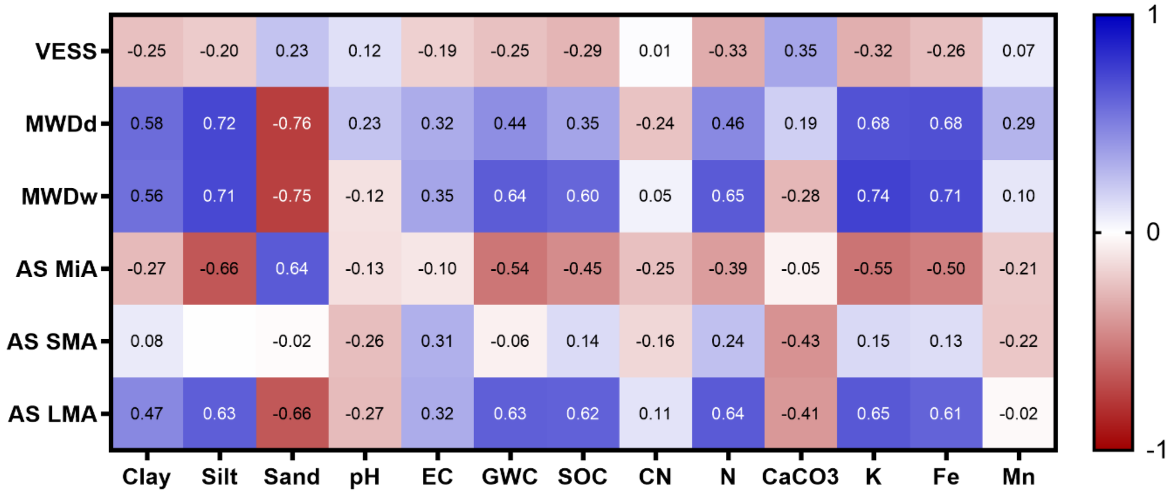


Figure 62. Heatmap of Pearson correlation coefficients between soil structure indexes and aggregation agents for British soils

AS for the British soils presented some striking correlations. Indeed, contrary to previous findings and the theoretical understanding of aggregation, AS MiA presented an inverse correlation with all of the aggregation agents except with sand. On the contrary, AS SMA and AS LMA presented positive correlations with some of the aggregation agents, although AS LMA correlations were stronger. Thus, AS LMA presented a significant direct correlation with clay and silt (p-values 0.0001 and < 0.0001) and inverse with sand (p-value < 0.0001). Additionally, AS LMA presented direct correlation with EC (p-value = 0.0105), GWC, SOC, N, K and Fe (p-values < 0.0001) and inverse with $CaCO_3$ (p-value = 0.0010).

6.8. Re-grouping soils according to aggregation agents

Soil sampling was designed assuming soils would be similar between neighbours and, therefore, tillage management impact on soil physical quality comparison between pairs. While this was the case for some neighbours, others had slightly different soils. After verifying that tillage importance predicting structure tests was lower than other factors, meaning that soil type was decisive, soils were re-grouped according to aggregation agents. This way, it would be possible to assess the tillage management effect among soils with comparable characteristics.

This section provides a description of each identified soil group according to their main aggregation/disaggregation agents. Thus, aggregation agents with significant correlations (p-values < 0.05) and with Pearson coefficients ≥ 0.50 were selected to perform principal component analysis (PCA) and cluster analysis.

6.8.1. Spanish soil groups based on aggregation agents

For the Spanish soils, the selected aggregation agents were Clay, Silt, GWC, SOC, CaCO3 and Fe. As a summary for cluster and PCA analysis, Figure 63 shows the five identified soil clusters per principal component 1 (Dim1) and 2 (Dim 2). It is possible to see some overlapping between clusters 3 and 4. To summarise the relationship between the soils and the aggregation agents, Figure 64 presents again principal component 1 (PC1) and 2 (PC2), but here soil samples are coloured by farm (instead of clusters) and the multiple aggregation agents considered, and their directions are shown with arrows (the arrow tip indicates increasing values for the aggregation agent). In any case, a summary of the different groups and their characteristics is provided below.

Group A (cluster 1 in Figure 63): 1-CT, 1-NT and 2-NT were greatly influenced by their moister soil conditions during soil sampling and a relatively high $CaCO_3$.

Group B (cluster 3 in Figure 63): 2-CT and 3-CT soils presented the highest clay, while silt contents were low. Moreover, those soils were in the higher range of SOC and had the highest Fe. Total $CaCO_3$ contents, which surprisingly presented an inverse relation with soil structural quality, was the lowest in those soils.

Group C (cluster 4 in Figure 63): 3-NT had the lowest silt contents and high clay but presented higher sand contents than the other soils. Additionally, it had the lowest pH and close to null $CaCO_3$ contents. Moreover, 3-NT presented lower SOC and Fe contents than 2-CT and 3-CT.

Group D (cluster 5 in Figure 63): 4-NT stood out due to its high silt content and somehow related high $CaCO_3$ content. Additionally, 4-NT had low clay, SOC and Fe contents.

Group E (cluster 2 in Figure 63): 4-CT, 5-CT and 5-NT presented similar soil characteristics as 1-CT, 1-NT and 2-NT being the main difference that they were collected at a lower soil moisture content. Additionally, they presented slightly higher Fe and K contents.

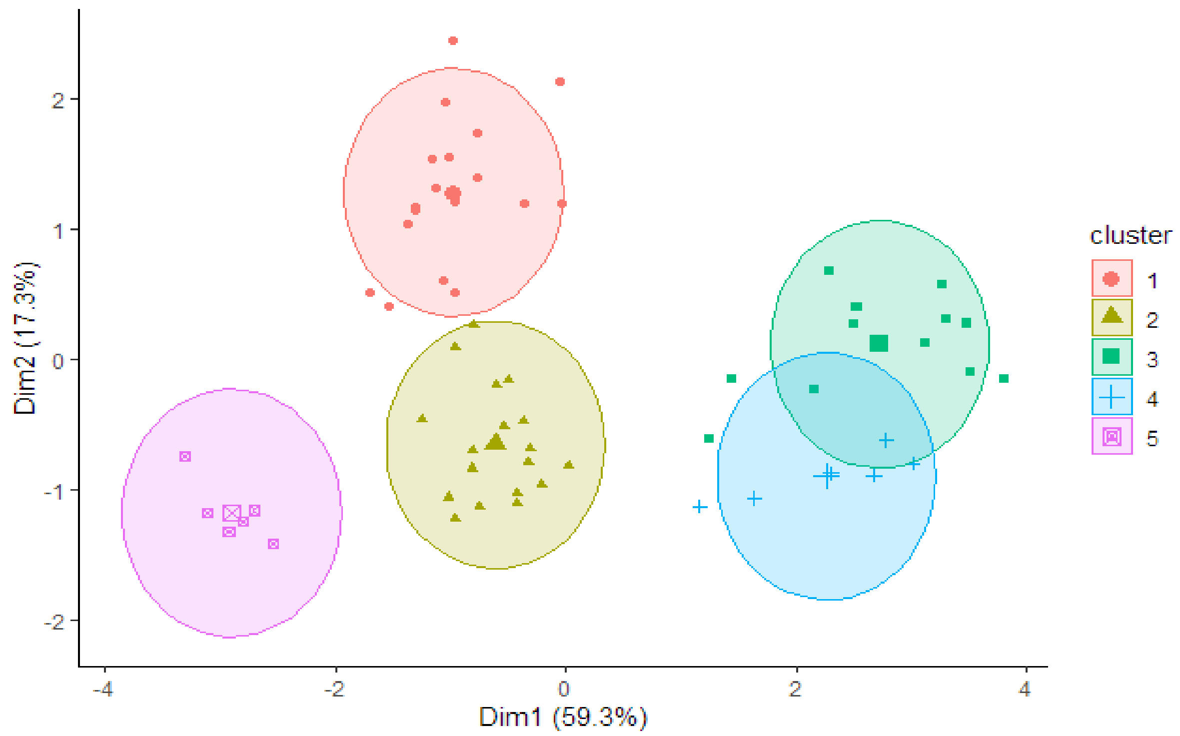


Figure 63. Spanish soils' clusters represented per principal components 1 and 2

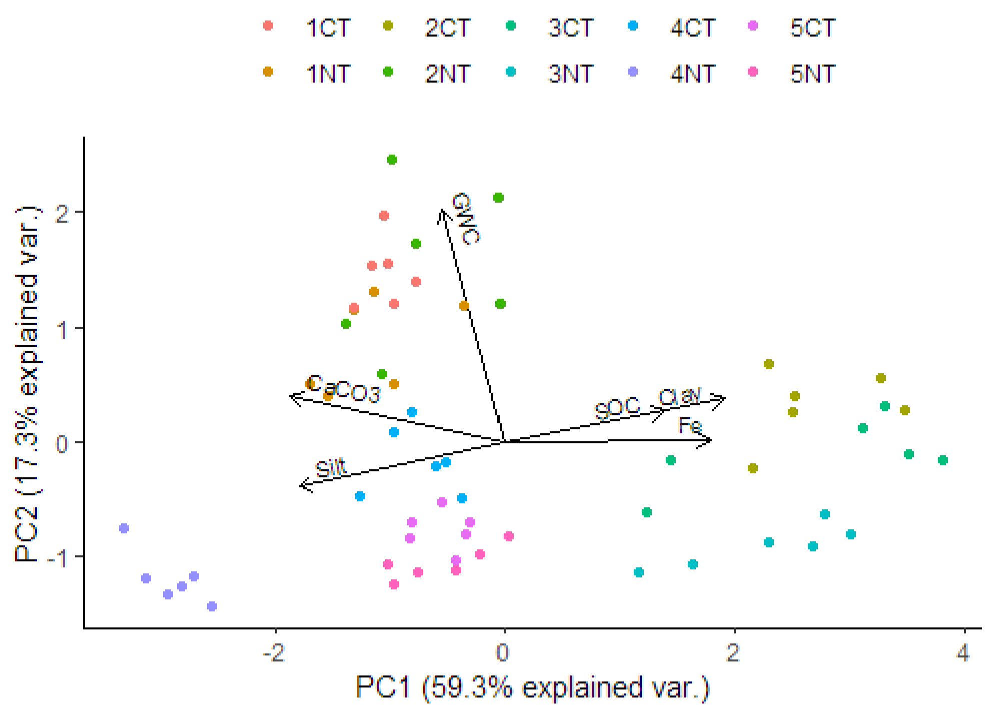


Figure 64. Spanish soils' principal components 1 and 2 with arrows representing variables' eigenvectors coloured by farm

6.8.2. British soil groups based on aggregation agents

For British soils, the aggregation agents considered in the clustering were GWC, SOC, N, Clay, Silt, Sand, K and Fe. Figure 65 shows the different soil clusters identified per PC1 (Dim1) and PC2 (Dim2), and Figure 66 presents the soil samples per farm with the direction of the aggregation agents.

Group F (cluster 1 in Figure 65): Soils from location 6, 7 and 9 presented low sand content, whereas silt contents were high and a range of clay contents. Additionally, GWC at the moment of sampling was higher than at the other fields. Moreover, these soils had high K and Fe contents and relatively high SOC and N.

Group G (cluster 2 in Figure 65): 8-NT and 8-CT presented intermediate sand and silt contents compared with the other soil groups and relatively low clay. Moreover, these soils presented relatively low SOC, N, K and Fe.

Group H (cluster 3 in Figure 65): 10-NT and 10-CT presented the highest sand contents among the sampled soils and lowest silt and clay. In contrast, other characteristics were very similar to group G.

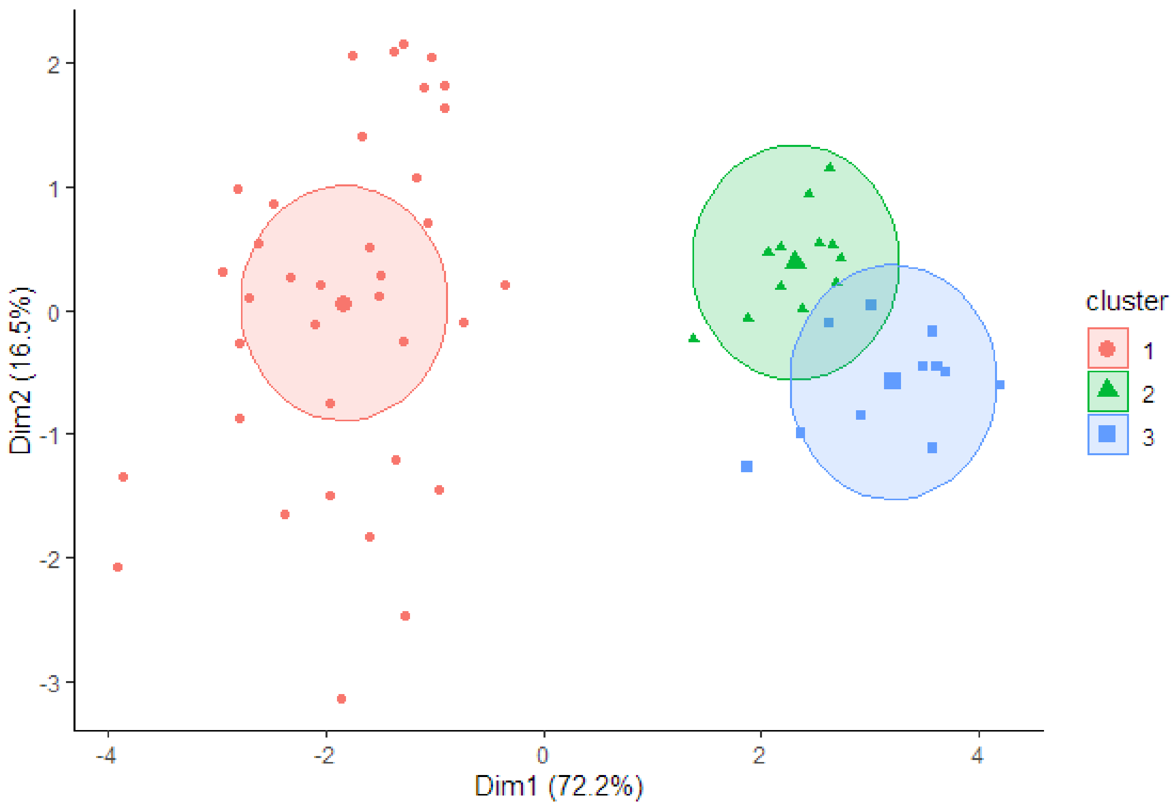


Figure 65. British soils' clusters represented per principal components 1 and 2

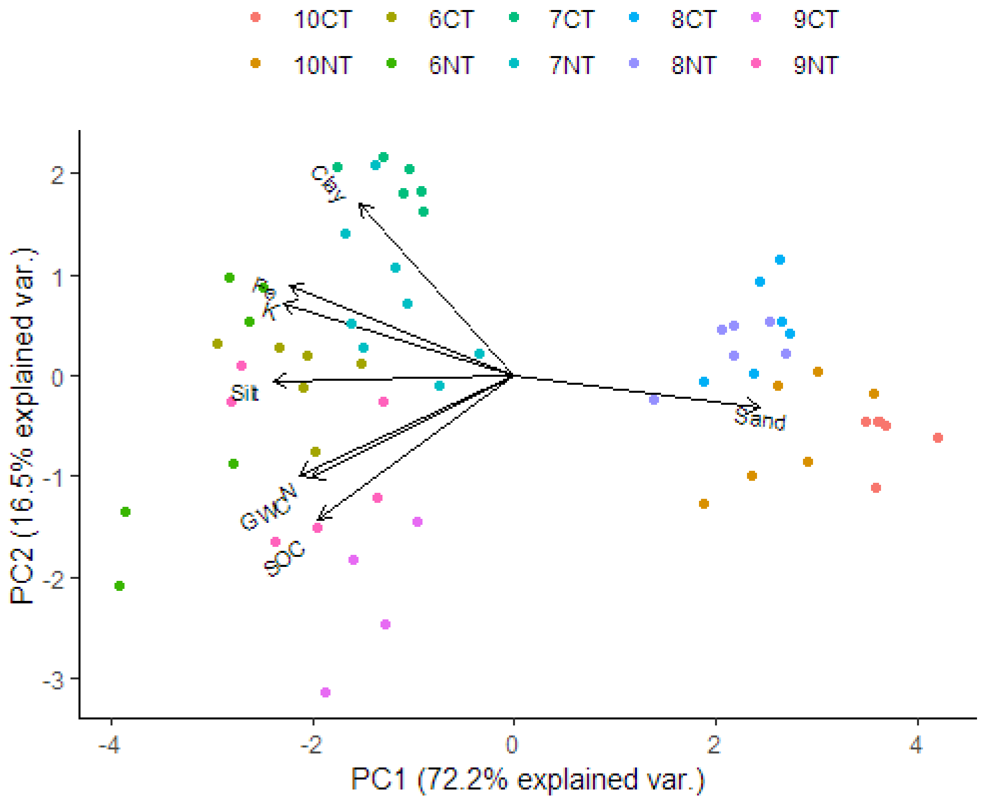


Figure 66. British soils' principal components 1 and 2 with arrows representing variables' eigenvectors coloured by farm

6.9. Tillage management impact on soil structure

Tillage management impact on soil structure was assessed for the identified soil groups comparing soils from no-tillage with soils from conventional tillage farms within each group. Additionally, the mean values of the soil structure tests from the different soil groups (no-tillage and conventional tillage combined) were compared.

6.9.1. Tillage management impact on soil structure for Spanish soils

For Spanish soils, the comparison between no-tillage and conventional tillage within soil groups was only possible in groups A and E, as the other identified groups had no representation of both tillage management strategies.

For MWD (Figure 67), when comparing MWD_d between no-tillage and conventional tillage in Group A and E, no statistically significant differences were found (p-values 0.8970 and 0.9711). Nonetheless, the MWD_d of Group A was significantly higher than the MWD_d of all other soil groups (p-values < 0.0001). No other statistically significant differences were found between soil groups for MWD_d. For MWD_w, no statistically significant differences were found between values of soils from no-tillage and conventional tillage farms in soil Groups A and E (p-values 0.5939 and 0.9971, respectively) nor between any of the soil groups.

For AS (Figure 68), in Group A, no-tillage soils presented statistically significantly higher AS MiA than conventional tillage soils (p-value 0.0112). No other differences between no-tillage and conventional tillage farms were statistically significant for the other aggregate size fractions nor in Group E. On the contrary, numerous differences between soil groups were statistically significant. Group B presented higher AS MiA and AS SMA than groups A, D and E (p-values < 0.0001). Group B AS SMA was also higher than for group C (p-value < 0.0001). Additionally, Group C presented higher AS MiA and AS SMA than group A and D (p-values < 0.0001), and Group E had higher AS MiA and AS SMA than group A and D (p-value < 0.0001). None of the differences between AS LMA between soil groups was statistically significant.

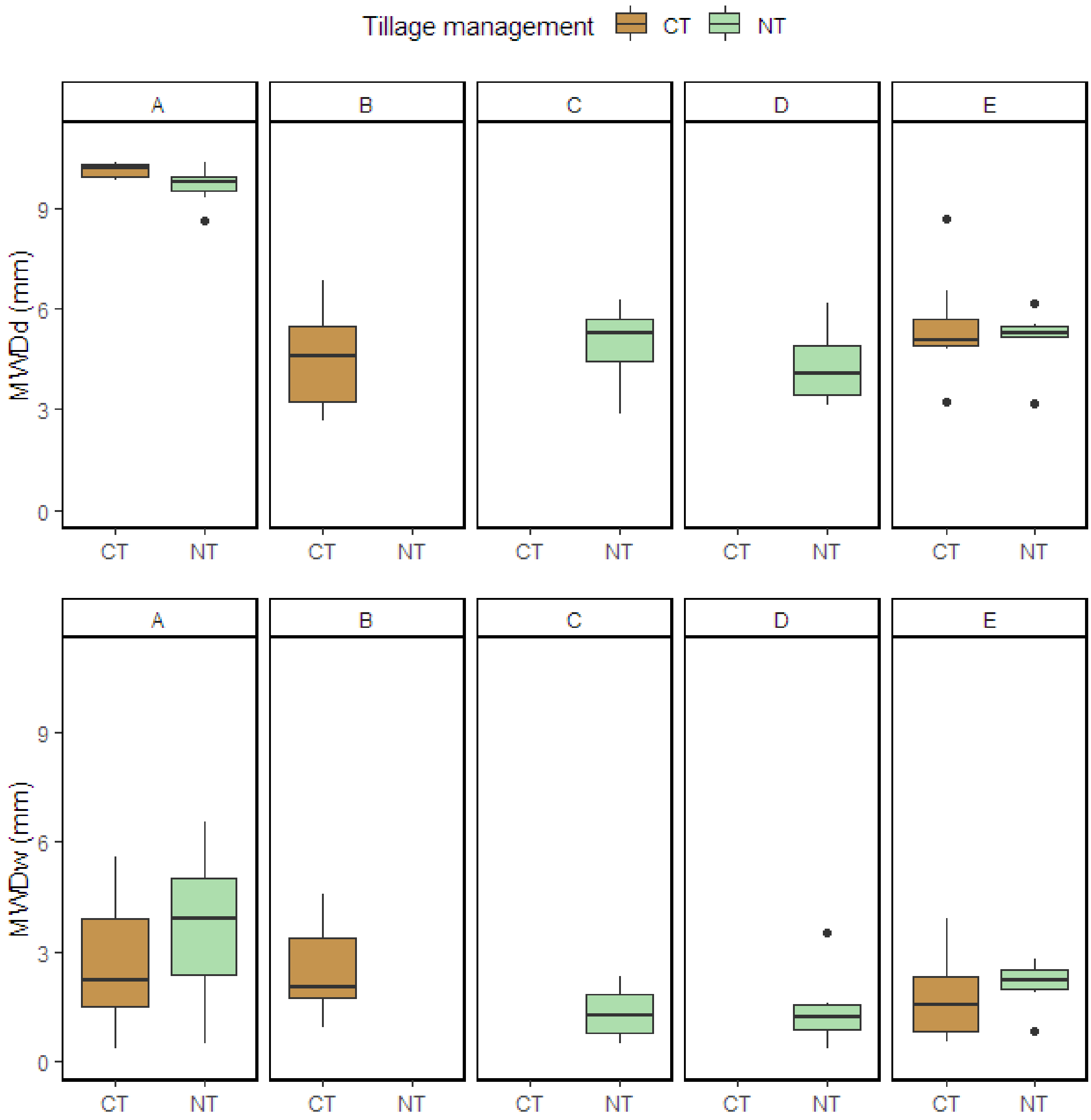


Figure 67. Mean wide diameter after dry (MWD_d) and wet (MWD_w) sieving of Spanish soils per soil group and tillage management. Graphs show pooled data per soil group and tillage management.

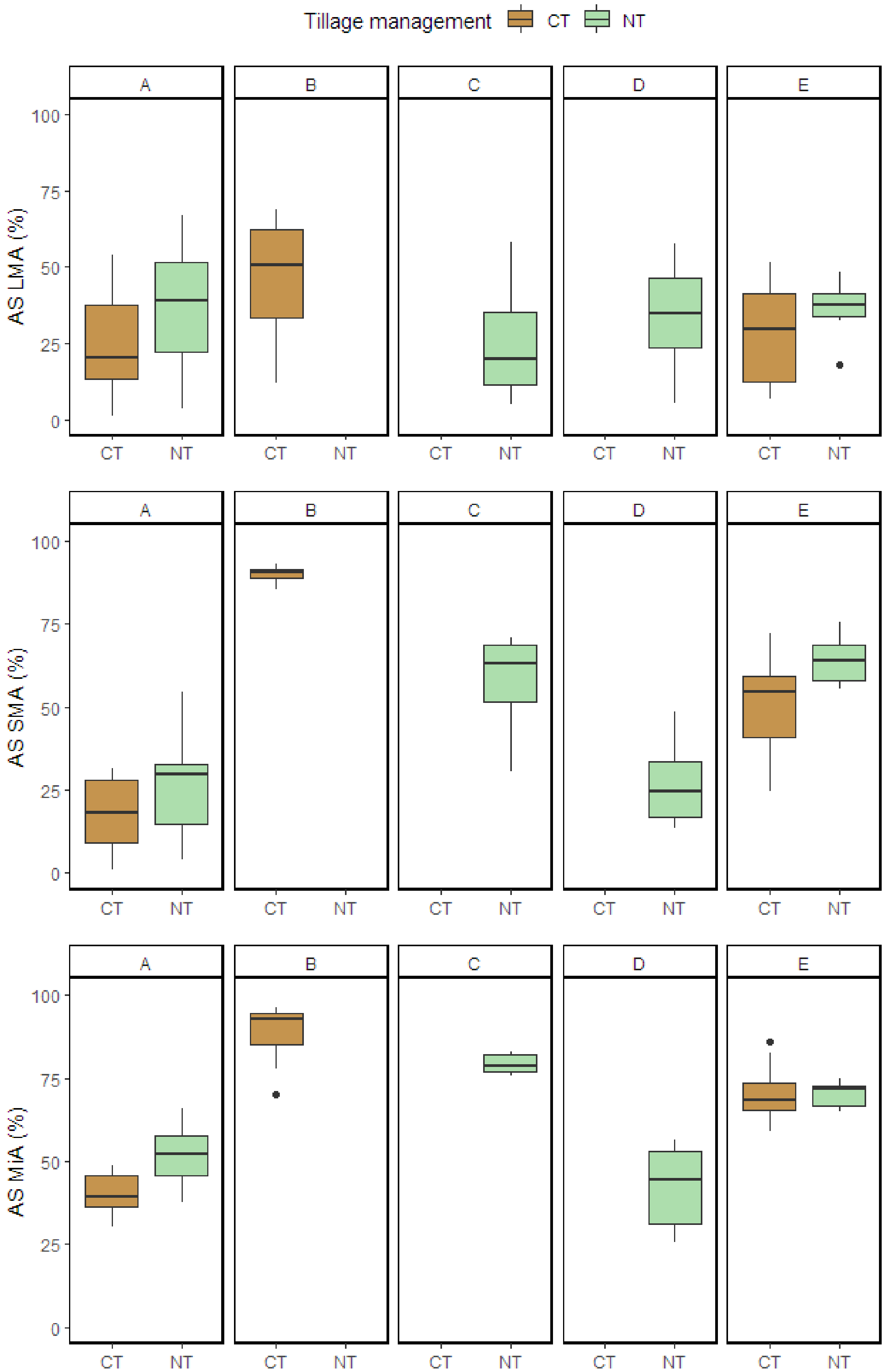


Figure 68. Aggregate stability (AS) of Spanish soils per aggregate size class, identified soil group and tillage management. MiA: microaggregates. SMA: small macroaggregates.LMA: large macroaggregates. Graphs show pooled data per soil group and tillage management.

6.9.2. *Tillage management impact on soil structure for British soils*

For British soils, the comparison between no-tillage and conventional tillage within soil groups was possible for the three groups.

For MWD (Figure 69), when comparing MWD_d between no-tillage and conventional within soil groups, no-tillage presented statistically significant higher values in Group F (p-value = 0.0060) and Group H (p-value <0.0001). Moreover, Group H presented significantly lower MWD_d than Groups F and G (p-values < 0.0001). For MWD_w, no-tillage also had higher values than conventional tillage management in Groups F (p-value < 0.0001) and G (p-value = 0.0103), while the difference in Group H was not statistically significant (p-value = 0.0897). Additionally, Group F had a higher average MWD_w than the other groups.

For AS (Figure 70), when comparing AS between no-tillage and conventional tillage within soil groups, neither AS MiA nor AS SMA showed statistically significant differences. On the contrary, AS LMA was higher in no-tillage fields than in conventional tillage fields in Group F (p-value = 0.0004) and G (p-value = 0.0022). Moreover, the average AS LMA of Group F was higher than Group G (p-value < 0.0001) and Group H (p-value < 0.0001). However, the average AS MiA from Group F was lower than those of Group G (p-value = 0.0038) and Group H (p-value < 0.0001).

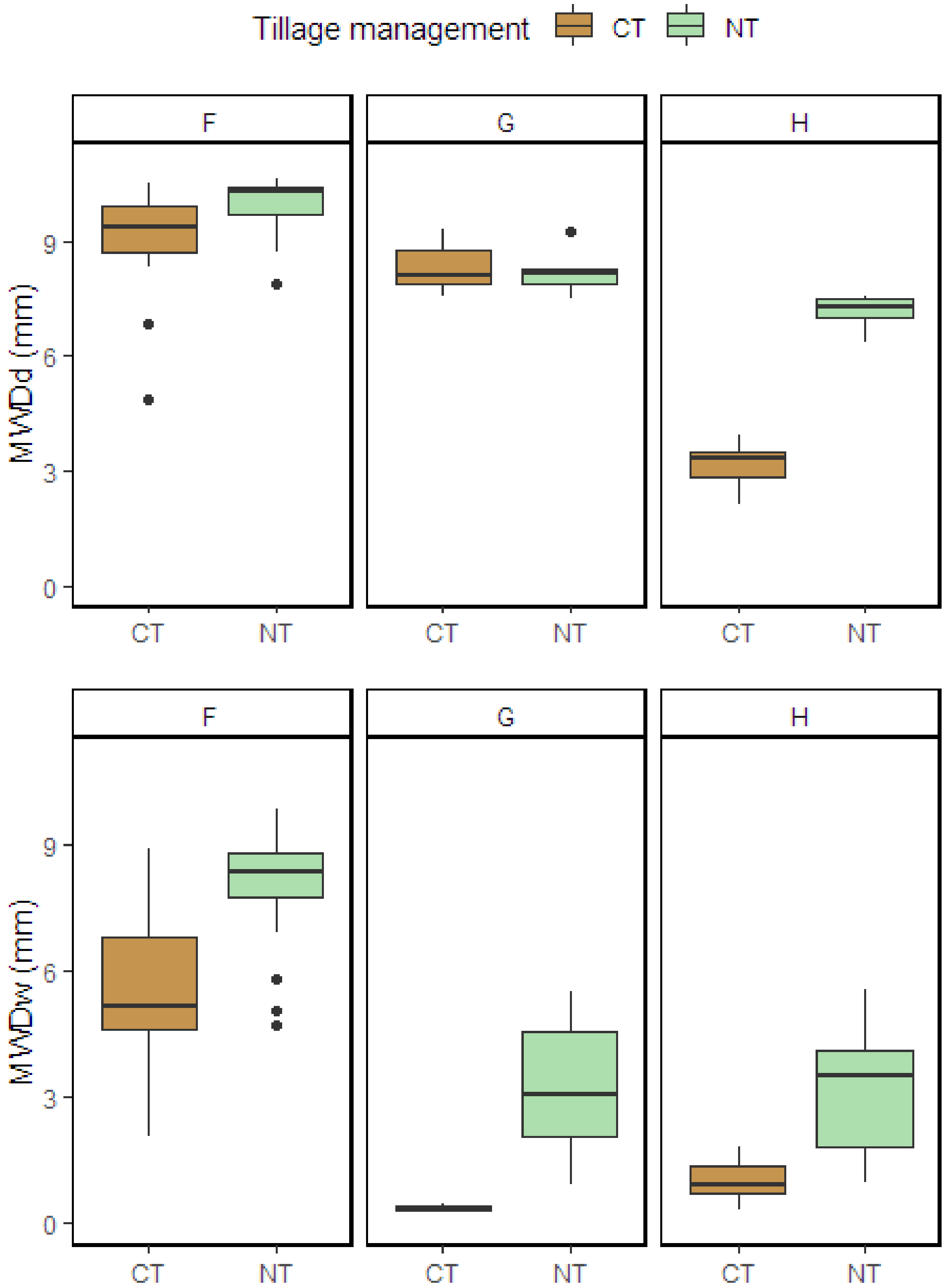


Figure 69. Mean wide diameter after dry (MWDd) and wet (MWDw) sieving of British soils per soil group and tillage management. Graphs show pooled data per soil group and tillage management.

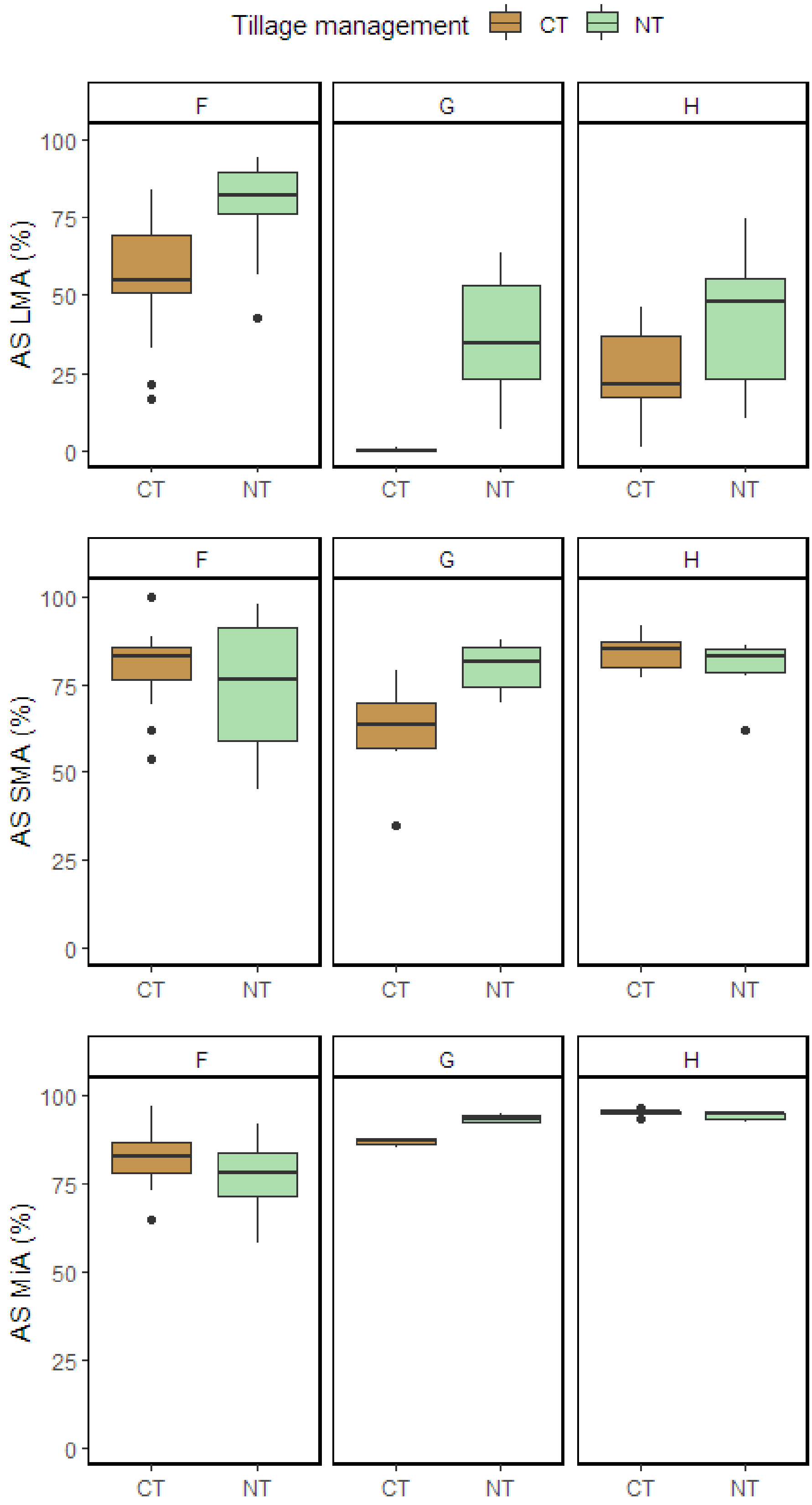


Figure 70. . Aggregate stability (AS) for British soils per aggregate size class, identified soil group and tillage management. MiA: microaggregates. SMA: small macroaggregates.LMA: large macroaggregates. Graphs show pooled data per soil group and tillage management.

6.10. Soil compaction assessment

This section presents the soil compaction assessment through BD measurement in the laboratory and PR on-farm. The assessment uses critical values from the literature.

First, the results of all tests are presented, and then the discussion focuses on the coherence between tests, the relationships with some soil parameters, soil structure and the impact of tillage management on soil compaction.

6.10.1.Bulk density results

Results for bulk density (BD) are shown in Table 19 and Table 20 for Spanish and British analysed soils, respectively.

Table 19. Spanish soils' bulk density for the fine soil and the soil with coarse elements

Field	BD_f (g/cm^3)	BD_{ce} (g/cm^3)
1-NT	1.59 ± 0.18	1.63 ± 0.19
1-CT	1.33 ± 0.11	1.38 ± 0.11
2-NT	1.46 ± 0.13	1.52 ± 0.13
2-CT	1.07 ± 0.18	1.23 ± 0.17
3-NT	1.53 ± 0.19	1.58 ± 0.18
3-CT	1.33 ± 0.25	1.40 ± 0.24
4-NT	1.38 ± 0.09	1.43 ± 0.09
4-CT	1.26 ± 0.10	1.32 ± 0.10
5-NT	1.61 ± 0.22	1.65 ± 0.21
5-CT	1.55 ± 0.19	1.61 ± 0.19

*Results show average ± SEM

Table 20. British soils' bulk density for the fine soil and the soil with coarse elements

Field	BD_f (g/cm^3)	BD_{ce} (g/cm^3)
6-NT	0.93 ± 0.08	0.95 ± 0.09
6-CT	1.04 ± 0.13	1.05 ± 0.13
7-NT	1.25 ± 0.16	1.30 ± 0.04
7-CT	1.06 ± 0.11	1.12 ± 0.15
8-NT	1.31 ± 0.16	1.35 ± 0.16
8-CT	1.33 ± 0.13	1.36 ± 0.13
9-NT	1.28 ± 0.08	1.36 ± 0.13
9-CT	0.93 ± 0.11	1.08 ± 0.19
10-NT	1.61 ± 0.07	1.61 ± 0.07
10-CT	1.30 ± 0.13	1.31 ± 0.13

*Results show average ± SEM

Critical bulk density values, situated at 1.65 for silty loam soils (USDA texture class) (Bowen, 1981 cited in Porta, López-Acevedo and Roquero, 1999) was reached only by BD_{ce} at 5-NT. 3-NT, 8-NT, 8-CT and 10-NT presented slightly coarser texture, and therefore the BD critical value was 1.80 g/cm^3 for the Fine sandy loam (USDA texture class), which was not surpassed. Similarly, 10-CT did not surpass its critical BD value, situated at 1.85 g/cm^3 for the Loamy fine sand (USDA texture class).

6.10.2. *Penetration resistance*

Initially, nonlinear regression on SPSS was intended to be used to fit measured data to Equation 16 and identify coefficients and R^2 values. For purposes of the curve fitting, data from the three sample points (averages) in each field were used at depths 0 – 5 and 5 – 10 cm, together with the bulk density of the fine soil, the GWC and the volume of the coarse elements obtained during bulk density determination.

Equation 16. Penetration resistance function

$$PR = \exp\left(a + b\rho_f + c\theta_g + dCE\right)$$

Those coefficient values were intended to be used to standardise penetration resistance measurements to gravimetric water content (0.2 g/g and 0.1 g/g at location 3) and then compare penetration resistance between no-tillage and conventional tillage fields at similar moisture conditions (results shown in Figure 71 and Figure 72 for the Spanish and British sites, respectively). Nonetheless, the model fit did not always return logical relationships between the variables, meaning that PR increased with bulk density and coarse elements but had an inverse relationship with soil moisture. Moreover, as already shown for the soil structure assessment, the data analysis shifted from comparing neighbour fields to comparing clustered groups. Therefore, rather than using the moisture corrected curves, PR field measures from 0 – 5 and 5 – 10 cm depth were used for further analysis. Additionally, due to the dry conditions at locations 4 and 5, it was impossible to take PR measurements. Therefore, maximum pressure exerted by the handhold penetrometer was recorded.

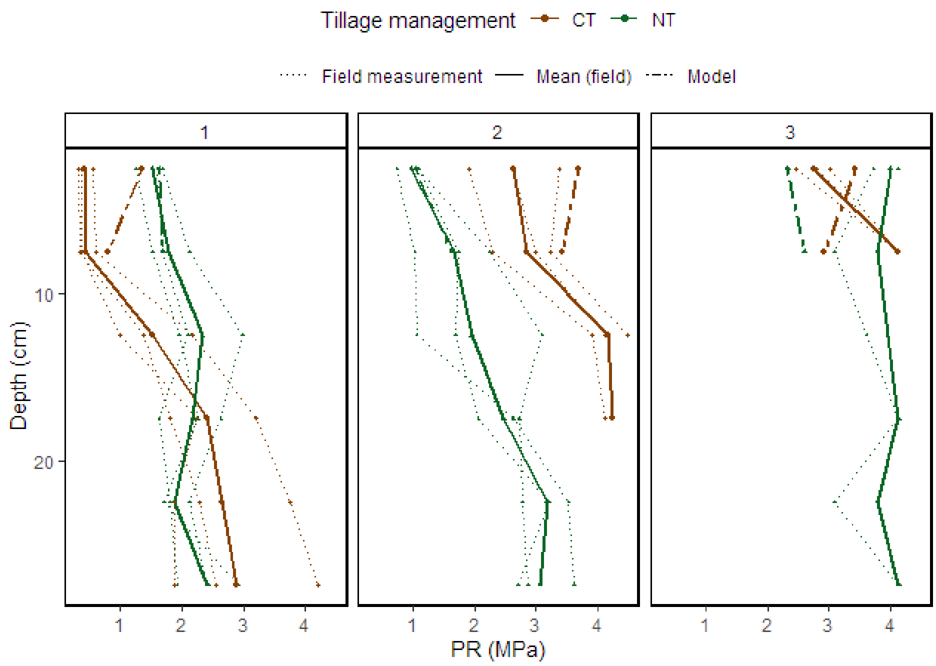


Figure 71. Spanish penetration resistance (PR) values for locations 1, 2 and 3. Graphs show field measurements, mean and model results per field.

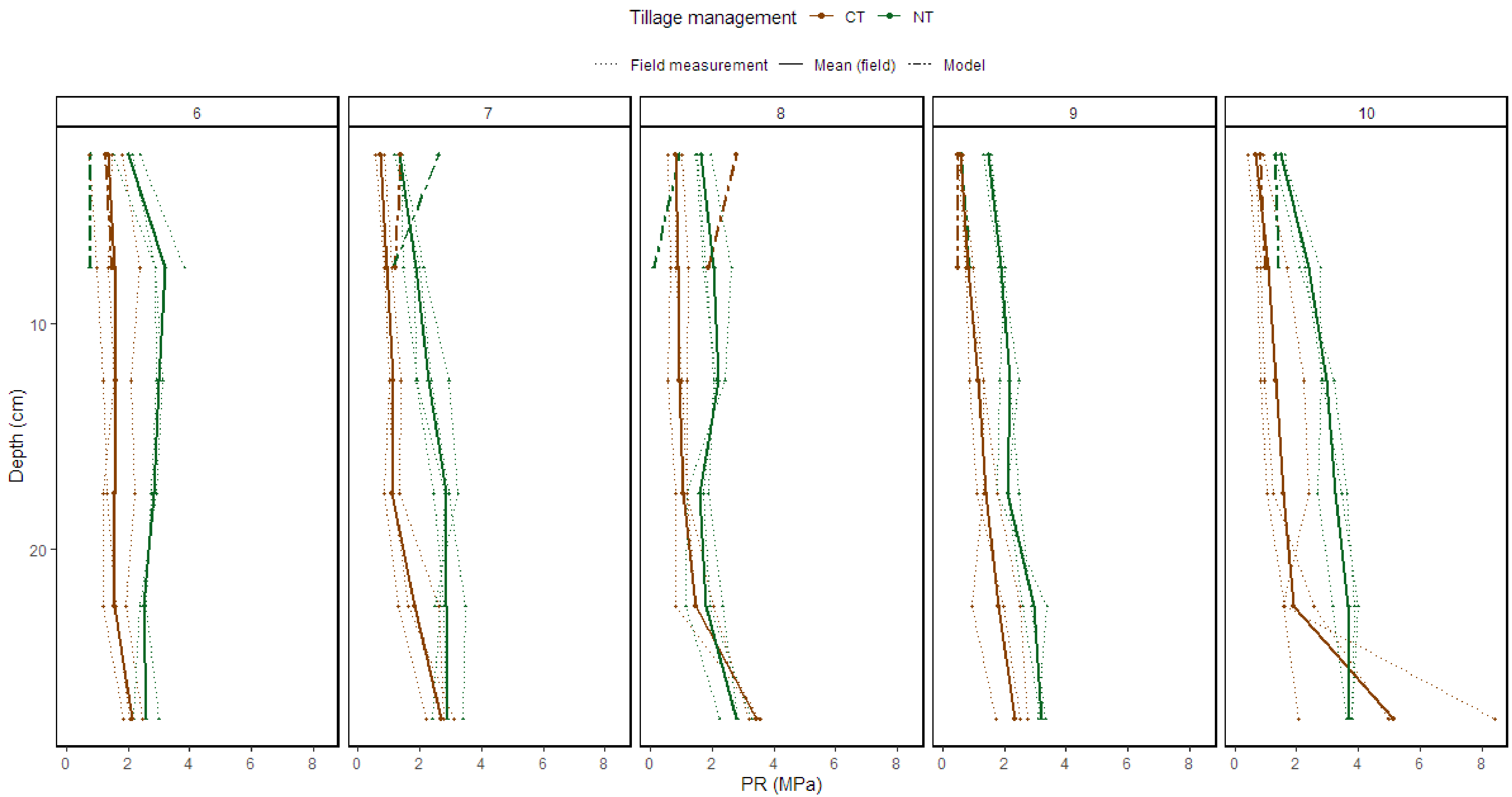


Figure 72. British penetration resistance (PR) values for locations 1, 2 and 3. Graphs show field measurements, mean and model results per field.

6.10.3. *Coherence between soil compaction tests*

PR and BD are expected to be directly related, as both parameters indicate compaction when values increase. Many studies support this hypothesis resulting in pedotransfer functions that express the relationship either with a linear or exponential function (Vaz *et al.*, 2011). However, the results of this research did not show a strong relationship, as Figure 73 and Figure 74 show for the Spanish and the British data. On the contrary, aside from the very hard soils with PR ≥ 4.13 MPa, the relationship between BD_f and PR for Spanish soils was inverse.

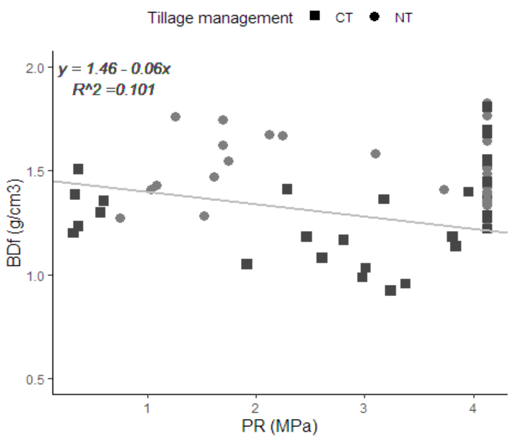


Figure 73. Relationship between bulk density and penetration resistance at Spanish fields. Fitted line excludes sites with PR ≥ 4.13 MPa. Graph shows data per sample site and depth

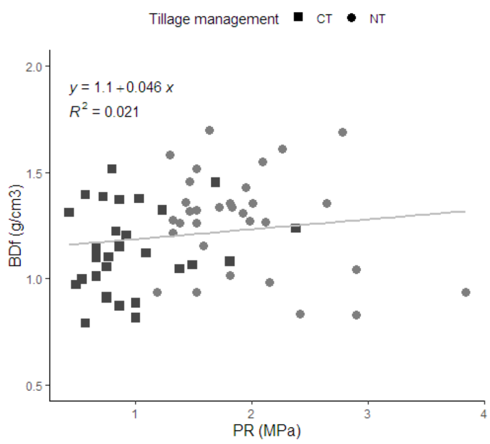


Figure 74. Relationship between bulk density and penetration resistance at British fields. Graph shows data per sample site and depth.

6.11. Relationships between compaction and structure

In this section, I discuss the relation between soil compaction and soil structure. Related to this, first, I discuss the limitations of penetrometers to assess soil compaction.

It is important to understand the limitations of penetrometers when assessing root development considering soil structure. In this project, root and crop development were not assessed. However, crops might present healthy conditions at penetration resistances higher than 2 MPa. This is because roots need a continuous pore space and a minimum pore diameter of 10 µm to grow (Gregaory, 2006, cited in Tracy *et al.*, 2011). Nonetheless, roots might apply other strategies such as sloughing of border cells, producing exudations, increasing root diameter, and incrementing root hair density when encountering compacted soil layers (Bengough *et al.*, 2006). Moreover, roots need to exert three times less pressure than metal penetrometers, as metal equipment create greater friction with the soil (Bengough and Mullins, 1990 cited in Whalley *et al.*, 2007).

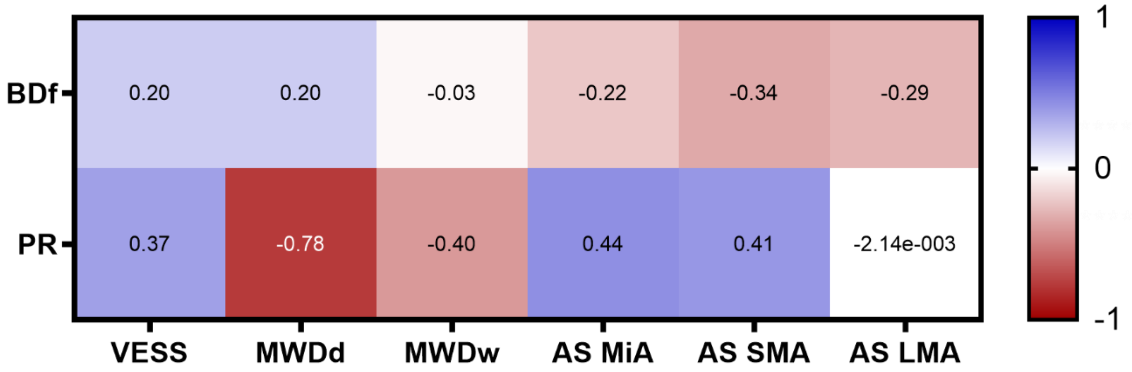


Figure 75. Heatmap of Pearson correlation coefficients between soil compaction measurements and soil structure indexes for Spanish soils

Figure 76. Heatmap of Pearson correlation coefficients between soil compaction measurements and soil structure indexes for British soils

From a soil structure development point of view, it would be expected that ASD dominated by smaller particles (lower MWD) translate in higher BD, whereas ASD dominated by bigger aggregates (higher MWD) translate in lower BD due to their associated inter-aggregate pore space. In this study, as can be seen in Pearson correlation coefficients presented in Figure 75 for the Spanish soils and Figure 76 for the British samples, the relationships between BD and MWD in Spain were direct for MWD_d and inverse for MWD_w, although not statistically significant. Whereas in the UK, the relationships were inverse and with MWD_w, it was significant (p-value = 0.0065).

The correlation between BD and VESS was only significant in the UK (p-value < 0.0001) but direct in both countries, meaning that the higher Sq. scores a soil had, the higher its BD and PR or compaction.

Regarding the relationships with AS, in Spain, BD was inversely related to all three aggregate size fractions considered for AS tests and were significant for AS SMA (p-value 0.0077) and AS LMA (p-value 0.0242). In the UK, the only significant correlation between BD and AS was with AS LMA (p-value 0.0045). These results align with the idea of well-developed soil structures, decreasing soil bulk density.

On the contrary, PR had direct relationships with all structure tests except with MWD tests in Spain. The correlations between PR and MWD were significant in Spain (p-values <0.0001 with MWD_d and 0.0017 with MWD_w) and in the UK (p-values 0.0247 and 0.0007, for MWD_d and MWD_w, respectively). Moreover, correlations between PR and AS were significant in the case of AS MiA and AS SMA in Spain (p-values 0.0005 and 0.1648) and AS LMA in the UK (p-value 0.0008). The correlation with VESS was significant in Spain (p-value = 0.0035) and in the UK (p-value < 0.0001).

6.12. Tillage management impact on soil compaction

Through the analysis of the relations between compaction tests with some soil properties and soil structure tests, it was possible to describe the behaviour of the different soil groups regarding soil compaction. Additionally, ANOVA tests between soil groups and between no-tillage and conventional tillage management within soil groups were performed to distinguish statistically significant differences.

6.12.1. Tillage management impact on soil compaction for Spanish soils

BD and PR results per soil group and tillage management for the Spanish soils are presented in Figure 77.

Group A (1-CT, 1-NT and 2-NT) presented lower PR than the other soil groups (p-value <0.0001) due to higher moisture contents at the moment of measuring. Nonetheless, these soils had average or even high BD due to low SOC and low AS.

Group B (2-CT and 3-CT) presented > 2 MPa but not as extreme PR values as groups D and E, at similar moisture contents (p-values 0.0277 and 0.0027, respectively). Higher PR values than those from group A might be explained due to a combination of lower moisture conditions and higher CE_v. Additionally, Group B BD values were significantly lower than group A, C and E (p-values 0.0066, 0.0146 and 0.0032, respectively). Group B soils had high clay content and SOC, which can affect compaction directly due to their physical properties and also indirectly due to their positive impact on soil structure.

Group C (3-NT) had high and extreme PR values and average to high BD, which might be explained because of higher sand content. In the case of BD, being related to fewer micropores, and in the case of PR, to increased friction.

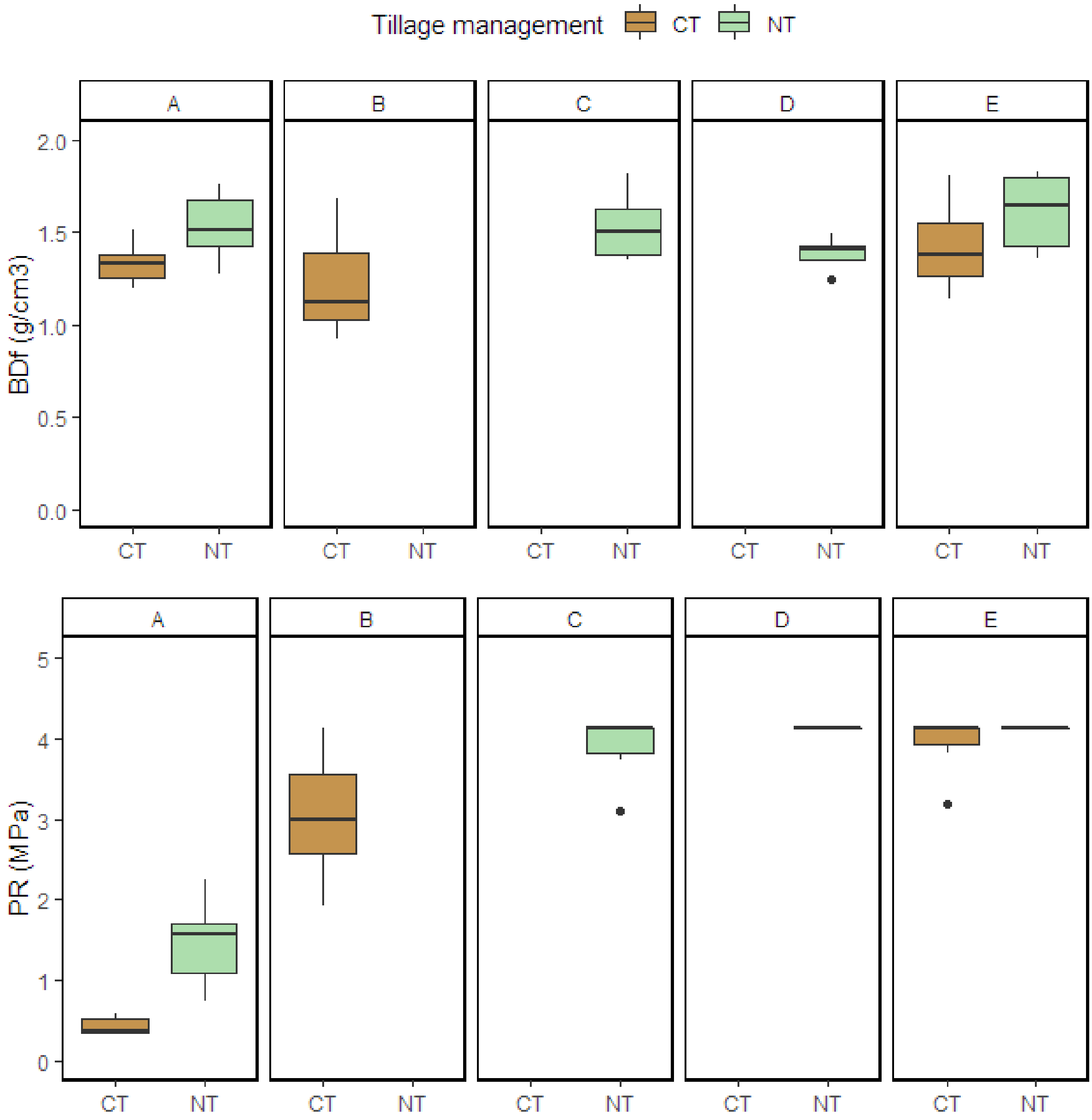


Figure 77. Compaction tests per identified soil group and tillage management at Spanish farms. BDf: bulk density of the fine soil. PR: penetration resistance. Graphs show pooled data per soil group and tillage management.

Group D (4-NT) presented extreme PR values and average to high BD, which might be explained due to low GWC in the case of PR, and low AS and high SC fractions in the case of BD.

Group E (5-CT, 5-NT, 4-CT) presented extreme PR (the recorded values corresponded to the maximum pressure the penetrometer operator was capable of exerting without even penetrating the soil surface, rather than actual compactness). Those values were due to a combination of dry soil conditions and less developed soil structures. 4-CT had slightly moister conditions than the previous group of soils, which would explain its slightly lower PR.

When comparing the tillage management effect on BD in Spain at groups A and E, there were no statistically significant differences (p-values 0.0876 and 0.0746, respectively). However, group's A, PR values were significantly higher for no-tillage than for conventional tillage (p-value < 0.0001), but not so in group E (p-value 0.9576), where maximum values were recorded at location 5 sites due to dryness, and slightly lower values correspond to slightly moister 4-CT measurements.

6.12.2. Tillage management impact on soil compaction for British soils

At the British fields, Group F presented lower BD values than Group G and H (p-values 0.0092 and <0.0001, respectively), probably due to higher SOC content and bigger aggregates (higher MWD_d and MWD_w), leaving more inter-aggregate pore space. There were no other significant differences between soil groups for BD nor PR, suggesting that small differences in particle size contents between Groups H and G did not affect compaction.

Nonetheless, when comparing tillage management, significant differences could be found. No-tillage had significantly higher BD than conventional tillage fields in Group F (p-value = 0.0211) and in Group H (p-value = 0.0089). Whereas in Group G, BD values were more similar between the tillage management strategies (p-value 0.9999). Moreover, no-tillage had higher PR in all soil groups (p-values < 0.0001 for Group F, 0.0020 for Group G and 0.0010 in Group H).

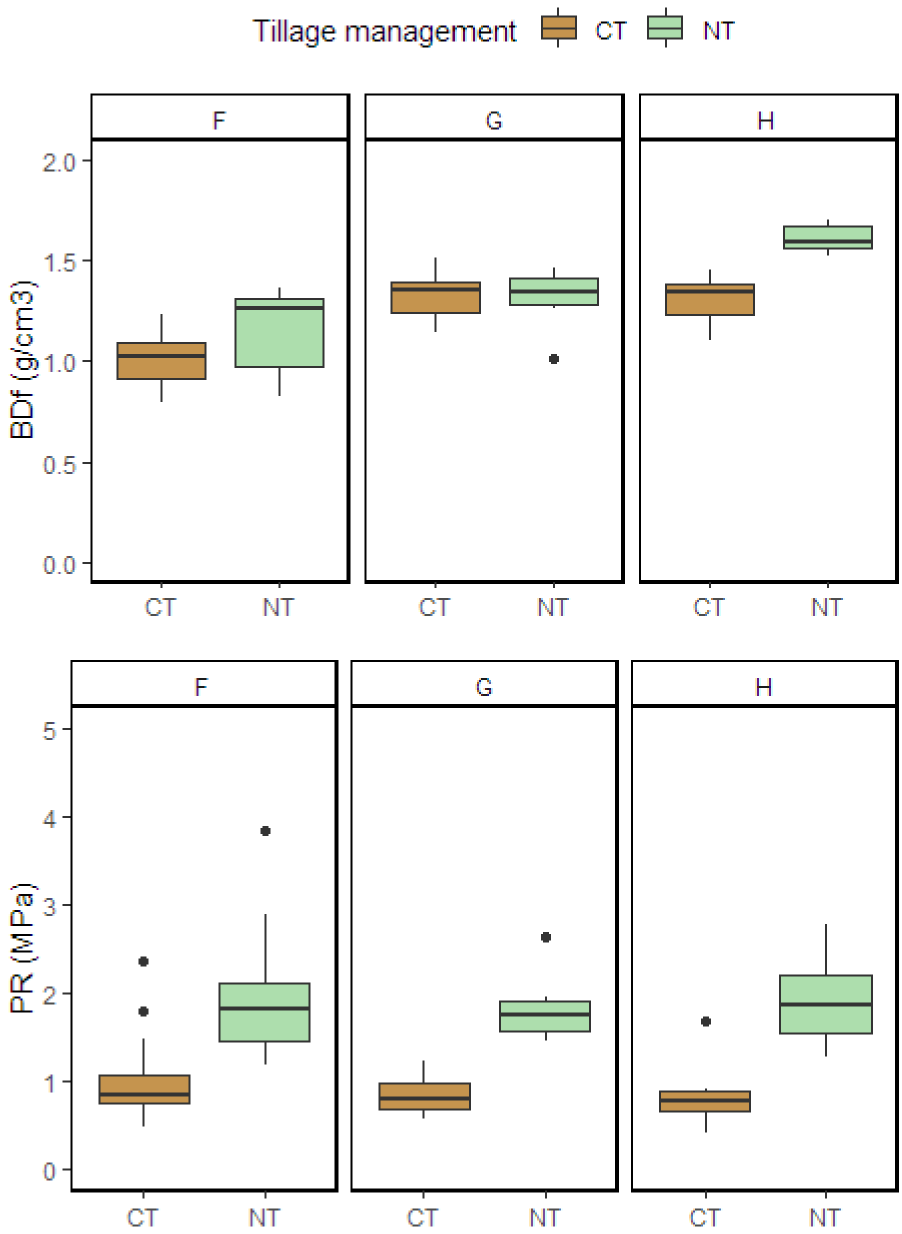


Figure 78. Compaction tests per identified soil group and tillage management at British farms. BDf: bulk density of the fine soil. PR: penetration resistance. Graphs show pooled data per soil group and tillage management.

6.13. Tillage management impact on soil physical properties

In this section, I discuss how the results of this research fit into previous findings in the Mediterranean and Atlantic biogeographical regions. For that purpose, I use sections of previous work on the topic of conservation tillage.

No-tillage and conventional tillage pursue two distinctive strategies. Conventional tillage searches to homogenise soil properties across the field and achieve a *'till'* to increase seed-soil contact and so improve germination and crop establishment. On the contrary, no-tillage questions the need for tillage for agricultural production and searches to improve structural stability to enhance soil environmental functions, including biomass production.

> "One of the main soil health benefits of conservation tillage, is that it increases soil structure stability because of the reduction of the mechanical disruption and the increase in organic matter. Evidence for this under Mediterranean conditions, was found in Greece (Sidiras, Bilalis & Vavoulidou, 2001) and in Spain for different soil types, with loam and clay textures and with calcium carbonates (Hernanz *et al.*, 2002; Álvaro-Fuentes *et al.*, 2008; Apesteguía *et al.*, 2017).
>
> Also in Spain, Plaza-Bonilla et al. (2013) studied the effects of no-tillage adoption on soil aggregation on a chrono-sequence in a loam Typic Xerofluvent (Soil Taxonomy, 1994). Starting from conventional tillage, they compared soil properties after 1, 4, 11 and 20 years of conservation practice. The results showed a high correlation between water stable aggregates (AS) and soil organic carbon. They also found that after 11 and 20 years of no-tillage the proportion of large water stable aggregates was greater than those found in conventional tillage plots and even those from plots after only 1 or 4 years of no-tillage adoption. However, these differences were restricted to the surface soil layer (0-5 cm). Deeper (5-10 cm) layers only showed differences after 20 years of no-tillage adoption and at increased depths no statistically significant differences were found. Thus, no-tillage benefits on soil aggregation were a function of time and soil depth." (Veenstra, Cloy and Menon, in press)

In this research, the importance of tillage management explaining soil structure was situated below other aggregation agents. In Spain, soils from group B, with higher clay, SOC and Fe, presented the highest AS. Nonetheless, MWD results were overtaken by group A due to the influence of GWC during sampling (increasing aggregate size). Soils from group B were from conventional tillage fields, and no comparable no-tillage fields were sampled, as neighbour fields had lower clay, SOC and Fe contents. On the contrary, in the UK, soils from group F with the highest clay, SOC and Fe also presented the highest MWD_w and AS LMA compared with soil groups G and H with higher sand and silt contents, but surprisingly AS MiA was higher in groups G and H.

When comparisons between no-tillage and conventional tillage were possible for the Spanish soils, the only significant difference was found in AS MiA, where no-tillage scored higher values in group A. This group of soils was characterised by greater GWC and a relatively high $CaCO_3$ content, which increased cohesion among soil particles against mechanical disturbances during the dry sieving resulting in the highest MWD_d. However, moisture and $CaCO_3$ seemed to increase disaggregation during wet sieving and AS tests. Indeed, AS MiA in group A was significantly lower than in groups B, C (with high clay but also more sand content than the other Spanish soils) and E (with similar characteristics than group A, apart from the GWC and slightly higher Fe and K).

In the UK, no-tillage presented statistically significant higher MWD and AS LMA in soil groups F and G, but not in group H. Soil group H had similar characteristics than group G, except for presenting higher sand content. However, this did not translate into overall lower MWD or AS than in Group G.

Additionally, regarding the effect of depth, Barut and Celik (2017) found that on clay soil in Turkey, under all the studied tillage strategies, AS increased in depth, and no-tillage had greater AS than conventional tillage (38.52% and 28.09%, respectively). On the contrary, in this research, no consistent results were found between 0 – 5 and 5 – 10 cm depth sampling layers, and therefore data were pooled for the remaining analysis.

Sheehy et al. (Sheehy *et al.*, 2015) found the greatest difference in MWD between no-tillage and conventional tillage on a silty clay soil (0.28 and 0.58 mm, respectively), whilst on clay soil, the differences were not always statistically significant. In this research, Spanish soils' PSD was dominated by silt, and no significant differences were found in neither group's A and E, which had Sandy silt loam texture.

High BD values under no-tillage have usually been related to the lack of mechanical disturbances, which progressively results in compaction (Du et al., 2010). Whereas, low BD values in conventional tillage fields have been attributed to the intensity of mechanical operations that lead to breaking apart the soil aggregates (Afzalinia and Zabihi, 2014; Dikgwatlhe et al., 2014). Accordingly, in the East Mediterranean region of Turkey, compaction tendency decreased when conventional tillage practices were used compared to the reduced and no-tillage practices (Celik *et al.*, 2017).

A set of BD analysis in a variety of soil textures are shown in Table 21.

> "Penetration resistance values in these studies, when performed, correlated with BD values. Karamanos et al. (2004) reported bulk densities dynamics for the growing season, concluding

that after 5 months no-tillage duration, BD became the lowest but similar to conventional tillage values. Nonetheless, the overall results show that, with some exceptions, in general BD is greater in no-tillage fields.

Bescansa et al. (2006) attributed the higher BD values under no-tillage to a reorganisation of the soil structure and pore system. They studied soil porosity, and results showed an increase of pores below 9 µm, resulting in greater soil water content in no-tillage fields, compared to conventional tillage, which had bigger pores with lower water holding capacity." (Veenstra, Cloy and Menon, in press)

Table 21. Bulk density values for different soil textures and tillage systems in the Mediterranean region. Source: (Veenstra, Cloy and Menon, in press)

Country	Soil texture	Bulk density (kg m-3)		Reference
		No-tillage	**Conventional Tillage**	
Spain	Clay	1.69 – 1.78	1.50 – 1.55	(Apesteguía et al., 2017)
Spain	Clay	1.05 – 1.20	1.04 – 1.13	(Ordóñez Fernández et al., 2007)
Greece	Silty clay	1.31 – 1.48	1.09	(Cavalaris and Gemtos, 2002)
Greece	Clay loam	1.27	1.37	(Karamanos, Bilalis and Sidiras, 2004)
Spain	Clay loam	1.62	1.52	(Bescansa et al., 2006)
Italy	Sandy clay	1.42	1.16	(De Vita et al., 2007)
Spain	Sandy clay loam	1.51 – 1.64	1.25 – 1.33	(Pelegrin et al., 1990)
Spain	Sandy loam	0.91 – 0.95	1.04 – 1.05	(Gómez-Paccard et al., 2013)

In Germany, Vogeler et al. (2009) found that bulk density with reduced tillage decreased their initially high values after five years, presenting similar values to conventional tillage after that period; although the subsurface layers, at 20 cm depth, were still presenting higher compaction in the reduced tillage plots. In the UK, Newton et al. (2012) found that bulk density values of no-tillage and conventional tillage (and other tillage strategies) did not vary significantly on a sandy-loam soil. At the same time, Ball et al. (1997) found that BD was significantly higher under no-tillage than under conventional tillage at imperfectly drained clay loam and clay soils.

In the case of this research, when comparing no-tillage and conventional tillage management, BD in Spain was higher in no-tillage fields, although the differences were not statistically significant. Those results correspond to soil groups A and E, with Sandy silty loam texture. At the same time, PR was highly influenced by GWC and impeded at many locations due to soil dryness. When measurements were taken, NT showed higher values (group A). Whereas in the UK, no-tillage presented significantly higher BD at soil Groups F with textures that ranged from silt loam to sandy silt and H (sandy loam and loamy sand) but not at G (sandy loam). Moreover, PR values were higher under no-tillage at all soil groups. Therefore, results suggest that no-tillage does not significantly influence soil compaction in Spain, while in the UK, it increases soil compaction, although a conclusion between soil texture appropriateness to avoid compaction when adopting no-tillage can not be drawn.

6.14. Conclusions to the scientific assessment of tillage management impact on soil physical properties

- Random forest models showed that tillage management strategies had a lower influence on soil structure than other aggregation/disaggregation agents.
- In Spain, soils with high AS MiA also presented high AS SMA, both aggregate size classes presenting similar trends when analysing their relationships with aggregation agents, while AS LMA showed weak relationships with aggregation agents. On the contrary, in the UK, AS LMA presented higher correlations with the aggregation agents compared to AS MiA and AS SMA.
- VESS has an immense value as holistic assessments of soil quality and, if not with aggregation agents, presented good correlation with compaction.
- MWD, particularly in Spain, was strongly influenced by GWC at the sampling moment, which also appeared to have a negative impact on AS MiA and AS SMA (together with $CaCO_3$). As moisture content is variable in the field, MWD is not considered an appropriate index to compare soil structural quality between farms sampled on different days and under different conditions. This problem could be overcome by monitoring MWD behaviour under different GWC during the year. While in the UK, it appeared to be well correlated with aggregation agents and not as biased.
- AS, AS MiA and AS SMA in Spain and AS LMA in the UK showed stronger relationships with aggregation agents and, therefore, constitute good indexes to assess soil structure quality.
- PR was also highly dependent on GWC; some measurements were even impossible to take due to soil hardness caused by its dryness. Moreover, the standardisation of PR values to specific soil moisture to compare values from different fields measured in different conditions was not always returning logical soil behaviour data. Therefore, it is recommended to use PR field measurements, with the precaution of contextualising the data. Nonetheless, for a single field, penetrometers ease of use and quick turn-over of results constitutes a valuable tool for farmers to assess the development of their soils and identify compaction problems.

- On the contrary, BD_f constituted a robust method to assess soil compaction and compare tillage strategies. BD_f values decreased with AS, indicating lower compaction when soil structures are water stable.
- When comparing no-tillage and conventional tillage management within similar soil groups, no-tillage presented similar or better-structured soils but also similar or higher compaction.

Chapter 7.
Reassembling the multiple soils: conclusions

Figure 79. Chapter 7 cover photo: eroded soil at the Bardenas Reales, Navarre, Spain

7.1. Introduction to reassembling the multiple soils

In this chapter, I review the main contributions of this work to the fields of ANT studies, adoption of farming innovations, no-tillage impact on soil quality and interdisciplinary studies in soil science. To do so, first I summarise the findings. Then, I discuss the contributions of findings and the ANT based analytical framework. In Figure 80, I summarise the main research arguments and findings.

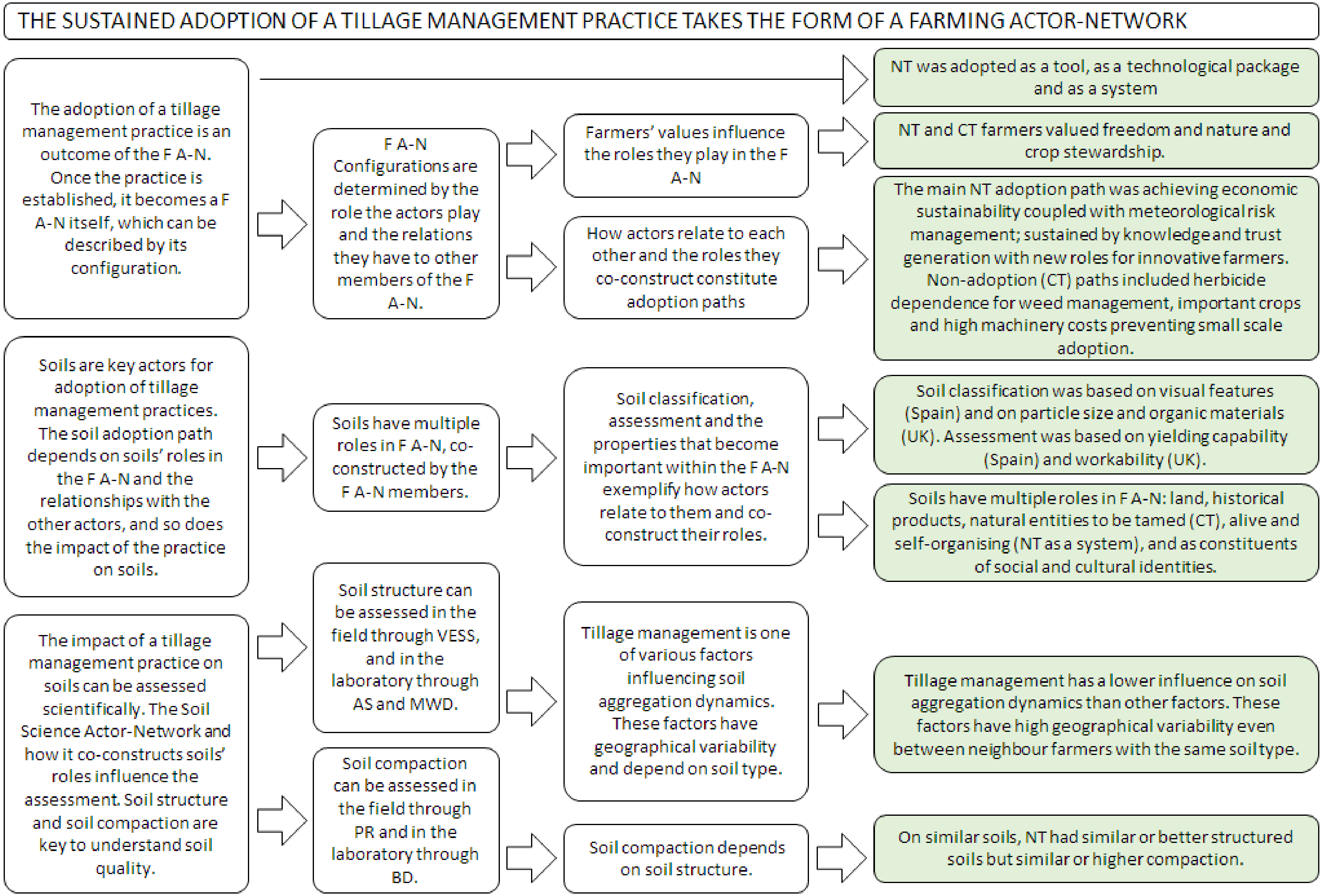


Figure 80. Main arguments (in white) and findings (in green) in studying tillage management adoption and impact on soils. F A-N: Farming actor-network. NT: No-tillage. CT: Conventional Tillage. VESS: Visual Evaluation of Soil Structure. AS: Aggregate Stability. MWD: Mean Wide Diameter. PR: Penetration Resistance. PR: Penetration Resistance. BD: Bulk Density.

7.2. Main findings

7.2.1. Main findings in the adoption of no-tillage

The research approach understood adoption as a negotiated outcome of farming actor-networks. To identify the main drivers and constraints for adoption, I followed the paths that information, power, materials, etc., took across actors and their relations. This way, it was possible to arrive to the following conclusions:

- No-tillage was enacted differently by different farming actor-network configurations, which resulted in no-tillage enacted as a tool, as a technological package and as a system. This finding adds to the previous acknowledgement of no-tillage being applied in different manners and the importance of practices' definition when calculating adoption rates, mainly because accounts such as 'time since last tillage' might distort the reality of rotational or strategic tillage.
- Different paths, defined as chains of actors, their relationships and negotiations, led to the adoption of no-tillage or conventional tillage. This finding is contrary to framing drivers and constraints as isolated because data showed these are instead articulated by many actors. Moreover, it also adds to the discussion about directions in the circulation of power relations, which commonly are framed in the literature as top-down (e.g. importance of conservation policy) or bottom-up (e.g. importance of farmers' associations) but might be best understood as negotiations.
- No-tillage is mainly adopted due to economic reasons to reduce management costs. However, this thesis, by understanding the adoption as a path and relating it to market constraints and climatic risks, detaches adoption from the simple economic maximisation rationale. Instead, it shows that adoption is better understood as a strategy for ensuring economic sustainability and risk management.
- High costs of no-tillage seed drills were a barrier for adoption when no-tillage was assessed positively, particularly for small farmers, hobby farmers, or when the drill had to be used as a tool among other tools according to the assessment of field conditions. This finding informs about the importance of manufacturing cheaper, small machines to increase no-tillage adoption in a farming landscape in which not all farmers are professional farmers with big size fields or traditional farmers have a variety of tools to choose from for seedbed preparation.
- Related to the previous conclusion is the understanding of marginal land use in arable farming, which receives less investment due to lower paybacks. No-tillage promotion on these soils,

often more vulnerable to degradation due to its characteristics (e.g. topographical location at a slope, salinity, etc.), would require flexible adoption across farms and low-cost equipment.

- No-tillage adoption as a tool required flexibility to change planned field operations after assessing field conditions. Therefore, business farmers (with bigger farms and more employers) did not adopt no-tillage in that form. Rather they adopted it as a technological practice, which in turn involved the systematic application of total herbicides before seeding. This finding informs about how modern agriculture fosters big size farms and the use of technology at the expenses of the intimate relationship between farmers and soils, diminishing the capability to respond to soils' dynamism.
- Herbicides played decisive roles in no-tillage adoption. They had the roles of phytosanitary products, toxic agrochemicals and marketed products in different farming actor-network configurations. While the first one enabled the adoption of no-tillage, the second was a barrier, and the third increased the mistrust about their effectiveness. Although many no-tillage farmers were trying to reduce herbicide use, especially due to concerns of glyphosate being harmful and the possibility of being banned, all no-tillage farmers used it in their fields. This finding informs about the controversial relationship between no-tillage and environmentalism and the dependence of no-tillage on low-priced and effective herbicides, particularly because straw burning is banned.
- No-tillage was negatively assessed by some farmers because of causing yield reduction. This was related to the identity of the 'good farmer' who maximises yield. Identity, which was co-constructed by the farming actor-networks. Nonetheless, this modern farming paradigm was changing. Consequently, the importance of yield was decreasing in favour of overall farm benefits and reducing environmental impact.
- Economically important crops such as sugar beets and potatoes were hindering no-tillage adoption due to seedbed and harvest requirements. However, no-tillage could be adopted with rotational tillage. This finding informs about the importance of linking tillage management to crops, the market and even diets and nutrient requirements.
- Social media and the internet favoured farmer-to-farmer knowledge exchange and access to technoscientific information, even internationally. Consequently, farmers had access to a range of information about no-tillage and other practices. Additionally, farmers developed networking roles that helped to sustain no-tillage adoption by increasing the relationships that supported those farming actor-networks, particularly when no-tillage was adopted as a system. This finding contributes to the understanding of network building and knowledge exchange.

7.2.2. Main findings in the multiple roles of soils in farming

In the particular matter of farming and tillage management practices, I have shown that soils were multiple. In chapter 5, I have discussed soils' multiplicity in the farming actor-networks, and in chapter 6, I have assessed soils' quality as the natural entities I understand they are but in relation to fulfilling the function of biomass production. The multiple soils that appeared in the researched farming actor-networks were:

- Soils entangled with land, with connotations of heritage and stewardship, particularly in the Spanish case due to language.
- Soils as historical products. Not as geologically given but as co-evolved with land use. This role was identified in some cases in the UK and fostered farmers' acknowledgement of the impact and the need for sustainable farming practices.
- Soils as untamed natural entities to be tamed through assessment and technology to adopt a productive role. This responds to the 'myth of the garden' and the 'good farmer' in which nature flourishes thanks to human intervention.
- Soils as alive and self-organising entities. This responds to beliefs of nature as relational, self-organising and evolving to climax ecosystems. This role was found mainly in no-tillage farmers who adopted no-tillage as a system.
- Soils as resources, with an economic value. These roles were linked to soils' productivity, the land market for buying or renting land and accountability for land uses that damaged soils' productive capability. Nonetheless, tensions around these issues and in relation to land stewardship appeared on communal or rented land and in the UK when potatoes or sugar beets were grown.
- Soils as constituents of social and cultural identities. For example, soils in the Bardenas Reales had a social and cultural role in connecting people to their farming traditions.

Moreover, soil properties were partially unveiled according to their relations. Thus, in farming actor-networks, the properties that became important and which ruled soils' classifications and assessments were:

- Soils' diversity and dynamism. Diversity in the sense of uniqueness and differentiation; and dynamism in a relational and temporal sense, with changing properties and roles in time according to their relations with other actors.
- Soils in Spain were classified according to visual features (e.g. colour and stoniness), while in the UK, the classification was based on particle size and organic materials.

- Soils in Spain were assessed based on their yielding capability, distinguishing ‘good’ productive from ‘bad’ marginal land. Nonetheless, soils had productivity limits that could not be overruled by technology nor other inputs. While productive soils were intensively farmed, on marginal land soils adopted other roles, including experimentation with no-tillage and other conservation agriculture practices.
- Soils in the UK were assessed based on workability, distinguishing ‘light’ from ‘heavy’ soils, which related to coarse texture and clays, respectively. While ‘light’ soils were easier to work to establish a seedbed, ‘heavy’ soils did not only require more work but also related to weed and pest proliferation, compaction, water excess, etc., although once established, produced higher yields. The costs associated with farming ‘heavy clays’ made it more cost-effective, adopting no-tillage on those soils but easier on ‘light’ soils.

7.2.3. Main findings on no-tillage impact on soils

Once established the roles soils took in farming actor-networks and how they were classified and assessed, it was possible to discern the impacts of conventional and no-tillage on soils. In the farming actor-networks, the main impacts were:

- Different intensities of tillage for seedbed preparation had positive impacts on soils in conventional tillage farming actor-networks. This related to soils as untamed, requiring human intervention to be productive. The practice involved assessing fields’ conditions to select the most appropriate tool. Occasionally, this led to the adoption of no-tillage as a tool.
- Conversely, farmers who had adopted no-tillage as a technological package had a ‘one solution fits all’ approach. Nonetheless, their impact on soils was likewise assessed as positive, based on applying technologies reproducing theoretical conservation agriculture principles that benefitted soils life and self-organising capabilities.
- Farmers who had adopted no-tillage as a system in relation to conservation agriculture principles assessed the practice positively. This assessment was based on understanding soils as alive and self-organising, with natural productive capability, and providing conditions that fostered soils’ life, such as organic matter additions and no soil disturbance due to tillage.
- However, no-tillage farmers were dependant on cheap total herbicides. These were enrolled as necessary phytosanitary products, although in some cases they were toxic agrochemicals or marketed agri-businesses products, and as such, they were negatively assessed as harming soils, human health and the environment or being expensive, ineffective products.

- Compaction was a major soil degradation problem in all farming actor-networks. In conventional tillage farms, compaction was alleviated through tillage or subsoiling, while in no-tillage farms, there were different approaches. In some no-tillage farming actor-networks, cover crops and organic matter inputs were increasing soil self-structuring capability, whereas, in other farming actor-networks, strategic tillage was applied to alleviate compaction.

Crop residue retention, crop rotation, and cover crops are conservation practices, which some farmers associated with no-tillage. Their assessment was:

- Crop residue retention with no-tillage or conventional tillage was a source of pests and diseases in Spanish conventional tillage farming actor-networks; a by-product in British conventional tillage farming actor-networks that bailed straw and sold it; and a source of valuable fresh organic matter to enrich soils in the rest of farming actor-networks; the latter favoured but not necessarily led to no-tillage adoption.
- Crop rotation was assessed as a positive practice, particularly to use different herbicides for weed management and use leguminous crops to fix nitrogen. Nonetheless, due to climate constrictions, some rotation crops were not possible to grow in Spain.
- Cover crops were assessed as a positive practice. In Spain, only farmers who adopted no-tillage as a system were experimenting with cover crops on marginal land. Whereas in the UK, it was more extended and used to increase farm biodiversity, avoid nutrient leaching and enhance soil conservation, particularly across no-tillage farms. Nonetheless, farmers were encountering problems of competition (nutrients and water) with crops.

The scientific assessment on soil physical quality (soil structure and soil compaction) comparing no-tillage with conventional tillage on soils (farm management) with otherwise similar aggregation agents showed:

- Tillage management strategies had a lower influence on soil structure than other aggregation/disaggregation agents, as indicated by the random forest models.
- When comparing no-tillage and conventional tillage management within similar soil groups, no-tillage presented similar or better-structured soils but also similar or higher compaction.

7.3. Research limitations

In this section, I summarise the most important limitations of this study. A detailed discussion of the potential and limitations of particular methods and equipment can be found in chapter 3, the methodology.

Initially, the research was designed to collect data from different biogeographical regions to assess how variability in agro-environmental and social factors influenced no-tillage adoption and its impact on soil physical quality. However, ANT and soil assessment from real-world farms has shown that the relationships between actors involved in those processes is complex and varies not only across space but also with farming actor-network configurations. Therefore, results should be interpreted as case studies performed in the Mediterranean and Atlantic biogeographical regions rather than representative farming standards of these biogeographical regions. Further in-depth research of the multiplicity of roles taken by the actors enrolled in farming actor-networks and how this affect farming actor-network configurations would improve the understanding of the geographical patterns across Europe.

Additionally, the farming actor-networks were built with data collected from farmers. Interviewing other actors involved in agriculture would enrich the discussion of the tensions. However, it would also displace the focus of the farming actor-networks from the farm and its non-human actors. Nonetheless, it would be interesting to explore how the enactment of soils loses the direct relationships with their material body, and soils take abstract roles as they are enrolled in other actor-networks.

This project would have benefited from feedback discussions with the participant farmers or a closer collaboration throughout the research stages. This would have improved farming actor-network configurations descriptions. Additionally, it would have been interesting to add a session in which the results of the scientific assessment of soil quality would have been presented to participants, enabling the detailed analysis of how farmers make sense of and give meaning to technoscientific data. In other words, how farmers interact with technoscientific data in their farming actor-networks. The latter was considered during the project, but due to time constraints, it was neglected. However, the topic was discussed in the interviews, which allowed a contribution to the understanding of the roles of technoscientific information in the farming actor-networks.

7.4. Contributions to ANT studies

The ANT based analytical framework used five main arguments: actor-network configurations are formed by actors and their relations, configurations determine how actor-networks operate, actors have multiple roles, those roles are co-constructed by the actor-networks in which they are enrolled, and non-humans also have an impact on social change. In this section I assess how effective the analytical framework and the methods to collect and analyse data were in translating the theoretical arguments into tools to study adoption and impact of tillage management practices. Particularly, I highlight the contributions to ANT studies by using matrices for the analysis of actor-network configurations, comparing several independent actor-networks, using the concept of multiplicity in those comparisons and my addition to the discussion of non-human agency.

Data was collected from semi-structured interviews with farmers. Interview design focused on identifying actors and the relations that hold them together in farming actor-networks. The interviews' loose structure included questions addressing interviewees' farms, farm challenges, soils, knowledge circulation and relation with several other actors identified during the literature review and pilot studies. The interviews were transcribed, coded and analysed using matrices. This traceability of the results back to the original data granted robustness to the method and adhered to ANT's principles of conclusions arising from the actor-networks themselves.

Matrices proved to be versatile tools to reassemble actor-network configurations. Latour (2005) suggested to use flashcards for each actor, so that they could be shuffled and reorganised. Situating actors in rows had the same versatility by rearranging the rows. Furthermore, matrices had the additional benefit to enable the comparison between networks. Situating each actor-network in a column made it easy to identify the presence or absence of a particular actor and by defining the actors' role in each cell, it was also possible to compare the roles they had in different actor-networks. Organising the rows and comparing the columns allowed to reassemble the actor-network configurations and to understand which actors were connected and co-created actors' roles and knowledge claims.

A focus on reassembling and comparing actor-network configurations has been used previously in innovation studies. Wang et al. (2015) in China and Yoo et al. (Yoo, Lyytinen & Yang, 2005) in South Korea, investigated the diffusion of mobile commerce technologies by comparing actor-network configurations in various points in time. While Alexandrescu et al. (2017) compared actor-network configurations across time and space to study the applicability of constructed knowledge. Comparing actor-network configurations at various points in time is based on Callon's (1986) four moment of actor-networks formation: problematisation, interessement, enrolment and mobilisation.

Nonetheless, I think that analytical frameworks that compare configurations only in time assume a linearity in innovation development and that there is one actor-network that evolves. I reassembled actor-networks for each interview, not assuming that those actors were part of the same actor-network. The novelty of the analytical framework is to perform multiple comparisons across several cases of the adoption or non-adoption of an innovation, each case as an independent actor-network, and identify differences and similarities in their configurations (actors' roles and relationships) using matrices. This process was critical to distinguish different ways of adopting no-tillage.

The notion of multiplicity was also crucial to distinguish differences between tillage management practices. While the matrix method allowed to easily identify a variety of roles in different actor-networks by comparing the descriptions, the description exercise itself allowed to identify multiple roles within one actor-network. Multiplicity enables the analysis of the underlying complexities of reality, avoiding simplification (Law & Mol, 2002; Van Der Duim, Ren & Thór Jóhannesson, 2013). In general studies that apply this concept research in depth one actors' multiplicity. I used multiplicity to study the roles of soils in farming actor-networks, but I also used it in the comparisons between configurations. I found the focus on co-existing multiple ontologies of human and non-human actors and how social relations get ordered around them crucial to understand differences in adoption. Through multiplicity I found differences between farming practices that would not have been possible with a different approach (e.g. the multiple roles of soils, herbicides, and no-tillage). Therefore, I argue that innovations' adoption variability has to be considered as occurring in time, space (the development and the geographical perspectives) and enactments.

The assumptions that non-humans have an impact on social life and that their agency is a relational product were more controversial to translate into practice. I started to build the concept of agency from the notion of impact on social change discussed in 'Reassembling the social' (Latour, 2005). This understanding of agency evolved by adding the idea of agency being enacted or a relational product of the actor-network. The latter was based on 'Reassembling the social' (Latour, 2005), and the work of Mol, who stated that 'actors are afforded by their very ability to act by what is around them' (Mol, 2010:p.258). Furthermore, it nurtured from other authors such as Callon and Law (1997), who argued that non-humans are not simply resources or constraints, but interactive effects and that action is both a relay and unpredictable. Thus, in my research agency is not intentional nor rational. Agency is not unique to human nor lively entities. Agency is the impact that all actors make in their actor-networks, it is how they help to stabilise the configurations or generate a change. Agency is to exercise the capability of translation, and translation is the modification of a flow (e.g. knowledge, material, energy, etc.) that circulates through the actor-network. Indeed, I refused to distinguish mediators from intermediaries, because for me there is nothing that 'transports meaning or force without transformation' which is the definition of an intermediary given by Latour (2005:p.39). Everything is an actor. The question is if the actor is part or not of the actor-network re-assembled in the research, which depends on the research question and the methodology.

In any analysis, non-humans' agency will always be explained through the human account. It is only possible to address the agency of non-humans when they are in actor-networks that bond with them and enact them. The difficulty to account for non-human agency is not in their incommensurability, but in deciding whose account matters between multiple co-existing commensurabilities. One of ANT critiques is that it favours natural sciences as reliable sources of non-human accounts. However, throughout the thesis I have argued that scientific enquiry, constitutes one of many ways to relate to natural entities. Therefore, and understanding the risk of scientific authoritarism, I decided to use the concept of multiplicity to account for multiple non-human agencies. Using interview data I analysed the roles of non-humans, particularly soils, what they are and what they do within the farming actor-networks as an account of farmers acting as their spokesperson. Moreover, I assumed that how farmers identified, described and explained soils was with the language and ideas negotiated within their farming actor-networks (Hinchliffe, 2007). On the other hand, my own soil assessment following soil science methods generated an independent account.

7.5. Contributions to farming innovation studies

Following the previously described theoretical arguments of the ANT based analytical framework, two further arguments were used to study adoption of tillage management practices: farmers' values influence the role they play in the farming actor-networks, chains of actors linked to and co-constructed by each other constitute adoption paths. Furthermore, I argued that soils had multiple roles in farming actor-networks and that classification, assessment and soil properties that emerge within farming actor-networks influence both: soils' agency co-constructing tillage management practices and the assessment of tillage management impact on soils within the farming actor-network. In this section I discuss the effectiveness of those arguments in studying farming innovations.

7.5.1. Farmers' roles in co-creation of farming innovations

My research, and the ANT approach are in line with the shift from considering agro-innovation as a linear process from the scientific information sources towards the passive adopters to recognising farmers' involvement in the knowledge production of innovation. By applying ANT, I assumed knowledge is based on co-evolution between the practices, the context, and the different actors involved, integrating non-scientific actors in knowledge production (Schneider *et al.*, 2012). Farmers' active role in knowledge production is granted in ANT by the mere fact of farmers' enrolment in the farming actor-network.

Accordingly, for ANT, knowledge is a relational effect, a product of the interaction between members of heterogeneous networks. Same as scientists interact with their objects of study in the laboratory, farmers interact with everything and everyone within their farming networks. Those are the human and non-human actors such as the soils, crops, rain, neighbours, agrochemical salespeople, etc. Through those interactions, farmers acquire their local and experiential knowledge. Moreover, ANT states that actors negotiate with other members of the networks. A negotiation is not a linear interaction; actors do not only receive information, actors contrast, dispute or agree to the information. They translate the message into their own terms and transmit it following their own interests. By all those means, actors transform the value of the information. Therefore, by taking an ANT approach, farmers' potential role in innovation was extended from 'active adopters', an approach that recognises farmers' site-specific knowledge as necessary for the adaptation of scientific knowledge to local conditions (Burgess, Clark & Harrison, 2000) to 'active knowledge producers', an approach which recognises that new information is generated by farmers and that this information further circulates in the networks. In conclusion, as active members of their networks, farmers co-produced valuable knowledge and contested, strengthened or modified existing knowledge.

This active role of farmers in the co-creation of innovation was described in chapters 4 and 5. In chapter 4, it was shown that all farmers did different on-farm experiments, including testing new crops, crop varieties, machinery, management or just ideas. These sometimes were in collaboration with other farming actor-network members such as agri-businesses, manufacturers, research or agricultural extension institutes or, in Spain, cooperatives. Nonetheless, many times it was due to farmers' initiative and their engagement with multiple networks. Those networks ranged from the local elderly farming community to the international community, accessed through travelling and the internet.

Moreover, as farmers play multiple roles in farming actor-networks, they were active in innovation in multiple ways. For example, traditional farmers diversifying their production by recovering local and traditional crops and practices, or the environmentalist farmers starting conservation agriculture practices. Some farmers, particularly (but not exclusively) those who adopted no-tillage as a system, had a role as innovators co-constructed by the farming actor-networks. For example, farmers publishing their experimentations around soil biological properties in social media, receiving visits from other farmers to access information about their practices, or building new farming tools with other locals. Therefore, farmers' role as knowledge co-creators and innovators was present in all farming actor-networks but became dominant in some cases.

Furthermore, I explored the argument of farmers' roles and values influencing adoption of tillage management practices. Values and attitudes have long been studied to understand farmers' motivation in agro-environmental decision-making and environmental behaviour (Marr & Howley, 2019). The agency of the decision making in those behavioural approaches is centred in the farmer, while in the ANT based analytical framework applied in this thesis farmers' roles and values are co-constructed by the farming actor-network in which farmers are enrolled in. I found farmers valued freedom, naturalness and 'growing something' in Spain, while in the UK similar values of producing food, 'doing nature' and hard work were declared. Those values did indeed shape their motivations to farm and to do it without harming nature. However, those values were shared across no-tillage and conventional tillage farmers. The adoption of no tillage was not motivated by environmental care, opposed to the a productivist motivation of farmers applying conventional tillage. In light of the results, I agree with Marr and Howley (2019) that the divide between environmentalist and productivist is an oversimplification. Moreover, the analysis showed that in farming, environmental and productivist values are co-existing, entangled and co-produced.

Some studies distinguish between farmer (or farm) typologies or orientations. Marr and Howley (2019) differentiated: business, production, farm health, lifestyle and environmental orientations among their interviewed farmers. Darnhofer et al. (2005) applied a decision tree method using farmer typologies which focused on attitudes towards organic farming. While the farming styles framework applied by Van der Ploeg (1992) identified huge farmers, greedy farmers, cowbreeders, cowmen and intensive farmers in Friesland (The Netherlands). I found farmers having multiple roles, co-constructed within their farming actor-networks. The roles I found that relate to tillage management practices were business farmers, small farmers, hobby farmers, traditional farmers, innovative farmers and environmentalist farmers. Multiplicity means that the same actor can have different roles, and being enacted by the actor-network means that it is not in the actors' power alone to change their role. Therefore, I would not use these roles to classify farmers, but as an additional tool to understand farming actor-networks' configurations and complexities.

7.5.2. Non-human roles in co-creation of innovations

The main arguments in my ANT analytical framework regarding non-humans were that they had an agency capable of influencing the adoption of tillage management practices and that non-humans could also be multiple. Particular attention was given to the roles of soils, but the framework allowed the identification of various important non-humans that played key roles in shaping farming actor-network configurations.

In other studies about adoption of no-tillage and conservation agriculture, non-humans are identified as environmental and technological factors. This often puts nature and soils in a passive background where social life happens as for example in the one-fits-all agro-technological innovation approaches. Opposed to this view is nature determinism, in which social life is dictated by natural forces (Swidler, 2009). Somewhere in between, are the environmentalist approaches that see nature as active but separate of humankind and it becomes a victim of artificial (non-natural, anti-natural) human activity (Swidler, 2009). Nonetheless, the important point here is not to establish a universal truth about non-human agency. The question is: what roles do non-humans play in the studied actor-networks?

Indeed, more importantly than any findings confirming an active role of non-humans is to include the possibility into the analytical framework. The diverse soil roles I found in farming actor-networks (summarised in: Main findings in the multiple roles of soils in farming) show that the nature of the agency of non-humans varies in different actor-networks, it is not always the same. Agency is co-constructed between the actor-network members, therefore it is not our duty as researchers to establish what an actor can or cannot do, it has to arise from the data analysis. The limits of agency are also subject to negotiation (Law, 1992). Nonetheless, in all cases of this research non-humans, were dynamic and influenced social change. However, there were differences in agencies as for example soils that were enacted as alive and self-organising entities, which became key actors in shaping farming actor-network configurations, or more passive enactments of soils as untamed natural entities to be tamed that, nonetheless presented resistance to human dominance. To include these enactments and negotiations into the analysis has shown to be important to understand the different ways of adopting an agricultural innovations, or, better said, the co-construction of agricultural innovations.

The focus on soil classification, assessment and soil properties in each farming actor-network provided a frame to analyse soils' roles. More specifically, it enabled to disentangle soils as black boxes or as punctualised actor-networks. This exercise, permitted both to understand how soils were enacted and what they were able to do according to their enactment. While the frame was highly influenced by my soil science background and might resemble scientific ways to organise soil knowledge, the frame proved to be useful to identify soils' plurality in the sense of their diversity across space, soils' dynamism with changing properties in time, and, soils' multiplicity with different roles in the same space and time. Moreover, it provided information about how the farming actor-networks negotiate values, meanings and symbols with soils. Similarly, a focus on roles, classification, assessment and properties enabled to understand the plurality, dynamism and multiplicity of other non-human actors such as sugar beet and potatoes, weeds, herbicides, straw, machines, etc. The concept of multiplicity and that these multiple roles are enacted by wider actor-networks are key to understand conflicts in co-creation of innovation.

7.5.3. Adoption as a translation: adoption paths

The ANT based analytical framework I developed assumed that adoption of a tillage management practice is an outcome of the farming actor-network. Once the practice is established, it becomes a farming actor-network itself, which can be described by its configuration. Those configurations are determined by the role the actors play and the relations they have to other members of the farming actor-networks. Furthermore, in those configurations it is possible to distinguish adoption paths, which are chains of actors that relate to each other and co-construct their roles.

Investigating adoption through the ANT based analytical frame considers co-creation of innovation as a dynamic translational issue. It connects the innovation to the enactment of the innovation. This is the building and sustaining of an actor-network, in which all actors play a role in translating and negotiating the innovation and in holding it together. The analysis consists in deploying innovations into its constituent parts: the actors and their relations. The success of the application of the analytical frame is in finding differences in the actor-network configurations: the human and non-human actors that are enrolled, the roles they play, or their relationships. These differences impact the functionality of the assemblage. Thus, the importance of the application and findings of the analytical frame is the acknowledgement of innovations being enacted by the actors that form them, which inevitably evolves into a multiplicity of innovations. In the case of this research, there were meaningful differences between no-tillage as a tool, as a technological package and as a system.

Previous studies on farming innovation and on no-tillage have highlighted network formation as a tool to spread and support innovation. In the diffusion of innovations model information is carried to the farmers through a variety of actors, including agricultural extension services, company dealers, other farmers, etc. (Rogers, 2003). My findings, add further empirical evidence to the existing ANT based research of no-tillage adoption that shows that the adoption of a tillage management requires fundamental transformations of the innovation, so that what was successfully adopted, functioning and operating was not a transferred technology but a newly co-created no-tillage (Coughenour & Chamala, 2000). Furthermore, Scheniders' et al (2012) ANT based co-creation of innovation study in Switzerland showed that changes in conventional farming actor-networks require the transformation of those networks and the formation of new bonds for no-tillage to be sustained in time. Those transformations are in the roles actors play in farming and the relations that bind them together. My findings in Spain and the UK support these claims in the sense that information and other flows bind actors together in chains (adoption paths) and besides circulating through the network they also enact and transform the actors, which is a continuous process.

In an adoption path, actors are joint by conduits through which circulate different flows. Actors translate those flows modifying what is circulating. The conduits between actors support a diversity of flows (energy, material, money, etc.). All interactions enable the collective action, in this case no-tillage, and also the re-making of the farming actor-network. This means that each interaction is a negotiation in which not only what is circulating is translated and transformed but also the involved actors.

In chapter 4 I distinguished Spanish no-tillage adoption paths and British no-tillage adoption paths by their main actors or the nature of the flows. Those were: income: subsidies, markets, cooperatives and yields in Spain and Brexit, grain merchants, land and yield in the UK; weather and water: managing the risks; crops: crop innovation, rotation, and greening areas in Spain and diversification, cover crops and innovation in the UK; weeds and herbicides; machinery and contractors; knowledge and trust. I explained how farming actor-networks operated, which is the established functioning and interaction within actors in the paths. Furthermore, I identified the tensions which could cause change and differences in the paths configurations. Finally, I focused on the drivers and constraints which were the changes in the configuration and functionality of the adoption paths in response to the tensions. In this exercise it is possible to see that tensions were translated differently in various farming actor-networks, leading to re-negotiations in the configuration of the adoption paths and to the adoption or non-adoption of no-tillage.

A fundamental difference between mine and previous ANT based studies of no-tillage adoption is in its positioning regarding the sustainability versus productivist narratives. Coughenour and Chamala (2000), Schenider et al. (2012), and Gray and Gibson (2013) clearly defined no-tillage as the desired practice and assessed conventional tillage as an environmentaly harmful practice. On the contrary, and despite providing scientific evidence of no-tillage environmental impacts (or the reduction of them), my positioning was more neutral. This helped to find values around nature, environmentalist roles and behaviours in both, the no-tillage and conventional tillage farmers. Importantly, it also drew attention to non-adoption of no-tillage due to high dependence on potentially harmful herbicides.

7.6. Contributions to soil science: interdisciplinary research on soils

In this section I reflect on the last steps of the ANT based analytical framework: re-assembling soils' multiplicity. By doing so, I cover ANT use as an overall approach to put into dialogue social sciences methods, qualitative data, and findings with soil sciences methods, quantitative and semi-quantitative data, and findings. The nexus being the soil and the circulation of soil knowledges. In this case, I reflect on the translation into soil science of the multiple co-existing ontologies of soils.

Throughout the thesis, I have argued in favour of understanding soils' ontology as multiple, enacted and negotiated in the actor-networks in which they are enrolled. Indeed, soils interact with a diversity of practices and build many soil knowledges (Krzywoszynska & Marchesi, 2019). Earlier in this chapter I have summarised my findings of different roles soils had in the farming actor-networks, which are analysed in detail in chapter 5. Despite not analysing in depth the different ontologies soils have in soil science, I have presented different definitions of soils and related concepts applied in science in chapter 2 (see section: Focus on soils). Furthermore, I made explicit my own positioning regarding how I relate to soils, which I have applied to chapter 6, in which I followed soil science methods to conduct an assessment of no-tillage impact on soil structure and compaction of case study soils.

I maintain that soils' multiplicity is enacted by different actor-networks. The consequences of this co-construction of soils are that definitions of soils are not perceptions of independent natural entities that remain immutable and continue to act alienated from these definitions. On the contrary, and despite their own agency and negotiating capability, they become more of what they are enacted to be in the actor-networks in which they are enrolled. Therefore, to finish the thesis, I highlight the importance of soil scientists' participation and connection to other ways of interacting with soils in order to enrich and endure the discipline.

Throughout the thesis I have also situated the role of science in society (see section: Science and interdisciplinary research). Currently, it has been argued that we live in a '*post-truth*' society in which science has lost authority in knowledge production. Some soil scientists see this as a failure of their science communication skills and call for more interactions with farmers and land users to break myths of scientists pertaining to an 'elite' class that endures its status through the social construct of 'facts' (e.g. see: Bouma, 2018). Contrastingly, in my research, participant farmers were knowledgeable of their soils and valued scientifically produced information with which they actively engaged (e.g. searching for peer-reviewed papers on the internet or visiting extension institutes). Nonetheless, they were critical about scientific methods and the appropriateness to infer information from the studies to the reality of their farms. Moreover, they had concerns about issues, which the scientific community is currently researching, and to which it responds in multiple forms without an agreement.

Despite that, farmers critically assessed knowledge claims and experimented on their farms with those ideas that made more sense to them. I argue in favour of soil scientists engaging with these communities to co-produce soil knowledges. In fact, the notion of 'multifunctional soils' already enables the layering of soil roles or functions. Extending soils' multifunctionality to an ontological multiplicity widens the scope of valuable soil knowledges. Interdisciplinary reaching to social sciences and the humanities and transdisciplinary research with stakeholders has the potential of adding layers to soils' multiplicity, enabling a more comprehensive understanding of what soils are and what they are able to do.

Translating multiple soil knowledges into soil science is required to enrich and endure the discipline, to achieve a more comprehensive understanding of soils and ultimately to ensure sustainable relationships between people and soils. Only by understanding what soils are and what they are able to do it is possible to assess the impact of human activity on soils. However, there are many conflicting roles and translation is not always possible. Indeed, the difficulty of putting into conversation the qualitative data from the interviews with farmers and the quantitative data from my measurements and analyses is not due to the nature of the data, but the ontology of the soils under scrutiny. According to the findings, no-tillage can increase aggregate stability and aggregate size but also compaction. However, what do these findings mean for a soil that is entangled with land, an historical product, an untamed natural entity, an entity that is alive and self-organising, a resource with economic value or a constituent of social and cultural identities? Answering these questions beyond speculation, requires further bonding and negotiating with the farming actor-networks and empirical data collection about their translations of scientific data.

The negotiation of soils' roles in actor-networks is an ongoing process. An actor never possesses a definitive role because actor-networks are dynamic and in constant evolution, with shifting relationships and new bonds created or broken. Nowadays, soils are finally receiving some attention beyond soil science with a wider awareness of soils' degradation and human impact on them. Conduits to soils have been extended from many actors, and soils are being translated in a variety of ways. Soil scientist should engage in these processes so that the soils that are enacted in their studies also translate into society.

In relation to the soil that is enacted through our scientific activities, I highlight the importance of qualitative or semi-quantitative data to frame holistic research. While some soil scientists call for a more quantitative discipline to respond to social demands of information (see: Hartemink and McBratney, 2008), others highlight the need to recover holistic approaches that link soil parameters back to soils as natural bodies (Ibáñez & Boixadera, 2002; Ortiz Silla, 2015). Those soil scientists call to follow the classical integrated approach in soil science, studying and understanding soils from soil formation factors to components, properties, structure and organisation, pedogenic processes, soil types, landscape distribution, evolution in time, land uses, and degradation or rehabilitation effects of human activities, etc. (Ortiz Silla, 2015; Macías, 2015). In this approach, qualitative and semi-quantitative data from cartographic analysis, field descriptions and field tests provide a necessary holistic frame to which more detailed research can link.

In this interdisciplinary study, three topics have emerged as particularly interesting to be further explored in future research in collaboration with farmers:

- The importance of soil dynamism in farming actor-networks: Indeed, in soil science, the notion of 'soil health' responded to the need to assess dynamic properties that change with land use or even with management (contrasting with inherent properties that result from pedogenesis - soil formation processes- which are more stable) (Ortiz Silla, 2015). Nonetheless, 'soil health' is rarely continuously assessed; rather, it is taken as a state compared to a standard (in this research, it was conventional tillage when assessing no-tillage impact). Therefore, it would be beneficial to increase the work that is already studying soil properties through time. Moreover, collaborating on this topic with farmers in on-farm research would improve the scaling of cycles that depend on their practices.
- Soil testing and meaning-making of technoscientific data in farming actor-networks: Data from this research show that price is the major barrier preventing farmers from requesting more soil tests and that there is a growing interest in analysing soil properties beyond nutrient content (although the latter is common practice in the UK to inform fertilisation plans). Soil extension experiences in Australia, in which farmers actively participated in soil sampling and discussing tests' results, improved participants' learning processes and their confidence in performing sustainable management (Andersson & Orgill, 2019). In such transdisciplinary research, there is potential to study how technoscientific data circulates in farming actor-networks and interacts with their actors.
- No-tillage improving soil structure but increasing compaction: Results of the scientific assessment of physical quality show that if differences were found between no-tillage and conventional tillage management on otherwise similar soils, the direction of these results was towards better structured but more compact soils. Nonetheless, how these soils interact with crop growth and the environment on and off-farm (but in the real world) has to be further explored to comprehensively assess the meaning of the results.

In conclusion, this interdisciplinary thesis set out to holistically understand no-tillage adoption and its impact on soils with an ANT approach. This approach enabled understanding the complexity and dynamism of adoption paths and so, how adoption drivers and constraints were enacted and sustained by broader farming actor-network configurations. From the many adoption paths, I have focused on those in which soils were key actors. Specifically, I investigated the relationships between farmers and soils and the results showed that both were entangled by action and co-constructed each other. Indeed, farmers' roles, values and practices were co-constructed through the relationships with their farming actor-networks, in which the multiple soils had dominant roles. Simultaneously, soils' roles, classifications, assessments and the properties that emerged as important were also negotiated outcomes from their farming actor-networks. Therefore, I argue in favour of assessing soils' quality taking into account their multiplicity.

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Figure 81. References cover photo: Coffee break during fieldwork, UK

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Appendices

Figure 82. Appendices cover photo: Fine soil < 2 mm and coarse elements

Appendix A. Semi-structured interviews with farmers

The following questions constitute a list of topics discussed with farmers. General topics of inquiry are marked in italics and questions in which to focus are marked in bold. First, the questions to no tillage farmers are presented, and alternative questions to conventional farmers are shown below. Note that NT stands for no tillage and CT for conventional tillage.

Day-to-day network and access to it

1. Tell me about your farm. *Family property, size, number of fields, different tillage practices, different crops, cover crops, animals, number of workers, buildings*

- Why do you grow these crops and not others?
- *If it is not a family property:* Do you come from a farming family? Did you grew up in a farming environment?
- How long have you been farming?
- Do you do any contracting work?

Response to tensions

2. Have you ever faced big challenges at your farm? How did you solve them? *Was this with NT or CT? Was NT a solution to a specific situation?*

- Have you ever had a very bad yield, or crop loss? Do you know why? What did you do? *Was this with NT or CT?*

3. What are your biggest worries relating to the farm today?

4. How do you plan to deal with them?

Soils

5. What are your soils like?

6. Ideally, what would your soil be like?

- Do you think you can improve your soil?
- How important is this for your farm?

7. Have you had to adapt your farming practices because of your soil type? *Drainage, texture, depth, organic matter, coarse elements, fertilizers, pH…*

- How much investment does this mean?
- Is this at different fields with different soils or have the soils changed over time?

8. How do you know what the quality of your soils is? (Do you go to the field and dig? Do you take samples for analysis? Do you hire a soil scientist?)

Research and advisors

9. Have you participated in other research projects?

10. What do you think researchers can do for you?

- Have you worked with advisors?
- What are your impressions about them?
- Do they solve your needs?

Access to NT information and network change

11. Tell me about how and why you adopted NT.

- How did you first hear about NT? *Did you always know about NT?*
- What were your first impressions about NT?
- Did you learn about NT before implementing it at your farm? How?
- Was it easy to find and finance the machinery? Are you happy with the one you have now? Where did you get it from? What are the most significant differences between NT and CT machinery?
- How was your first experience with NT? How much extension did you convert?
- Which other changes did you do at your farm? *Crop rotation, residue retention, cover crops, herbicides…*
- Have you changed something since then?
- Are there any other practices that you find interesting and want to try out at your farm? Are these in combination with NT or independent?
- Are your local conditions particularly appropriate for NT?
- Do you think you will continue with NT?

Innovative farmers

12. Is there any farmer you admire? Has she/he changed your way of thinking about farming?

- How did you meet? How did you contact with her/him?
- Have you travelled to visit specific farms or farmers?

13. Do you think you have changed other farmers' way of thinking?

Further network tensions

14. Do you have an insurance? What does it cover?

15. Which requirements does it have?

16. Do you find it easy or difficult to find a market for your products? How do you do it?

17. How do environmental regulations affect you?

18. Do you think that receiving farming subsidies has been relevant in adopting NT?

Contractors

19. Do you work with a contractor? Can you explain me how you work with her/him?

- How or where did you find the contractor?
- What does she/he do at the farm?
- Have you ever had any problems to book her/his services?
- Do you have a discussion about what has to be done and how to do it? Is this you telling her/him what you would like to have done?
- Do you discuss some other farming issues with her/him?
- Do you think discussing farming issues with she/he can help you?
- Do you discuss with her/he about how the season is going in a more general picture, not only at your farm?

20. Have you ever discussed NT with her/him?

Social media

21. Do you have a social media account?

22. Do you use it? How?

- Do you follow other farmers? Do you follow other people who are not farmers? Whom?
- Do you post regularly? What are your posts about?
- Do you have fun using twitter?
- Tell me what do you think about your social media accounts, for what are they useful?
  - *Farming press*

23. Do you follow any farming press?

- Are they printed or online?
- Are they here from the UK?

24. Do they write about NT?

25. Have you ever been interviewed, or participated in another way in a publication?

Farmers associations

26. Are you a member of any farmer association? What does the association do for the farmers?

- Is this a NT association?
- What does the association do for you?
- Do you have meetings, farm visits…?

- How do you participate?
- Does the association provide you information about farming practices? How does it do that?
- Have they told you about NT?
- *Alternatively:* have you met other farmers who do NT? How many do you know? Tell me about the situations, where, how, who…

27. Do you like being a farmer? Why/ why not?

28. What do you like the most about farming?

Questions for conventional tillage farmers:

Access to NT information and network change

11. Tell me about how you learned about NT.

- How did you first hear about NT? *Did you always know about NT?*

12. Have you used NT in the past? Tell me about it.

13. What do you think about NT?

- Do you think your local conditions may be appropriate for NT? Why/ why not?
- Do you think you would be able to access the relevant machinery? Why/why not?

14. Do you think you might try NT in the future? Why/why not?

- Are there any other practices that you find interesting and want to try out at your farm? Are these in combination with NT or independent?

Appendix B. VESS score chart

Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 Friable Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			 Fine aggregates	 The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 Intact Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil			 High aggregate porosity	 Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 Firm Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			 Low aggregate porosity	 Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 Compact Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			 Distinct macropores	 Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			 Grey-blue colour	 Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

Figure 83. VESS Score chart. Source: SRUC, Aarhus University and UEM.

Appendix C. VESS assessments Spanish examples

At locations 1 and 2, all fields from no tillage and conventional tillage farmers presented healthy soil structure, in the range of friable and intact VESS scores (Figure 84 and Figure 85). Some sampling sites at the no tillage fields at these locations presented very superficial soil layers with better soil structure (smaller and rounder aggregates). Some conventionally tilled sites also presented shallow surface layers. However, this better structured soil layers' scores had low impact on overall scores due to their shallowness. Soil colour at 1-NT soil blocks changed from 10YR 5/4 in the first 2 – 4 cm to 10YR 5/3 underneath and 1-CT colour changed from 10YR 5/2 in the first 4 – 7 cm to 10YR 5/3.

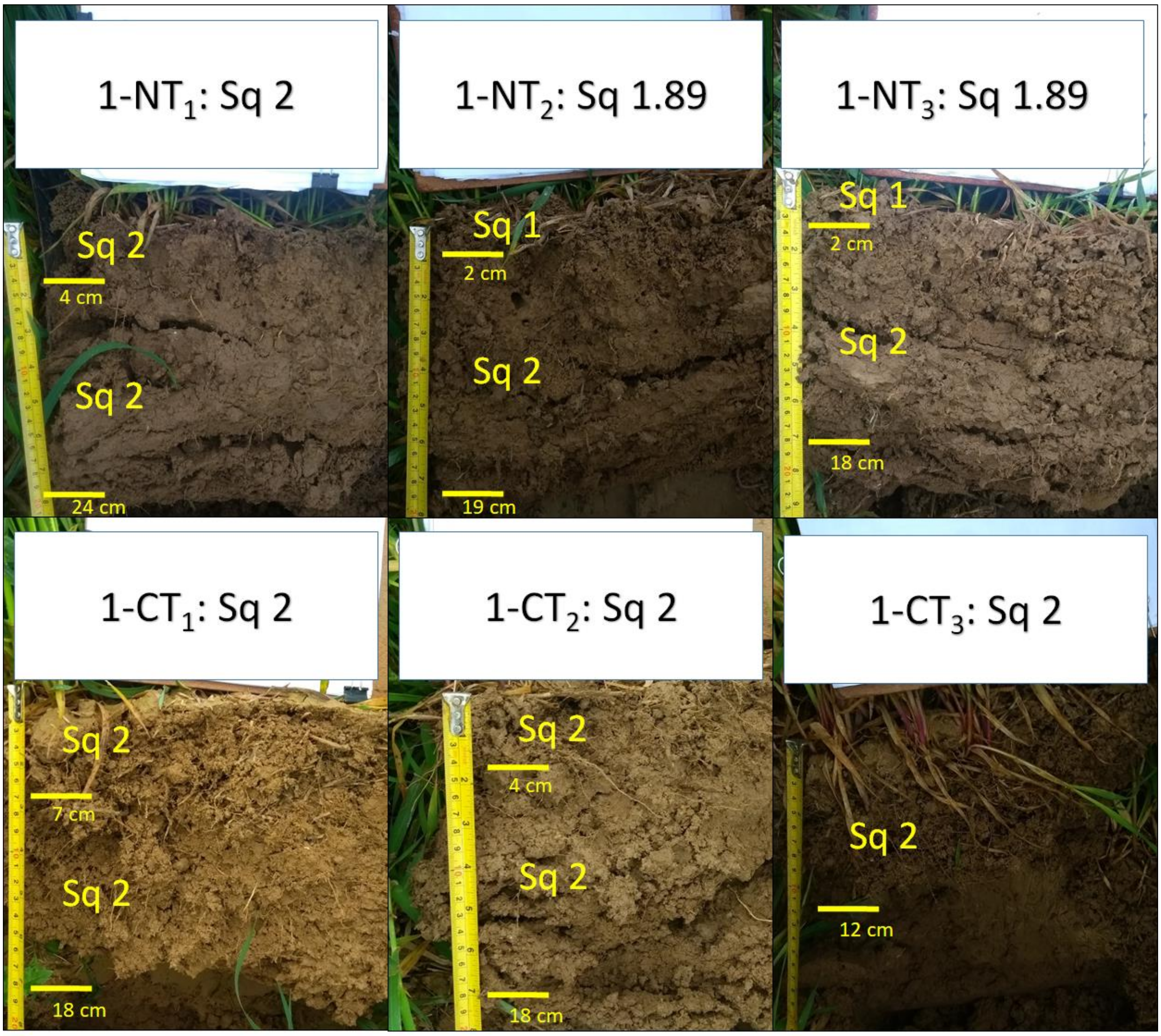

Figure 84. Location 1 soil blocks and VESS scores

Soil colour at 2-NT was 2.5Y 4/4 throughout the soil while soil colour at 2-CT was 10YR 4/4. 2-CT soil presented a matrix of very small aggregates, smaller than 2 mm, with some firm, bigger aggregates (>7 cm). Porosity was high across the soil and the field, with high content of coarse elements of a calcareous nature. No earthworms were found in this field, although evidence of biological activity was found in rounded aggregates.

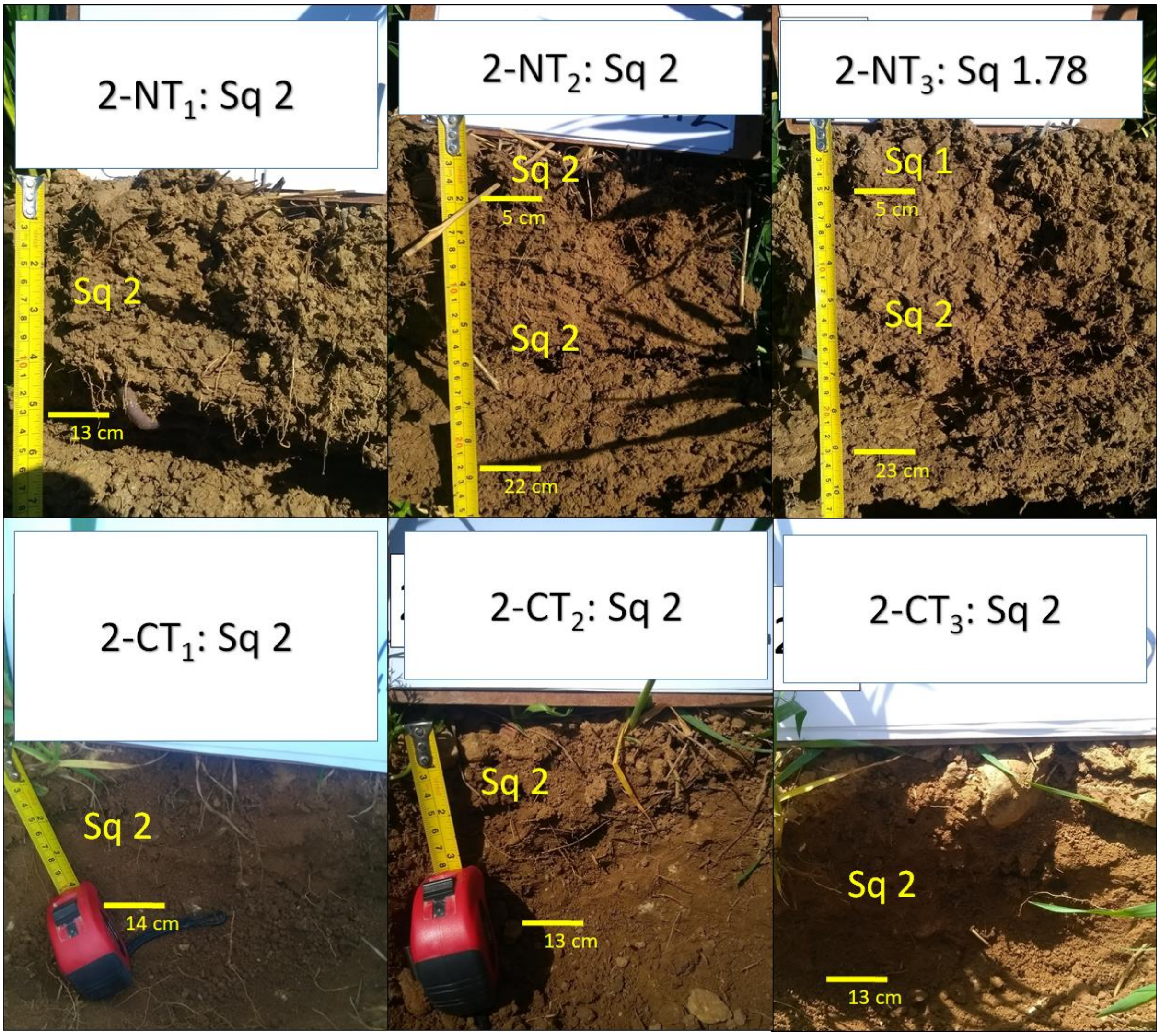

Figure 85. Location 2 soil blocks and VESS scores

At location 3, 3-NT presented firm to compacted VESS, suggesting a need to change management practices; whereas 3-CT scored for intact VESS assessment (Figure 86). 3-NT presented earthworm channels; the soil was very hard especially in the third site due to dry conditions. Although at some sampling sites the porosity was low and there were fewer roots, there was no visible limitation for root development. Aggregates were a mixture of bigger than 1 cm angular aggregates and smaller around 6 mm rounded aggregates. Site 1 had colour 5YR 5/4 whereas sites 2 and 3 were 7.5YR 5/4. Site 1 at 3-CT field presented well developed aggregates between 1 and 6 cm, with an angular shape, that broke into smaller aggregates. The second site presented buried crop residues and clods of 7 cm, whereas the soil matrix had smaller (~ 2 – 3 mm) rounded aggregates. Roots were visible across the soil. In this site, there was a superficial crust of 2 mm. The third site presented ant activity, resulting in a very loose soil. All sites presented coarse elements and accumulations of $CaCO_3$. Soil colour in 3-CT first site was 7.5YR 4/3 whereas in the second and third it was 10YR 3/4.

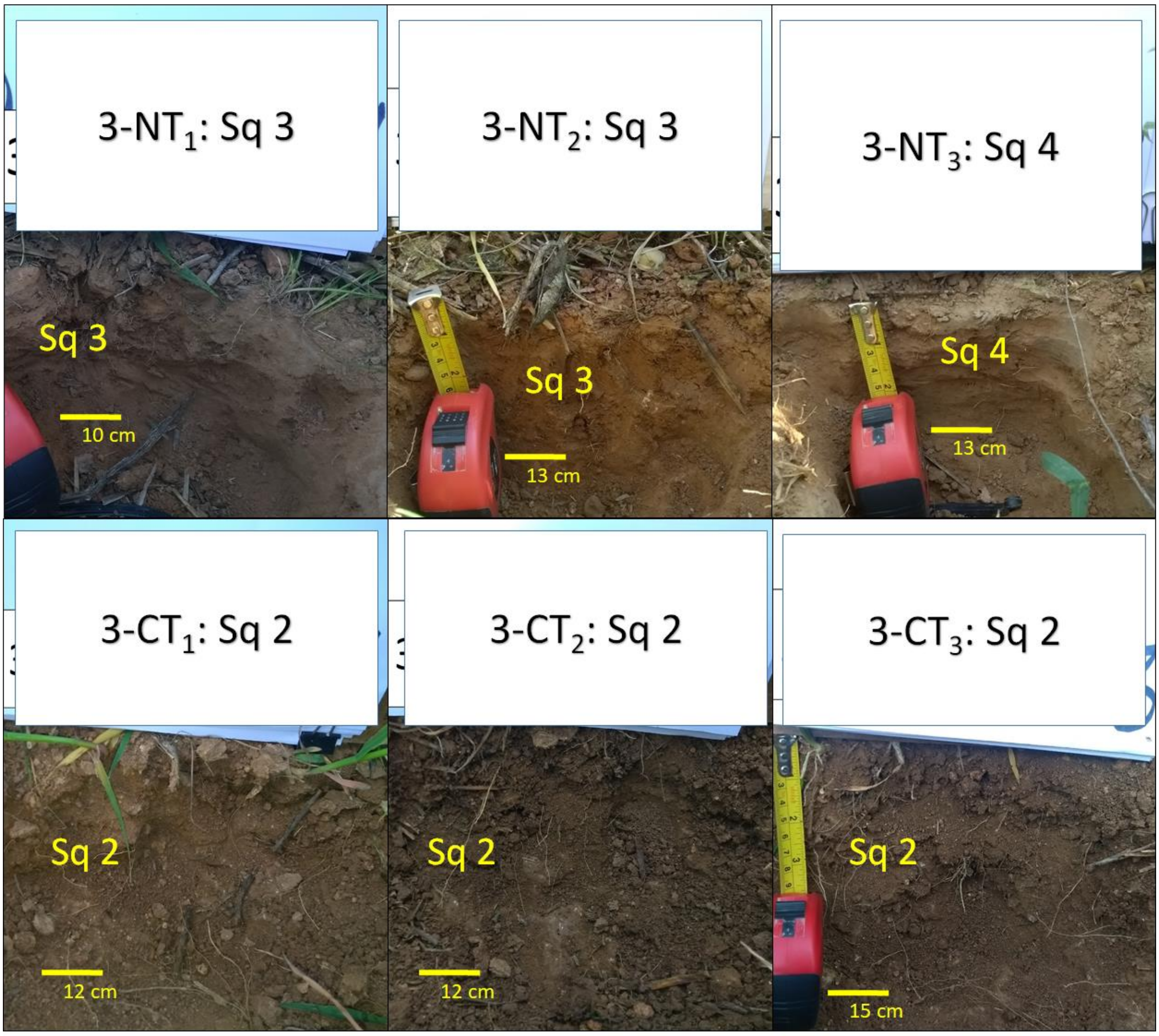

Figure 86. Location 3 soil blocks and VESS scores

At location 4, 4-CT presented compact and firm VESS scores that suggest a requirement for management change; while 4-NT scored intact VESS throughout the field (Figure 87). 4-NT presented 2.5Y 6/4 colour across the field. At the first 4-NT site, the surface horizon presented buried crop residues, big aggregates, and the next soil layer presented earthworm channels and round aggregates smaller than 6 mm in a matrix of angular 1.5 cm aggregates. At the second and third site, the soil presented bigger aggregates that broke into smaller aggregates of 6 mm, mixed with rounded aggregates of 1mm. At 4-CT field the soil matrix colour was 10YR 5/3. The first site presented a surface horizon (5 cm deep) with smaller than 6 mm hard aggregates. The second horizon presented less roots and porosity, and bigger size aggregates (1 cm). Additionally, this horizon presented mottling with colours 10YR 6/4 and 7.5YR 5/6, some were associated to roots and pores, although the field was also at the limit of two parental materials of distinguishing colours. Therefore, the final VESS score was firm. This mottling was not found at site 2 nor site 3 of the field. At the second site, there was evidence of earthworm activity and also a first 5 cm deep soil layer. Additionally, there were 7 mm wide and 1 cm deep cracks in surface. Here, the second soil layer overall porosity was lower, but macropores were observed, scoring for compact VESS. The third side, the soil broke into big aggregates of 1 cm and a loose matrix with low soil structure development, scoring for firm VESS.

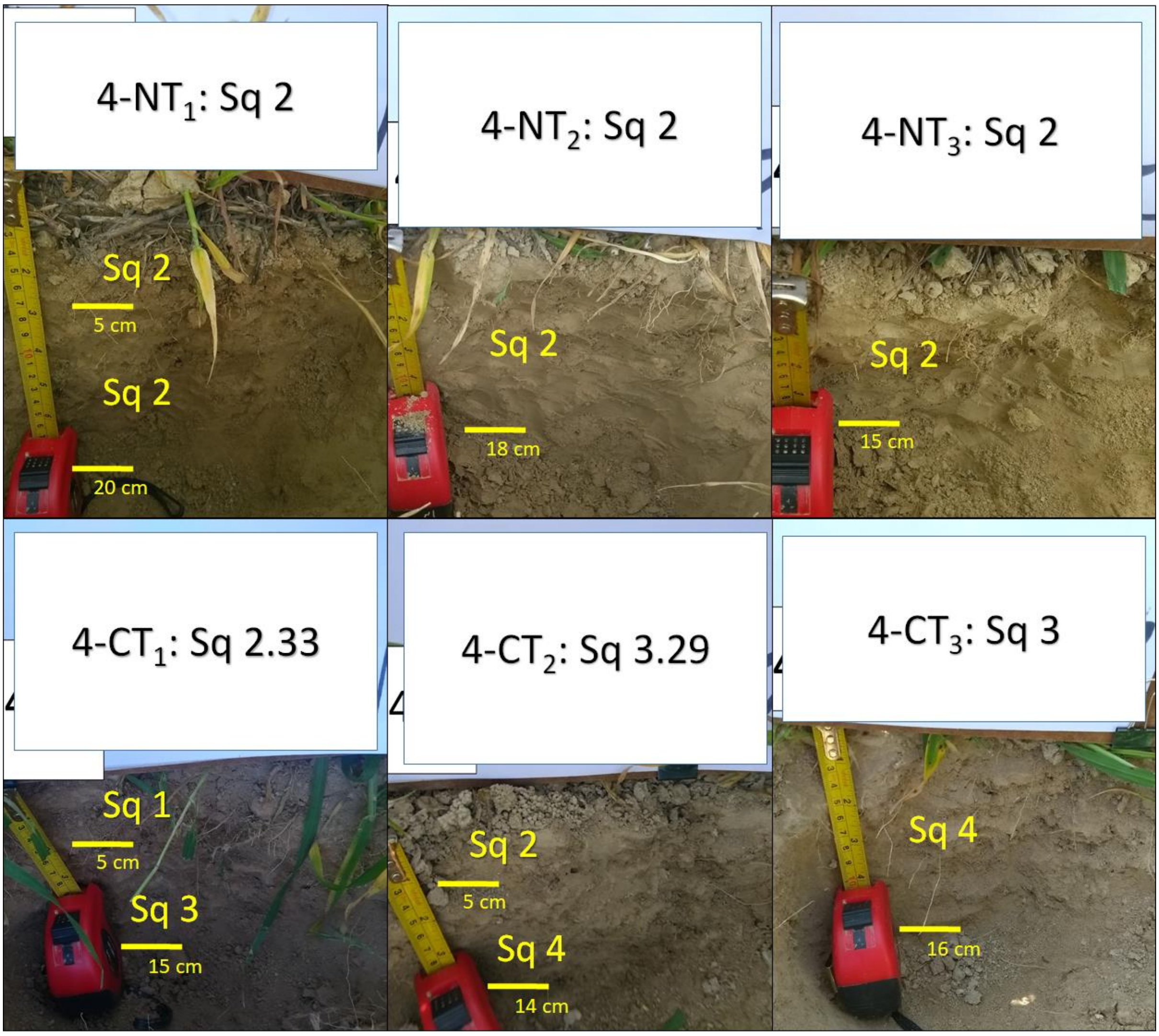

Figure 87. Location 4 soil blocks and VESS scores

At location 5, 5-NT presented one compact VESS score that suggested a requirement for a site specific intervention; while 5-CT scored friable and intact for the first 7 cm at two sites and firm at the third site and below the better surface layers, suggesting monitoring soil quality. Colour was 10YR 5/4 at both fields. All sites at 5-NT presented a very shallow (only 1 cm) surface layer. 5-NT first site had a 1.5 cm thick crust that broke in angular aggregates. The second soil layer was compacted and its structure was not developed. The second and third sites had rounded 2 mm size aggregates in surface (1 cm). The second horizon had roots and earthworm channels, and broke into angular aggregates of 0.7 – 1 cm. 5-CT had, at the first site, a surface layer with smaller than 6 mm subangular aggregates, roots, ants and high porosity. The second soil layer had less porosity, bigger than 1 cm aggregates, but still with some root and earthworm channels. At the second site, the surface layer presented a mixture of smaller than 6 mm rounded aggregates and bigger than 1 cm aggregates. There were crop residues on surface. The second soil layer also presented vertical channels. The third site had less roots but ant activity.

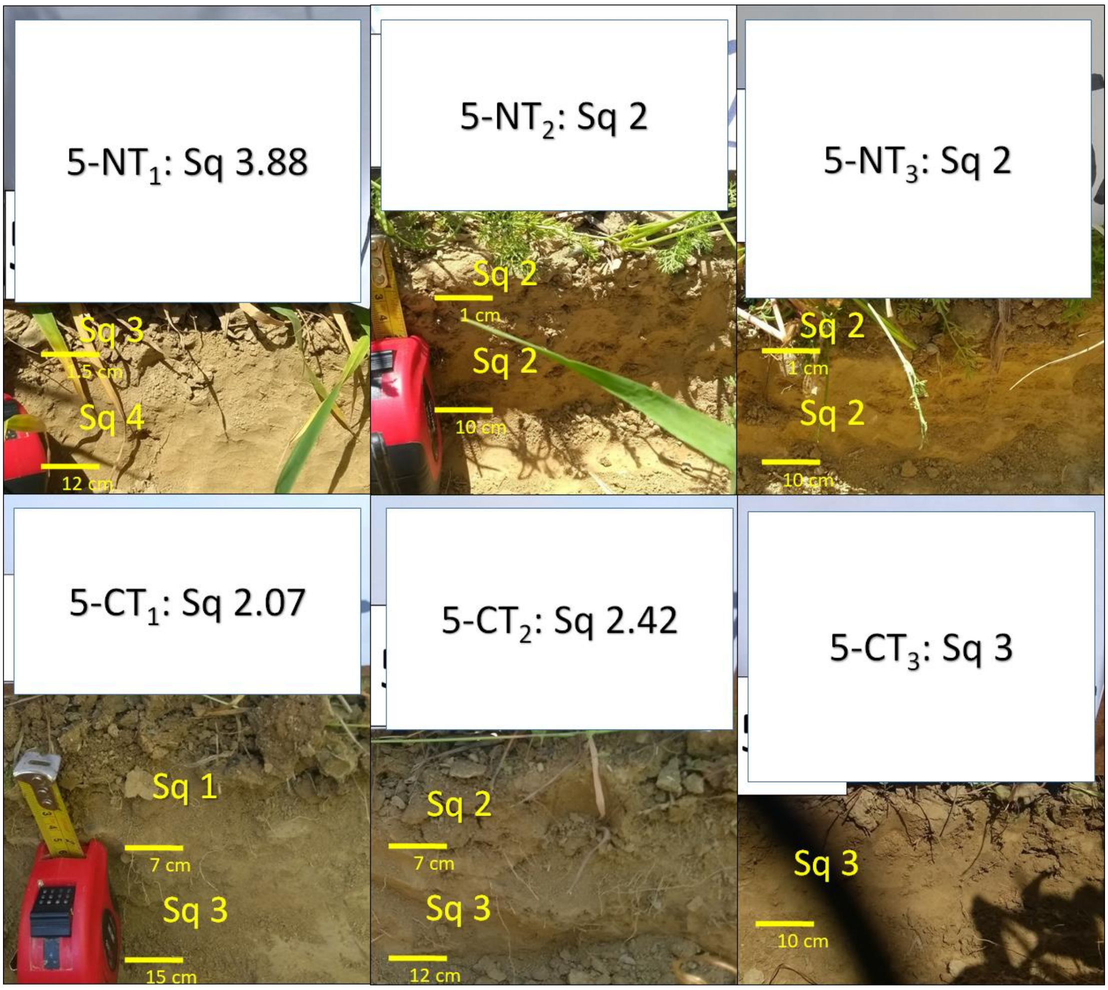

Figure 88. Location 5 soil blocks and VESS scores

Appendix D. Cluster analysis

Model-based clustering in R compares a range of models' performance according to BIC, best performing model in the case of the Spanish soils was VEI (variable volume, equal shape and orientation aligned to coordinate axes) with 5 clusters as shown in Figure 89 and for the British soils it was VEE (variable volume, equal shape and orientation) with 3 clusters as shown in Figure 90. How the identified clusters relate to aggregation agents is shown in Figure 91 for the Spanish and in Figure 92 for the British data.

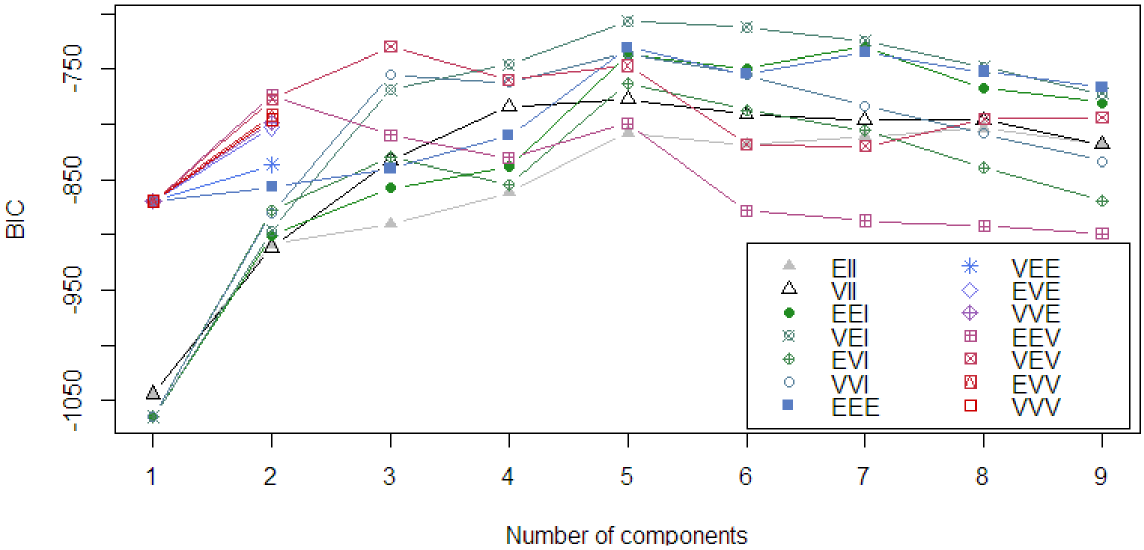

Figure 89. Model-based clusters' performance for Spanish soil samples

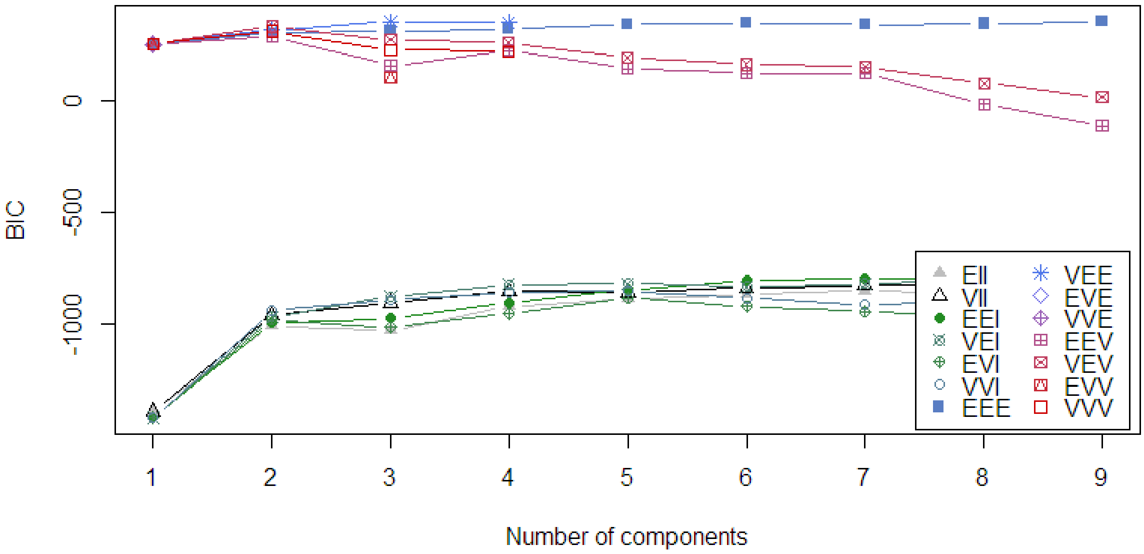

Figure 90. Model-based clusters' performance for British soil samples

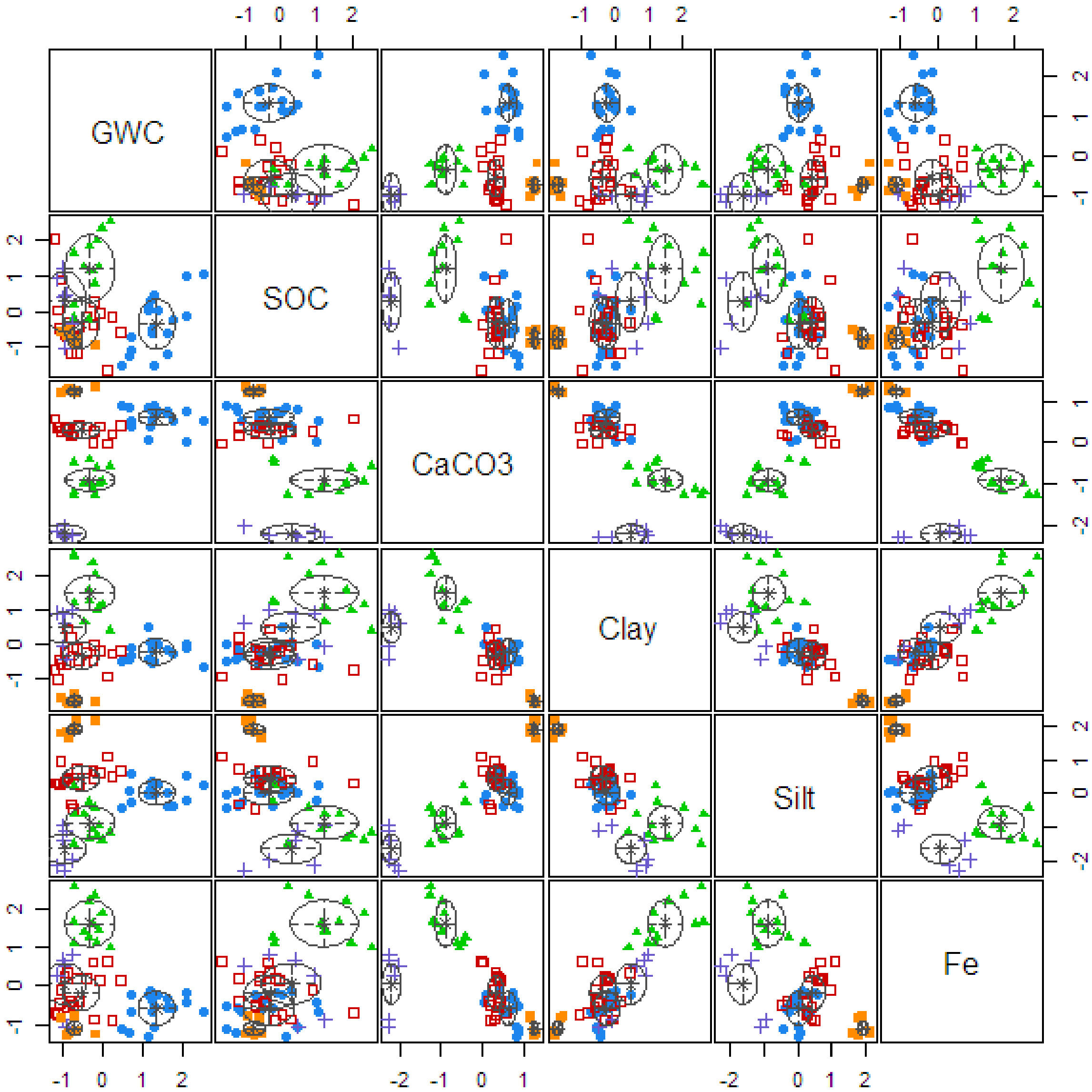

Figure 91. Sample classification according to model-based clustering for Spanish soils

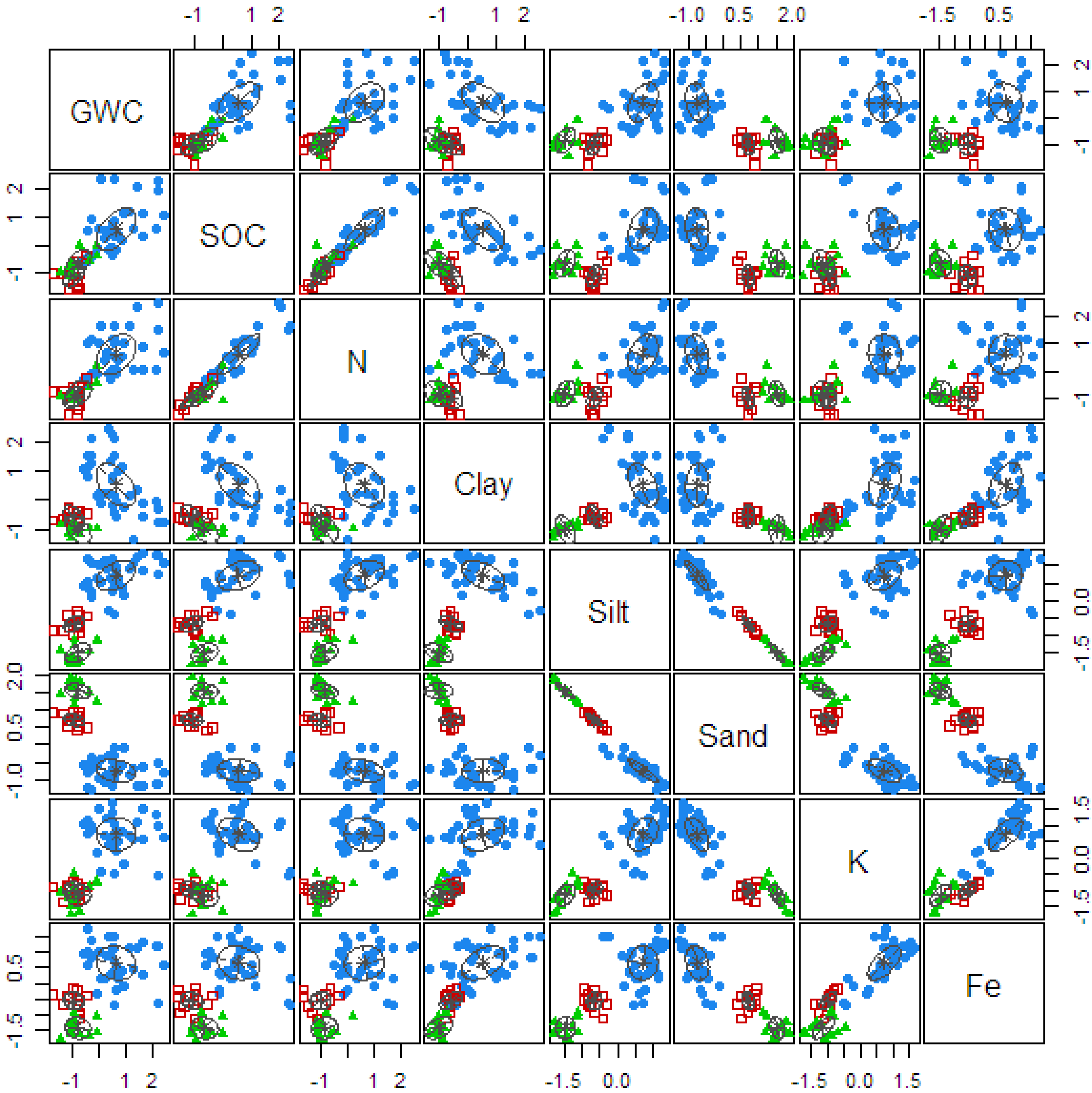

Figure 92. Sample classification according to model-based clustering for British soils