The contribution of urban horticulture to food security, resilience and health and well-being

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Abstract

Interest in urban horticulture (UH), both as a recreational pursuit and a research subject, has been growing in recent years. Its potential role in improving the nutritional security and physical and mental well-being of urban populations gained particular attention following the outbreak of the Covid-19 pandemic, which majorly affected people's lives around the globe. This thesis assesses the role of UH, specifically small-scale fruit and vegetable (F&V) growing in allotments and domestic gardens, in reducing our reliance on the globalised food system and alleviating the negative health and well-being effects of urbanised lifestyles, in the UK and wider Global North. First, in Chapter 2, I explore the role of urban agriculture in strengthening city resilience in the Global North through a systematic literature review and develop a conceptual model to highlight ways in which its resilience benefits could be enhanced. In Chapter 3, I assess UH food production potential in the UK using own-grown harvest data from the national 'Measure Your Harvest' citizen science project, estimate yields of different crops, and provide the first national-scale estimate of F&V production potential on UK allotments. Next, Chapter 4 assesses the role of own food production in allotments and domestic gardens in the UK in promoting F&V self-sufficiency and consumption at the household level, using a year-long food diary approach. Lastly, in Chapter 5 I investigate how different aspects of gardening may be associated with a range of health and well-being outcomes in the UK using an online survey of gardeners and non-gardeners, identifying a number of mechanisms through which it might promote well-being. Finally, I present a synthesis of my findings and discuss the implications of this PhD research for policy and practice and its contribution to existing research, closing with some suggestions for future work in the field.

Acknowledgements

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Declaration

This is an 'alternative format' thesis, with each data chapter (Chapters 2 to 5) presented as a stand-alone research paper. At the time of submission, Chapter 2 has been published in Sustainability (doi: 10.3390/su13031465); Chapter 3 is planned for submission to Nature Food; Chapter 4 is in review in Plants, People, Planet; and Chapter 5 is planned for submission to BMC Public Health. As such, each chapter has multiple authors listed. My contributions to each one are as follows:

Chapter 2

Design of project, collation, analysis and visualisation of data, conceptualisation, manuscript preparation, editing and submission.

Chapter 3

Management of project, data analysis and visualisation, manuscript preparation and editing.

Chapters 4

Design of project, recruitment of participants, data entry, collation, analysis and visualisation, manuscript preparation, editing and submission.

Chapter 5

Design of project, data collection, analysis and visualisation, manuscript preparation and editing.

Other authors listed contributed to each chapter as follows:

Jill L. Edmondson

Supervised study design, data collection and analysis, and contributed to conceptualisation, manuscript preparation, review and editing of all chapters.

Samantha J. Caton

Supervised study design, data collection and analysis, and contributed to methodological development, manuscript review and editing of Chapter 5.

Hamish Cunningham

Developed the MYHarvest database used for data collection in Chapter 3.

Jonathan R. Leake

Contributed to the planning and design of the MYHarvest project used for data collection in Chapter 3.

Roscoe Blevins

Conducted fieldwork for and managed the MYHarvest project (until May 2019) used for data collection in Chapter 3.

Miriam C. Dobson

Conducted fieldwork for the MYHarvest project used in Chapter 3.

Marta Crispo

Conducted fieldwork for the MYHarvest project used in Chapter 3.

This work involved human participants and was given ethical approval by the University of Sheffield ethics committee (application numbers 144905, 035588 and 041219).

Table of Contents

Chapter 1

General introduction

The global food system faces many challenges in terms of sustainability, resilience, and providing food and nutritional security to growing, increasingly urban populations. In addition to food supply issues, global urbanisation brings with it growing rates of non-communicable diseases and other lifestyle- and environment-related physical and mental health conditions. This thesis deals with the question of how urban horticulture (UH), and especially small-scale fruit and vegetable (F&V) production within cities, could help tackle some of these challenges, with a particular focus on the United Kingdom. I address this question utilising a combination of research methods, including systematic literature review, online survey, geographic information systems, national-scale online citizen science data collection and food diaries. In this first chapter, I introduce this topic, starting with an overview of some of the key challenges facing today's urbanised societies in terms of health, well-being and food security. This is followed by an introduction to UH and a brief review of the literature on how it might contribute to increased food system resilience and sustainability, nutritional security, and different aspects of health and well-being in the UK and the Global North. Having identified some key research gaps in the field, I close with a summary of the specific aims of this thesis and an overview of each data chapter (Chapters 2 to 5).

1. Challenges for the urbanising world

Today, urban areas host the majority of the world's population, and the process of urbanisation continues across the globe (UN, 2020), including in the UK, where 84% of the population is already urban (World Bank, 2022). While living in a city offers many benefits to individuals and society, it also comes with a range of issues for both human health and the environment, especially if rapid urbanisation goes unplanned (WHO, 2021b). Key threats to human health exacerbated by urbanisation, which have disproportionate negative effects on those living in more deprived neighbourhoods, include an increased risk of both infectious and non-communicable diseases, as well as pollution-related health conditions (Godfrey & Julien, 2005; Kuddus et al., 2020; WHO, 2021b). The rising global burden of non-communicable diseases, such as cardiovascular disease, type 2 diabetes, cancer and asthma, is closely linked to aspects of urban environments and lifestyles, including physical inactivity and unhealthy diets low in fruits and vegetables (F&V) and high in processed foods (Forouzanfar et al., 2015; WHO, 2003). In the UK, over two thirds of the population do not eat enough F&V, which is associated with around 18,000 premature deaths each year (Afshin et al., 2019). In addition, over a third of adults do not do enough physical activity, which is estimated to contribute to 1 in 6 deaths and an annual healthcare cost of £1.2 billion (British Heart Foundation, 2017; OHID, 2015). Overall, food-related ill health is estimated to cost the National Health Service £6 billion each year (Rayner & Scarborough, 2005).

Urbanisation is also associated with higher rates of mental health problems, including depression, anxiety, and loneliness, related to increased exposure to stressors such as overcrowded and polluted environments, reduced social support and low exposure to nature (Cox et al., 2018; Srivastava, 2009; Trivedi et al., 2008; Ventriglio et al., 2021). In addition, most cities are highly dependent on globalised supplies for food and other commodities, which are vulnerable to environmental, economic, and geopolitical disruptions, such as the recent covid-19 pandemic, continued climate change and the current war in Ukraine (Béné, 2020; Meerow et al., 2016; Wheeler & von Braun, 2013). As major consumers of energy and producers of greenhouse gases, cities also greatly contribute to climate change, while at the same time being particularly vulnerable to its effects due to the heat island effect resulting from a lack of vegetation cover and large expanses of concrete and other materials that absorb and re-emit heat (Mohajerani et al., 2017). To mitigate the negative impacts of urbanisation and protect and promote the health and well-being of society and the global environment, we need to redesign our cities.

2. Feeding our cities

Providing sufficient nutritious food for growing, increasingly urban populations in a sustainable way is a major challenge of our time. We have limited land for food production, much of which is managed using unsustainable agricultural practices that contribute to irreversible soil degradation (Yang et al., 2003), biodiversity loss (Dudley & Alexander, 2017) and considerable greenhouse gas emissions (Garnett, 2011; Vermeulen et al., 2012). In addition, the current food system is also highly wasteful

(Gustavsson et al., 2011) and the stability of our food supplies is threatened by increasingly frequent and severe extreme weather events and other effects associated with climate change (Li et al., 2009; Peng et al., 2004; Vermeulen et al., 2012; Wheeler & von Braun, 2013), as well as socio-economic and political crises (Béné, 2020; WFP, 2022). In the UK, we rely on foreign imports for about 63% of the national F&V supply (Defra, 2018) so, given the importance of these foods for a healthy diet, interruptions to these supplies could have serious negative implications for public health. Urbanisation has also been linked to increased risk of food insecurity (Szabo, 2016), which could be exacerbated by disruptions to the long, globalised food supply chains which many cities rely heavily on.

A key part of the food security problem is that healthy diets tend to be considerably more expensive than energy-dense but nutrient-poor ones (FAO et al., 2022), contributing to increased rates of overweight and obesity especially prevalent in urban areas (Ruel et al., 2017; WHO, 2021a). In addition, access to healthier food options in many deprived urban neighbourhoods is limited, which has led to large inequalities in diet-related health status, in the UK (Dimbleby, 2021; Rayner & Scarborough, 2005) and globally (FAO et al., 2022). This problem is getting worse as increasing monetary and fiscal subsidies for staple foods, animal source products and their derivatives further discourage the consumption of less subsidised commodities like fruits, vegetables and pulses, which as a result are becoming relatively more expensive and less accessible in many countries (FAO et al., 2022). Furthermore, the inflation in food prices resulting from the economic impacts of the recent COVID-19 pandemic and the war in Ukraine have contributed to a massive increase in the number of people unable to afford a healthy diet globally (FAO et al., 2022; WFP, 2022). To avoid an impending hunger and nutrition crisis, it is essential that we increase the resilience of urban food systems and improve equality of access to healthy food in addition to finding ways to produce food more sustainably and efficiently.

3. Urban agriculture in the Global North

Urban agriculture (UA) is the production of food within urban areas (FAO, 2018; Smit et al., 1996). In the UK, other European countries, and the USA, the predominant form of UA is urban horticulture (UH), which focuses on fruit and vegetable (F&V) production.

UH is increasingly recognized around the world for its potential to improve food security and sustainability, as well as providing social and ecological benefits (APA, 2019; Milan Urban Food Policy Pact, 2018; Morgan, 2015; Pulighe & Lupia, 2020). It can take different forms, including market gardens, allotments, community farms, and domestic vegetable gardens, and may involve both traditional and novel (e.g. controlled environment horticulture) cultivation methods. While in the USA, UH typically takes the form of community gardens (Grewal & Grewal, 2012), in the UK, the traditional sites of UH are allotments, plots of land rented to individuals for the production of F&V by local councils or private land-owners (Campbell et al., 2011).

Own food production on allotments and in domestic gardens in the UK played an important role during World War II, when it was actively encouraged by the government as part of the Dig for Victory campaign as a means to aid the war effort (Ginn, 2012). It is estimated that own-grown F&V production during this period contributed 18% (by value) to total production in the UK (Defra, 2017; Ginn, 2012). However, after the war, demand for and provision of allotments started to fall. Currently there are approximately 300,000 allotment plots in the country, but public demand has been on the rise since the turn of the century (apse, 2022; Campbell et al., 2013). In the UK, as well as in other countries, interest in 'grow-your-own' has been growing since the turn of the century and rose sharply in response to the outbreak of the covid-19 pandemic, and the high demand for allotments is unmet by the current supply (apse, 2022; Dobson et al., 2020a).

4. The benefits of fruit and vegetable gardening

Growing F&V within urban areas has a range of potential benefits. It can boost the resilience of food systems by diversifying sources and creating alternative, shorter supply chains (Sustainable Food Trust, 2020; Tendall et al., 2015) and improve food and nutritional security through increasing local availability of fresh produce. A further benefit is the increase in sustainability of the food system by enabling the recycling of urban waste (Schuetze et al., 2016) and reducing reliance on unsustainably grown commercial horticultural crops (Robinson & Sutherland, 2002; Watts & Dexter, 1997). Food gardening may also promote F&V consumption (Alaimo et al., 2008; Barnidge et al., 2013; Demark-Wahnefried et al., 2018; Kunpeuk et al., 2020; Litt et al., 2011; Nova et al., 2020; Sarti et al., 2017; Sommerfeld et al., 2010) and physical activity (Machida, 2019; van den Berg et al., 2010), helping to reduce or prevent overweight and obesity (Davis et al., 2011; Demark-Wahnefried et al., 2018; Duncan et al., 2015; Kunpeuk et al., 2020; Zick et al., 2013), as well as offering social (Dobson et al., 2020b; Firth et al., 2011; Kingsley & Townsend, 2006) and psychological benefits (Alaimo et al., 2016; Chalmin-Pui et al., 2021b; Genter et al., 2015; Hawkins et al., 2011; Machida, 2019; Sog et al., 2017a; Soga et al., 2017b; D. Wang & MacMillan, 2013; Wood et al., 2016). Better access to nutritious, fresh produce and other social and health benefits of engaging with UH may be particularly important for the urban poor and other disadvantaged groups, who are most vulnerable to the adverse effects of urbanisation and socio-economic disturbances (Dimbleby, 2021; FAO et al., 2020).

However, despite growing evidence for UH's various benefits, there are still a number of questions that remain unanswered in the field. In particular, quantitative estimates of its potential to provide food and improve well-being are scarce, and little research has focused on the ways in which its benefits could be maximised. This PhD research aims to fill some of these knowledge gaps to increase our understanding of the potential of small-scale fruit and vegetable production for promoting urban food security, health, well-being, sustainability and resilience.

5. Thesis aims, objectives and outline

5.1. Objectives

The overall aim of this thesis is to assess the role of UH, specifically small-scale fruit and vegetable (F&V) growing on allotments and in domestic gardens, in reducing our reliance on the globalised food system and alleviating the negative health and well-being effects of urbanised lifestyles, in the UK and the wider Global North. The specific objectives of the thesis are:

1. To better understand how urban agriculture in the Global North can increase city resilience and identify some pathways in which its contribution could be maximised.
    - What determines the success of UA in promoting city resilience in the Global North?

  - What challenges does it currently face that might limit its contribution?
  - How could its benefits be maximised through research, policy, and practice?

2. To assess the significance of own F&V growing for national food security and understand how own-grown crop yields are affected by management practices and local environmental conditions.
   - What are the typical yields of common own-grown crops in the UK?
   - How are own-grown crop yields affected by the type of growing space used, and whether crops were grown organically?
   - How do own-grown crop yields vary regionally within the country with soil type and growing season temperate?
3. To quantify the potential contribution of household F&V production to the self-sufficiency and diet quality of food-grower households in the UK.
   - What levels of year-round production and self-sufficiency can food-grower households achieve in different types of produce, and how does this vary across the year?
   - How much F&V do food-grower households eat, and how diverse is their F&V consumption?
   - How do certain aspects of growing practice (i.e. cultivated area, grower experience, gardening effort) and household size affect household food productivity and self-sufficiency?
4. To quantitatively assess the relationship between different gardening related variables and health and well-being in the UK to increase our understanding of the ways in which it can exert its beneficial effects.
   - Is the amount of time spent gardening in a typical week, self-reported amount of food produced, or having an allotment associated with self-rated general health, mental well-being, frequency of physical health

complaints, obesity, diet quality, physical activity level, or the amount of time spent outdoors?

5.2. Thesis outline

Chapter 2 introduces the concept of city resilience and the role that urban agriculture (UA) can play in strengthening resilience in the Global North through promoting food security and public health, building social capital, and contributing to circular economies. I explore this topic through a systematic review of the academic literature with the aim of identifying factors that determine the success of UA in providing resilience benefits, and challenges that can limit this. I then develop a conceptual model to highlight ways in which UA's resilience benefits could be enhanced through research, policy, and practice. [Objective 1]

Chapter 3 builds on previous research (Edmondson et al., 2019; Edmondson et al., 2020a; Edmondson et al., 2020b) aimed at determining the food production potential of UK allotments, gardens and other small-scale growing spaces using data collected via the national MYHarvest ('Measure Your Harvest') citizen science project. I use harvest data collected over five consecutive years from over 400 sites across the UK, as well as corresponding information on management practices and local environmental conditions, and perform a series of linear mixed effects analyses. This enabled me, firstly, to determine how the yields of common own-grown crops are affected by soil type, growing season temperature, type of growing space, and whether they were grown organically, and secondly, to provide the first national-scale estimate of own-grown fruit and vegetable production potential on UK allotments and its contribution to the national food supply. [Objective 2]

In Chapter 4, I investigate the importance of own-grown F&V production on allotments and in domestic gardens in providing food security at the household level, and whether it is associated with increased consumption of F&V. I do this by studying year-long F&V production, purchases, donations, and waste in 85 food-grower households across the country using a weekly food diary approach. This research enabled me to determine UK food-grower households' annual level of self-sufficiency in vegetables, potatoes and fruits, as well as their average F&V intake, dietary diversity in F&V, and amount of F&V waste produced. The findings have important implications for schemes to encourage small-scale own-growing in order to increase resilience in supply of F&V, promote F&V consumption and reduce food waste. [Objective 3]

Finally, in Chapter 5 I set out to determine how different aspects of gardening (i.e. weekly amount of time spent gardening, self-reported amount of food produced, and having an allotment) may be associated with a range of health and well-being outcomes in the UK. To do this, I used an online survey administered to both regular gardeners and non-gardeners, and a series of multiple linear and binary logistic regression models adjusted for key demographic and lifestyle factors known to be associated with health status. This allowed me to identify some of the mechanisms through which home and allotment gardening can exert its health and well-being benefits, to help guide efforts aimed at improving public health and well-being. [Objective 4]

Chapter 2

Increasing city resilience through urban agriculture: challenges and solutions in the Global North

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Abstract

Cities, which now host the majority of the global population, are vulnerable to environmental and socio-economic disturbances, which are likely to increase in number and severity in the near future. Urban agriculture (UA) could help increase the resilience of cities to a range of pressures and acute shocks by improving food security and public health, building social capital, and promoting circular economies. However, comprehensive assessments of its potential are still lacking. Here, we use a systematic review of the literature on UA in the Global North to identify factors that determine its success in providing resilience benefits, explore challenges that can limit this, and develop a conceptual model to highlight the ways in which it could be enhanced through research, policy, and practice. We define the success of UA in increasing city resilience as determined by five factors, which in turn depend on the amount of institutional and public support for UA, the presence of a sufficient knowledge base, communication and collaboration among different actors, and resourcefulness in finding alternative ways to use space and other resources efficiently. We close with a discussion of specific directions for research and practice based on the conceptual model developed here.

1. Introduction

1.1. City resilience

Hosting the majority of the world's population, today urban areas are facing an unprecedented number of threats, including natural disasters, pandemics, terrorism, water scarcity, poverty, and food insecurity. These risks are exacerbated by climate change, population growth, and continued rapid urbanisation, and are expected to increase in number and severity in the near future (IPCC, 2018; Morton & Blanchard, 2007; United Nations, 2017; While & Whitehead, 2013). In addition, most cities' dependence on global resources has made them highly vulnerable to shocks that can disrupt their current supply systems, the fragility of which has become obvious following the recent outbreak of the Covid-19 pandemic (Deelstra & Girardet, 2000; de Ruiter et al., 2016; FAO, 2020; Lal, 2020; Lang & McKee, 2018; Montague-Fuller, 2014). Therefore, to prevent an imminent disaster, cities must take prompt measures to better prepare for future crises.

The term resilience—often defined as "the ability of a system to absorb shocks of all kinds, and its capacity to adapt to changing conditions without losing any of its key functions" (Meerow et al., 2016)—has become a buzzword in urban planning, used to describe cities that can withstand and recover from various disturbances, including those caused by climate change and socio-economic crises (Lee & Lee, 2016; Olsson et al., 2016; Voskamp & Van de Ven, 2015). Resilient cities are proposed to be reflective, resourceful, flexible, redundant, robust, and integrated, characteristics which make them "safe to fail" (rather than fail-safe) in the face of challenges (*100 Resilient Cities*, 2019; McMillen et al., 2016). Since urban areas are complex, dynamic socio-ecological systems, city resilience is a concept that spans multiple dimensions and involves various systems and actors (Dezio & Marino, 2018; Olsson et al., 2016; Sharifi & Yamagata, 2014; Tendall et al., 2015). Appropriate institutional frameworks with equitable rights and decision-making processes are also argued to be an important aspect of systems resilience (Tendall et al., 2015).

1.2. Urban agriculture and resilience

As well as serving to meet basic needs, the food system is a key determinant of the health and wellbeing of society, with poor diets being a main cause of noncommunicable diseases and related deaths worldwide (Di Angelantonio et al., 2016; FAO et al., 2020; WHO, 2020). Thus, securing access to sufficient amounts of nutritious food for urban populations in the face of disturbance is a fundamental part of resilience (Baudoin & Drescher, 2008; Tendall et al., 2015). Most cities in the developed world are currently highly dependent on globalised supplies, which are vulnerable to environmental, economic, social, and geopolitical stresses (FAO, 2020; Ingram et al., 2020b; Sustainable Food Trust, 2020). As a result, supply disruptions and increasing food prices can severely impact consumers in urban areas, especially the urban poor (Dubbeling et al., 2019; Lal, 2020; Pulighe & Lupia, 2020). Increasing local production and developing shorter supply chains could decrease the likelihood of disruption to food supplies, enable the development of circular systems, reducing dependency on external inputs, while diversifying sources can provide "back-up" capacity and, thus, improve the ability of food systems to react and adapt to shocks (Dubbeling et al., 2019; IIED, 2013; Ingram et al., 2020a; Schuetze et al., 2016; Sustainable Food Trust, 2020; Tendall et al., 2015). There is growing evidence that urban agriculture can increase city resilience through a number of mechanisms, including, but not only, through increasing the resilience of food systems.

Urban agriculture (UA)—the production of food, mostly fruit and vegetables, within urban areas (FAO, 2018; Smit et al., 1996)—is increasingly recognized for its multiple social and ecological benefits by city governments around the world (APA, 2019; Calvet-Mir & March, 2019; FAO, 2020; Milan Urban Food Policy Pact, 2018; Morgan, 2015). During World War II, UA played an important role in increasing food security and boosting national morale in Britain and the USA, where household fruit and vegetable production was promoted through the *Dig for Victory* and *Victory Garden* campaigns, respectively (Lang & McKee, 2018; Mok et al., 2014). Following a period of decline in post-war years, urban agriculture is now enjoying a resurgence of interest in the Global North, which has recently spiked during the Covid-19 lockdowns (Chang & Morel, 2018; Colasanti & Hamm, 2016; Colding & Barthel, 2013; Deelstra & Girardet, 2000; Evans & Davies, 2020; Martin et al., 2016; Panagopoulos et al., 2018; Royal Horticultural Society, 2020). Today, UA takes various forms, from vegetable plots in private gardens, through allotments and community farms, to rooftop gardens and edible walls using technologically advanced, soil-free cultivation methods (Grewal & Grewal, 2012; Tomkins, 2019). While peri-urban agriculture (PUA)—the production of food on the outskirts of cities—is sometimes treated as a separate phenomenon from UA, the distinction between the two is not always clear-cut (FAO, 2018; Opitz et al., 2016). For the purposes of this study, the term UA will be used to refer to all forms and scales of growing food in both urban and peri-urban areas.

Perhaps the most obvious way in which UA can contribute to city resilience is by increasing household and citywide food security, especially in terms of micronutrient requirements, through the provision of fresh produce locally (APA, 2019; Calvet-Mir & March, 2019; Colasanti & Hamm, 2016; Deelstra & Girardet, 2000; Edwards et al., 2011; FAO, 2001, 2018; Frantzeskaki & Tilie, 2014; Grewal & Grewal, 2012; Hara et al., 2018; Sanyé-Mengual et al., 2015). Own-growing, in particular, can play an important role in supplementing the diets of more disadvantaged groups who have limited physical or financial access to fresh food (Baudoin & Drescher, 2008; Dubbeling et al., 2019; Ferreira et al., 2013; Lal, 2020; Pulighe & Lupia, 2020). However, importantly, UA can also increase the sustainability of the food system on a larger level, by enabling the recycling of organic urban wastes as fertiliser and reducing reliance on mineral fertilisers, which have considerable environmental costs globally (Cameron et al., 2015; Cordell et al., 2009; Dubbeling et al., 2019; Schuetze et al., 2016; Winiwarter et al., 2014). In addition, making use of spare space in urban areas can increase food production without devoting more scarce land to agriculture, while certain forms of UA can help protect crops from adverse weather effects and enable stable year-round production (Chang & Morel, 2018; Sanyé-Mengual et al., 2015; Winiwarter et al., 2014).

Several potential resilience benefits of UA also go beyond the food system. For example, promoting public health through improving access to fresh produce and providing a form of regular exercise (Calvet-Mir & March, 2019; Santo et al., 2016) could reduce the incidence of noncommunicable disease within the urban population, making cities better able to cope during crises caused by pandemics, terrorism, or natural disasters. Furthermore, the practice of food growing can play an important role in building social capital, fostering proactive attitudes, and collaboration, which are key determinants of the ability of communities to get through challenging times (Barthel et al., 2015; Beatley & Newman, 2017; Calvet-Mir & March, 2019; Frantzeskaki & Tilie, 2014; Mabon, 2019; Martin et al., 2016; McMillen et al., 2016; Santo et al., 2016). Urban farms can also create jobs and help fight unemployment and poverty (De Zeeuw et al., 2011; Dubbeling et al., 2019). Last but not least, vegetation cover provided by urban agricultural sites could improve air quality and decrease the urban heat island effect (UHI), potentially mitigating some of the acute effects of climate change (Deelstra & Girardet, 2000; De la Sota et al., 2019; Dubbeling et al., 2019; Scott et al., 2016).

However, despite growing evidence for UA's various benefits and increasing recognition of its potential to increase city resilience, it is still unclear how UA's success in providing these benefits could be enhanced. While previous research on UA has predominantly focused on issues in developing countries, the urgent need to increase the resilience of cities in the developed world is now also clear. The aim of this study is, therefore, to assess and conceptualise the success of UA in the Global North in order to answer to the following questions:

1. What determines the success of UA in promoting city resilience in the Global North?
2. What challenges does it currently face that might limit its contribution?
3. How could its resilience benefits be maximised through research, policy, and practice?

2. Methods

To gain a comprehensive understanding of urban agriculture in the context of city resilience in the Global North, a review of the academic literature was carried out. In order to minimise bias and improve replicability, a systematic approach was taken based on predefined criteria for the selection of relevant studies. An overview of the selection process is shown in Figure 1 below. Articles were identified using a combination of keywords connected by Boolean operators (i.e., AND, OR, and NOT), which could appear anywhere in the title, abstract, topic, or keywords of papers. Studies focusing on issues in the developing world and for which full-text was not available in English were excluded. To control for the quality of sources, only publications in peer-reviewed journals were considered. In order to ensure that issues are considered from a range of perspectives, no restrictions on article type, publication date, or journal title were applied.

The following literature database search was carried out in July 2019 through the University of Sheffield's StarPlus catalogue:

> *"urban agriculture" OR "urban farming") AND ("city resilience" OR "urban resilience") NOT ("africa" OR "developing countries" OR "developing world" OR "middle east" OR "latin america".*

Abstracts of all 73 returned articles were read and any non-relevant search hits (i.e., articles not related to the keywords) were manually removed. The remaining 53 papers were read in full and information related to the specific questions addressed by the study (i.e., 1. factors determining the success of UA in providing city resilience benefits; 2. current challenges for UA; 3. ways in which UA and its benefits could be promoted) was extracted and organised into emerging themes to characterise the success of UA in terms of the amount of resilience benefits it can provide, and was used as the basis for the development of a conceptual framework to illustrate potential pathways through which it could be promoted.

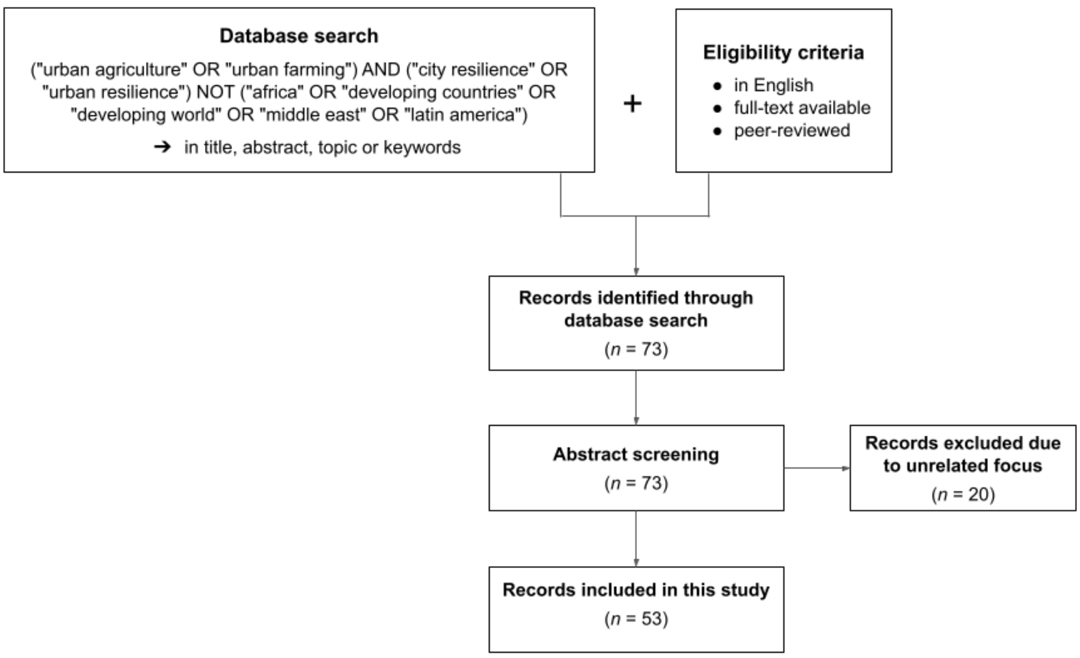

Figure 1. Study selection strategy for the systematic literature review.

3. Results

3.1. Bibliometrics

Applying all selection criteria and an initial screening of 73 abstracts (see Methods) resulted in 53 papers to be reviewed for this study (see Supporting Information Table S1). All reviewed papers were published after 2010 (most between 2013 and 2018) (Figure 2), in 39 different journals with focal subjects covering a range of topics (mostly related to sustainability, environmental science, and urban planning and policy, but also public health, geography, architecture, and engineering) (Figure 3). This reflects the novelty and inherently multidisciplinary nature of this research area, and also demonstrates the breadth of research that fed into the conceptual model we present in this study.

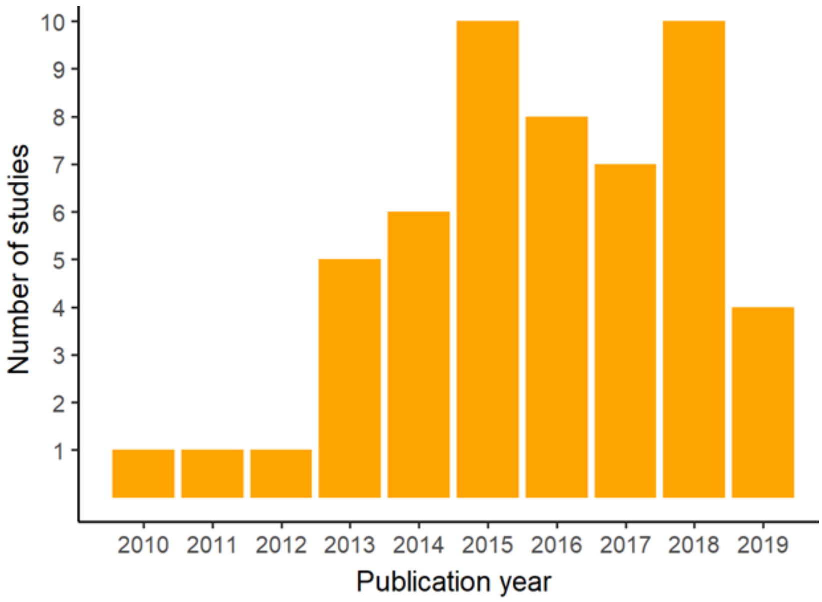

Figure 2. Distribution of reviewed studies by publication date.

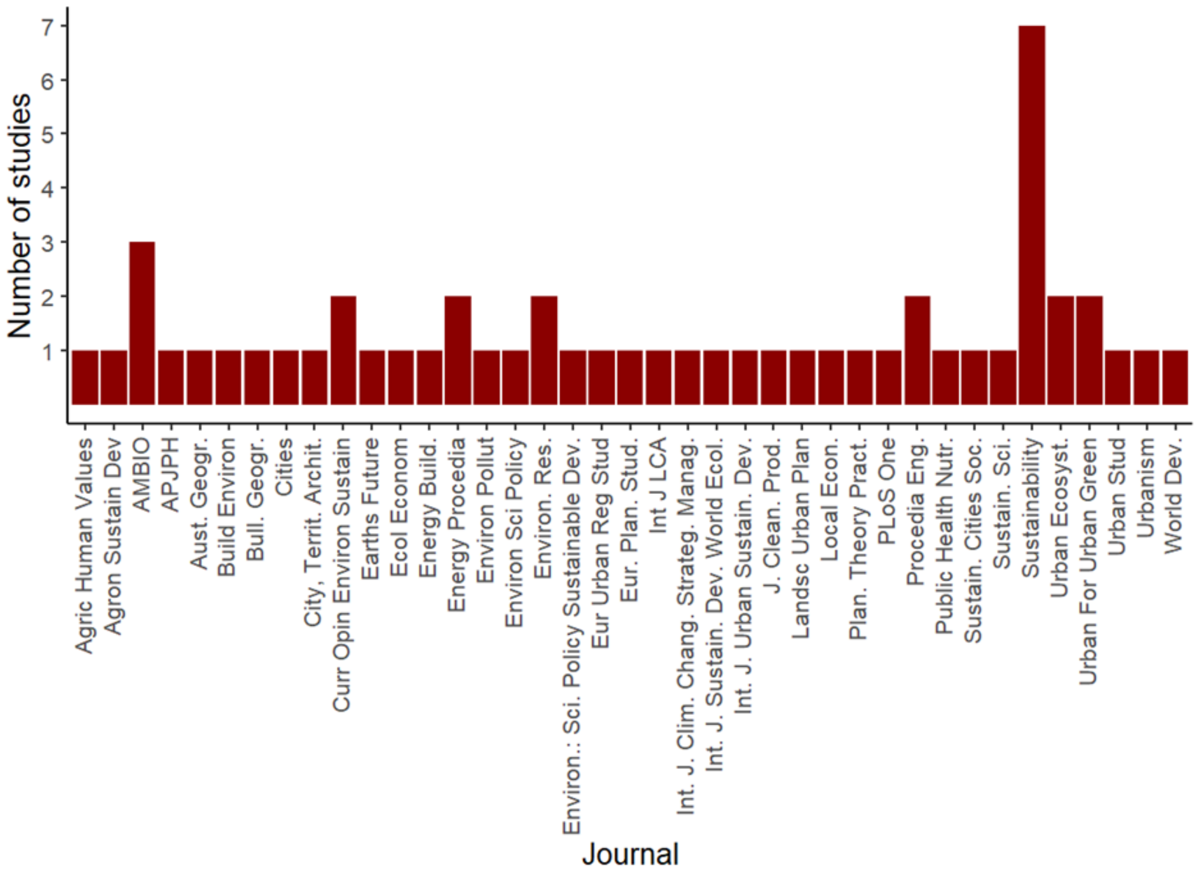

Figure 3. Distribution of reviewed studies by journal.

3.2. What makes UA successful?

Based on the reviewed literature, it is proposed that the provision of resilience benefits by UA in the Global North is determined by five factors (Figure 4): its scale (i.e., the amount of space dedicated to, and number of people engaged in food production in a city); the efficiency of production (i.e., crop yields per unit cultivated area and resource input); the extent to which it is integrated into the urban fabric (i.e., links with different urban systems including food, waste, and education), inclusiveness (i.e., equitable access to growing space and other resources needed to engage in UA, and to urban-grow food); and human and environmental safety (i.e., urban-grown produce is safe to consume and practices do not pollute the city's water supplies or cause harm to surrounding ecosystems). A range of potential issues related to the five key aspects of successful UA as proposed here (i.e., Scale, Efficiency, Integration, Inclusiveness, and Safety) was identified. The aim of the following section is not to provide an exhaustive list of these, but rather an overview of the different kinds of challenges that need to be addressed if UA is to play a more significant role in increasing city resilience.

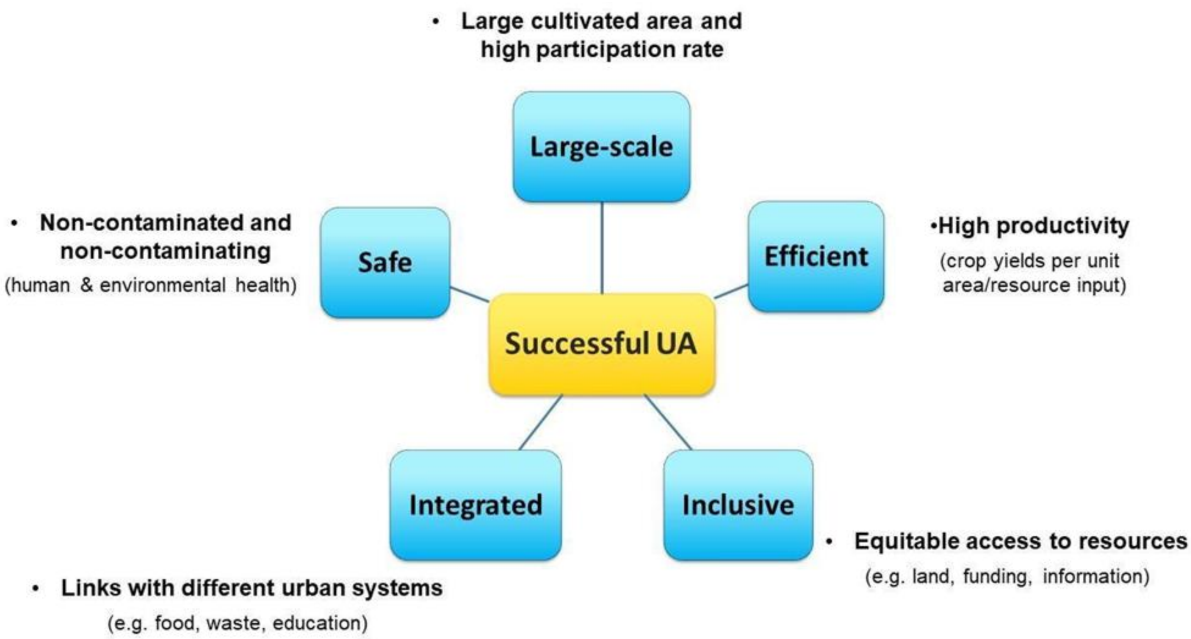

Figure 4. Key characteristics of successful urban agriculture (UA) in the context of promoting city resilience.

3.3. Current challenges for UA

3.3.1. Scale

Perhaps the most obvious constraint on the scale of UA is the limited availability of space in cities, which is coupled with the fact that both urban and peri-urban land is under severe pressure from different contradicting uses, including housing, industry, infrastructure development, and recreation (Faivre et al., 2017; Hara et al., 2018; Jagt et al., 2017; Ling & Chiang, 2018; McPhearson et al., 2014; Panagopoulos et al., 2018). Moreover, vacant space in dense urban settings is often found in small patches among built-up areas, which can prevent the development of larger farms (Privitera et al., 2018). Another issue is that not all available space may be suitable for food production: urban soils can be contaminated (Dezio & Marino, 2018; Panagopoulos et al., 2018; Voskamp & Van de Ven, 2015), while concrete cover can make some open areas unsuitable for traditional cultivation methods (Dennis et al., 2016; Scott et al., 2016). Although suitable rooftops and vertical spaces could be used to expand UA area (Beatley, 2011; Beatley & Newman, 2017; Dennis et al., 2016; Hara et al., 2018; Jagt et al., 2017; Sanyé-Mengual et al., 2015; Schuetze et al., 2016; Voskamp & Van de Ven, 2015), it is estimated that the global availability of these is low compared to the amount of vacant urban land, and, therefore, their contribution may be limited (Clinton et al., 2018), not to mention possible competition from other roof uses, notably photovoltaics (Sanyé-Mengual et al., 2018).

Nevertheless, it can be argued that in many cases the biggest issue is not the lack of space per se, but rather its availability for potential growers—in fact, a recent case study has found that, although there are social and techno-scientific challenges to achieving this in practice, in theory there is enough suitable growing space in a typical UK city to fully meet the fruit and vegetable demands of its inhabitants (Edmondson et al., 2020b). Several reviewed studies point to a lack of supportive policies, ownership issues, and prohibitive legal frameworks as being the main constraints on the scale of UA. On the one hand, measures to safeguard agricultural land in urban areas are often absent, or only temporary, allowing the fragmentation and gradual disappearance of farms (Buijs et al., 2016; Hara et al., 2018; Olsson et al., 2016; Plant et al., 2012; Scott et al., 2016). On the other, expensive land lease and zoning laws defining land use in different areas can limit opportunities to put more land to food production, and can sometimes cause the implementation of UA to outstrip policy and lead to farms being shut down on legal grounds (Beatley & Newman, 2017; Calvet-Mir & March, 2019; Chang & Morel, 2018; Clinton et al., 2018; Collier et al., 2013; Hara et al., 2018; Mabon, 2019; Olsson et al., 2016; Sanyé-Mengual et al., 2015).

Along with the availability of growing space, the level of participation by citizens is a key factor determining the scale of UA. It has been argued that certain forms of urban food production are dying out in some parts of the developed world (Panagopoulos et al., 2018). For instance, many commercial peri-urban farms in Europe have been abandoned or become inhabited by people with little interest in agriculture, and studies suggest that the majority of active growers in some cities are among the elderly (Dezio & Marino, 2018; Olsson et al., 2016; Panagopoulos et al., 2018; Sanyé-Mengual et al., 2018; Scott et al., 2016). Expensive land lease, lack of security of growing space, potentially high costs of setting up and operating farms in urban areas (e.g. for building materials, water, fertiliser, and electricity for supplementary lighting, or circulating water in some nonconventional methods) and limited demand for urban-grown produce can also be discouraging or prohibitive for those wishing to start a UA business or social enterprise (Chang & Morel, 2018; Clinton et al., 2018; Hara et al., 2018; Panagopoulos et al., 2018; Sanyé-Mengual et al., 2015; Schuetze et al., 2016; Winiwarter et al., 2014). Nonetheless, other forms of UA are becoming increasingly popular. For example, own-growing is enjoying a recent resurgence of interest in the UK, where higher participation is hindered by dwindling allotment supply (Dobson et al., 2020a; Royal Horticultural Society, 2020; Wicked Leeks, 2020).

3.3.2. Efficiency

It has been argued that, in many cities of the Global North, the knowledge of how to grow food is being lost (Chang & Morel, 2018; Ferreira et al., 2013; Mabon & Shih, 2018; Panagopoulos et al., 2018). A lack of skills among growers can mean that practices are inefficient (Plant et al., 2012), which, especially if the availability of growing space is limited, can limit food provision by UA (Chang & Morel, 2018; Scott et al., 2016). While alternative practices like aquaponics or hydroponics can allow for high yields in restricted spaces, these are still in relatively early stages of development and, thus, not yet well known among the public. In addition, technologically advanced methods can be quite expensive and may require specialist knowledge, which can be an issue for own-growers and small businesses and community initiatives that cannot afford the hiring of professionals (Mabon & Shih, 2018; Sanyé-Mengual et al., 2015; Schuetze et al., 2016; Winiwarter et al., 2014). While urban wastewater, organic materials, and energy streams could be exploited to decrease costs and improve the efficiency of production, the infrastructure and markets for such products are yet to be developed (Schuetze et al., 2016).

3.3.3. Integration

One main challenge in this area is linking urban producers with consumers. Due to high land prices in more central areas, commercial farms and market gardens are often established on the outskirts of cities, which can complicate the logistics of reaching customers (Hara et al., 2018; Olsson et al., 2016). Another potential issue for small-scale commercially-oriented projects is that many supermarket chains only accept fruit and vegetables of certain size and appearance, making it difficult for producers to secure contracts with them (Plant et al., 2012). Restrictions related to food safety (Olsson et al., 2016) and organic certification of produce (especially when grown using nonconventional methods) can present further obstacles (Sanyé-Mengual et al., 2018). Although alternative distribution systems and retail outlets (e.g. growers' markets) do exist for urban produce, these are not available everywhere, at least partly due to limited government support (Dixon & Richards, 2016; James & Friel, 2015; Olsson et al., 2016). In addition, it is often difficult for urban-grown produce to compete with the low prices available through globalised markets, especially in lower-income neighbourhoods where people cannot afford the alternative (Chang & Morel, 2018). As well as difficult access, cultural factors might also limit consumer demand for UA produce (Dixon & Richards, 2016; Sanyé-Mengual et al., 2018).

Another major issue is the widespread lack of comprehensive planning for resilient urban food systems and, in fact, for food in general: in some countries, there is no government department dedicated to food, and even in highly developed European countries like Sweden, Denmark, or Belgium, explicit strategies for urban food production are rare (Clinton et al., 2018; James & Friel, 2015; McPhearson et al., 2014; Monaco et al., 2017; Olsson et al., 2016). Another related issue is that grey and green areas tend to be treated as distinct systems in urban planning, and so potential synergies that could be achieved through their integrated management (e.g. water and organic waste could be recycled to provide a source of irrigation and nutrients, contributing to more resource- and cost-efficient closed-loop systems, green walls could increase the energy efficiency of buildings while improving air quality and local microclimate (Schuetze et al., 2016)) are seldom exploited (Berte & Panagopoulos, 2014; Frantzeskaki & Tilie, 2014).

3.3.4. Inclusiveness

Urban development patterns in many parts of the Global North have led to uneven distribution of green space, often favouring more affluent areas, making equitable access to growing space a major issue, especially in urban centres and for low-income or racially segregated communities (Berte & Panagopoulos, 2014; Buijs et al., 2016; Chang & Morel, 2018; Crowe et al., 2016; Dixon & Richards, 2016; Dobson et al., 2020a; Draus et al., 2019; Faivre et al., 2017; Mabon & Shih, 2018; McPhearson et al., 2014; Monaco et al., 2017; Olsson et al., 2016; Panagopoulos et al., 2018; Scott et al., 2016; Speak et al., 2015). In addition, the success of UA projects is often dependent on networking, social work, and business skills in addition to horticultural knowledge (Baibarac & Petrescu, 2017; Chang & Morel, 2018; Olsson et al., 2016). As well as growing space, relevant skills and access to financial and material resources is also distributed unequally, and even where support systems exist many people may be isolated from these geographically or due to socio-economic factors (Dixon & Richards, 2016; Edwards et al., 2011; Mabon & Shih, 2018; Olsson, 2018; Olsson et al., 2016). For example, the low-income and the elderly may have limited access or ability to use digital tools that could facilitate knowledge and resource sharing (Crowe et al., 2016), which will be crucial for realizing the potential of urban horticulture (Edmondson et al., 2020b).

Another crucial factor that can limit the positive impacts of UA is unequal financial and physical access to urban-grown food (Dixon & Richards, 2016; Jagt et al., 2017). Many areas lack walkability to urban farms and alternative food shops, and, for various reasons, local produce tends to have higher prices than that grown on larger, commercial farms. As a result, purchasing locally grown fruit and vegetables has become mostly widespread among people in higher-income groups, and producers in lower-income neighbourhoods often struggle to sell their produce, which may force them to raise prices, intensifying issues of unequal access to local food (Chang & Morel, 2018; James & Friel, 2015).

3.3.5. Safety

In some areas, urban soils and groundwater can contain high levels of heavy metals and other toxic chemicals due to industrial activities, current and past emission from vehicles or the use of amendment soil delivered from contaminated sites. This is coupled with a lack of detailed legislation regarding the safety of urban-grown food in some countries (and even where strict controls exist, domestic practices are not regulated), which has given rise to concerns over the health effects of consuming potentially contaminated produce (Dezio & Marino, 2018; Entwistle et al., 2019; Panagopoulos et al., 2018; Sanyé-Mengual et al., 2018; Schlecht & Säumel, 2015; Voskamp & Van de Ven, 2015). Air pollution near main roads and in urban centres has also been suggested as a potential health risk to people gardening in these areas (Panagopoulos et al., 2018).

Another possible issue is related to potentially inappropriate domestic agrochemical use. It has been argued that, as a result of reduced ecological understanding or in an attempt to enhance yields, some urban growers might use excessive amounts of fertilizers or pesticides, which could cause harm to the environment or introduce agricultural pollutants into the city's water and food supplies—although, due to the lack of monitoring of such residues in waterways or produce, the reality of these concerns is largely unknown (Chang & Morel, 2018; Kosanović & Fikfak, 2016; Plant et al., 2012).

3.4. Underlying factors

While there are a variety of potential issues that can limit the success of UA, there seem to be some common themes underlying them. These will be discussed in turn here.

3.4.1. Public support

In modern societies, there is often a cultural bias towards manicured landscapes, which people might associate with safety and higher quality of life and, thus, may prefer over green areas with a less tidy appearance, like many UA sites (Beatley & Newman, 2017; Draus et al., 2019; Panagopoulos et al., 2018). Urban food gardens might even be seen as a sign of poverty or under-development by some, who might not want to see these near their home or workplace (Colding & Barthel, 2013). Part of the reason for this could be what has been described as an "environmental generational amnesia", meaning that many people today fail to reconnect with and understand their dependency on natural ecosystems (Colding & Barthel, 2013), and as a result may have little interest in and underestimate the benefits that spending time in nature and growing their own food can offer. In addition, research suggests that the concept of urban agriculture—especially its more urban-specific forms, like aqua- and hydroponics—may be little known and understood among the public, and certain practices, such as highly engineered cultivation methods or animal farming, may have low acceptance (Sanyé-Mengual et al., 2018).

Single-family residential gardens take up a significant proportion of open space in many cities and, thus, hold great potential for increasing UA area (Ferreira et al., 2013; Haase et al., 2014; Kosanović & Fikfak, 2016; Privitera et al., 2018; Scott et al., 2016). However, this will require public willingness. A key issue can be that even if they are generally supportive of UA, due to busy schedules characteristic of modern lifestyles, higher levels of engagement may be outside the comfort zone of most people (Beatley & Newman, 2017; Collier et al., 2013). The importance of this factor is shown in the huge increase in interest in ‘grow- your -own’ in many countries during the lockdowns that followed the outbreak of the Covid-19 pandemic (for example, evidenced by rises in waiting lists for allotment plots in the UK (Royal Horticultural Society, 2020; Wicked Leeks, 2020)), when many people suddenly had more free time. Voluntary contributions to community gardens also tend to be limited and unreliable, and few people are likely to be willing to help with product distribution or provide financial support for projects (Sanyé-Mengual et al., 2018). The lack of long-term security of growing space, fees for garden use, difficult access to sites, including perceived access (e.g. allotment sites are often fenced off from non-members), and potentially insecure environments (e.g. risk of vandalism or presence of homeless “tramps” near sites) can also discourage people from getting involved in some forms of UA, while insecure funding for projects can make those who want to make a living from horticulture reluctant to start (Chang & Morel, 2018; Colding & Barthel, 2013; Hara et al., 2018; Jagt et al., 2017; Panagopoulos et al., 2018; Speak et al., 2015). Finally, conflicts amongst users of communal sites—especially if there is high cultural diversity in the group—have also been suggested as a potential issue limiting participation (Jagt et al., 2017; McMillen et al., 2016).

Another important social factor affecting the success of UA is the amount of demand for fresh local produce, which might be limited. Food shopping and consumption patterns in most parts of the developed world have become supermarketised, and many people may not give a high priority to sustainability in their product choices, or have a limited understanding of what constitutes a healthy diet (Dixon & Richards, 2016; James & Friel, 2015; Olsson et al., 2016; Sanyé-Mengual et al., 2018). In addition, reduced choice, difficult access, an absence of an enabling culinary culture, concerns over the safety of consuming urban-grown food, and beliefs that local produce—especially if organic—is always expensive can also make people reluctant to buy such products (Dixon & Richards, 2016; Sanyé-Mengual et al., 2015).

3.4.2. Institutional support

Another key factor that can limit the success of UA is the amount of support for it from authorities (Clinton et al., 2018; Jagt et al., 2017; Plant et al., 2012). Despite increasing recognition of its benefits and potential importance on various levels of governance (Milan Urban Food Policy Pact, 2018; Morgan, 2015), the fact that food production is rarely considered as an urban issue, and as a result UA tends to receive little attention in local council legislation and city planning, is frequently mentioned in the literature (Colding & Barthel, 2013; Coppo et al., 2017; Frantzeskaki & Tilie, 2014; Hara et al., 2018; James & Friel, 2015; McPhearson et al., 2014; Monaco et al., 2017; Olsson et al., 2016; Plant et al., 2012; Sanyé-Mengual et al., 2018; Scott et al., 2016). It has been argued that current and potential growing spaces in municipal ownership are often maintained as reserves for urban development, while zoning regulations put constraints on expanding UA area (Frantzeskaki & Tilie, 2014; Panagopoulos et al., 2018; Plant et al., 2012). Many peri-urban farms might be threatened by urbanisation, and liberalised legislation can sometimes allow anyone to purchase agricultural land and pursue activities other than farming, which poses a further threat to how scarce fertile land is used (Beatley & Newman, 2017; Frantzeskaki & Tilie, 2014; Hara et al., 2018; Olsson et al., 2016). Regulations related to producing food in urban areas are also sometimes absent, and in some cases a system of "organised irresponsibility" may be observed around complex issues like pesticide pollution, with multiple relevant agencies all assuming it to be another's responsibility (Kosanović & Fikfak, 2016; Panagopoulos et al., 2018; Plant et al., 2012; Sanyé-Mengual et al., 2018). Furthermore, it has been argued that governments might tend to subsidise export-oriented food production in order to promote broader national development, a strategy that is in contrast with building resilience through increasing local self-sufficiency (Dixon & Richards, 2016; Plant et al., 2012). Some international policies, such as the EU's Common Agriculture Policy (CAP), also promote the globalisation of markets and favour larger rural producers (Olsson et al., 2016). Although strategic declarations about creating more resilient urban food systems, acknowledging the role of UA in it, have now been made by many cities (C40, 2020; Milan Urban Food Policy Pact, 2018), specific targets and action plans are still relatively rare (Coppo et al., 2017)—although not absent (see e.g. (Sonnino, 2016)).

As a result of a lack of effective measures to facilitate their access to resources, smaller UA businesses may often struggle to compete with larger producers (Clinton et al., 2018; Dixon & Richards, 2016; Draus et al., 2019; Monaco et al., 2017; Olsson et al., 2016; Plant et al., 2012). While the development of multifunctional UA projects could provide additional income streams (e.g. through tourism or education), it requires additional investment and can still be complicated by banks' reluctance to fund "risky" urban horticulture projects (Chang & Morel, 2018) or contradictions in legislation relating to different activities involved (Olsson et al., 2016; Plant et al., 2012). City agencies have also been argued to take only a small part in efforts to ensure equitable access to healthy food for more disadvantaged communities—mostly leaving this task to community groups and NGOs—limiting some of the potential benefits of UA (McPhearson et al., 2014).

Lastly, limited governmental budgets and plans for green space development (for example, in 2016 only 1% of brownfields in England were proposed to be reused as green space (Scott et al., 2016)), and the fact that it usually focuses on parks, playgrounds, or urban forests, can also present a problem for UA, which tends to be given lower priority (Frantzeskaki & Tilie, 2014; Jagt et al., 2017; Mabon & Shih, 2018; Olsson et al., 2016). In addition, in larger-scale municipal-led greening initiatives sometimes the most disadvantaged areas get the least attention, and measures might overlook or even reinforce existing issues of spatial and social inequality (Buijs et al., 2016; Dixon & Richards, 2016; Draus et al., 2019; Faivre et al., 2017; Mabon & Shih, 2018; McPhearson et al., 2014; Panagopoulos et al., 2018; Scott et al., 2016). Moreover, the ways in which green spaces are increasingly incorporated into private development schemes can lead to "green stealth", a process of spatial exclusion through privatisation of these areas (Scott et al., 2016). Finally, while the concept of promoting resilience through ecosystem services and nature-based solutions (including UA) are increasingly well-known, the actual incorporation of these approaches into urban policy and planning is still weak in most parts of the Global North (Berte & Panagopoulos, 2014; Buijs et al., 2016; De la Sota et al., 2019; Draus et al., 2019; Ferreira et al., 2013; Panagopoulos et al., 2018), and may be sidelined in favour of hard engineering solutions that might provide more immediate results or direct economic returns (Baibarac & Petrescu, 2017; Beatley & Newman, 2017; Berte & Panagopoulos, 2014; Clinton et al., 2018; Mabon & Shih, 2018; McMillen et al., 2016; Scott et al., 2016).

3.4.3. Knowledge base

A likely reason behind sometimes limited municipal attention and policy support for UA is that, until recently, the quantitative evidence base for its various benefits, including its current and potential contribution to city resilience, was lacking (Berte & Panagopoulos, 2014; Clinton et al., 2018; Frantzeskaki & Tilie, 2014). One issue is that land cover and use characterisation at high resolution can be difficult and very time consuming, and as a result, such information is often sparse or lacking in sufficient level of detail (Clinton et al., 2018; Collier et al., 2013; Privitera et al., 2018). Estimating the area of rooftops and building façades suitable for alternative production methods is also problematic because many factors need to be taken into consideration (e.g. load-bearing, accessibility, availability of light) (Clinton et al., 2018; Voskamp & Van de Ven, 2015). In addition, data from different sources is sometimes inconsistent or difficult to integrate, not to mention that some essential information might be proprietary (Clinton et al., 2018; Hara et al., 2018). As a result of these factors, data on how much land is, or could be, used for food production in urban areas is often unknown—although recent research suggests considerable potential (Edmondson et al., 2020a; Edmondson et al., 2020b).

Another challenge is that a large proportion of food production in cities takes place on private gardens, allotments, and small farms where yields do not normally get recorded (Hara et al., 2018; Olsson et al., 2016). Although estimates could be made based on conventional agriculture or mathematical models, these may not reflect ground level realities (Collier et al., 2013). In the UK, the actual productivity of allotments and gardens has recently been estimated (Edmondson et al., 2019; Edmondson et al., 2020a; Edmondson et al., 2020b), but in other countries own-grown crop yields are yet to be quantified adequately to support arguments about possible levels of local self-sufficiency, and the role of different forms of UA in providing food security still requires further research (James & Friel, 2015; McGrail et al., 2015; Monaco et al., 2017). The economic characterisation of urban-grown food can also be difficult, as its value is affected by quality, production methods, and supply–demand conditions (Monaco et al., 2017). In addition, the safety of consuming urban produce is often uncertain as the presence of toxic residues in private growing spaces is seldom monitored. Similarly, the potential risk of agrochemical pollution in cities is largely unknown, with insufficient toxicity data, debated historical accounts, and mathematical ecosystem models, and a lack of consensus on what tests and thresholds should be used complicating its regulation (Clinton et al., 2018; Plant et al., 2012).

Another potential issue is that cultural services provided by UA are subjective and difficult—and arguably senseless—to translate into quantitative metrics, making it hard to provide evidence for these benefits (Haase et al., 2014; Mabon, 2019). Moreover, ecosystem service provision by urban food gardens is generally evaluated from the perspective of practitioners only. Very few studies so far have addressed public perceptions on UA, therefore, the extent to which an increase in its scale and its different forms would be supported by global society is not yet clear (Sanyé-Mengual et al., 2018). In addition, participatory research essential for studying social factors is time-consuming, and effective study designs can be difficult to create. As a result, participatory data sources are relatively rare and seldom have inter-annual continuity (Hara et al., 2018).

Finally, a fundamental problem is that, despite the growing popularity of the concept, it is still somewhat unclear what resilience actually means for urban planning and policy, let alone UA's role in it (Crowe et al., 2016; Mabon & Shih, 2018; Sharifi & Yamagata, 2014). These uncertainties, combined with the fact that UA sites do not usually provide direct economic benefits to local authorities, can make them reluctant to increase the provision of growing space, and can limit the effectiveness of measures intended to promote UA practice (Clinton et al., 2018; Haase et al., 2014).

3.4.4. Communication and collaboration

Another key factor that can limit the success of UA is a lack of communication and collaboration among researchers, policy-makers, and communities. Multiple authors argue that weakened social bonds and a decreased sense of participation, characteristic of modern urbanised societies, have resulted in decreased informal learning and exchange of knowledge among individuals and groups—importantly between generations—making the social memory of UA vulnerable (Buijs et al., 2016; Chang & Morel, 2018; Crowe et al., 2016; McGrail et al., 2015; Olsson et al., 2016). In addition, limited connection and collaboration between individual initiatives and agents working across larger scales can present a barrier to knowledge and resource sharing, and to building a critical mass on debate (Olsson et al., 2016). The potential reluctance of smaller UA initiatives to work with larger companies or institutions, or accept advice from external experts, can be a problem because a lack of support from stakeholders with better access to information and resources (for example, councils could act as "anchor institutions" to provide security for community-based urban horticulture businesses (Edmondson et al., 2020b)) can limit the success of projects (Draus et al., 2019; Frantzeskaki & Tilie, 2014; Hara et al., 2018; Mabon & Shih, 2018; Molnar et al., 2010; Olsson et al., 2016; Panagopoulos et al., 2018). In particular, the spread of alternative UA practices can be hindered by a lack of willingness to collaborate, as well as by proprietary control of knowledge and tools for innovation (Baibarac & Petrescu, 2017; Crowe et al., 2016). For instance, most rooftop greenhouse projects currently operate in isolation, which likely limits their success and technological development (Sanyé-Mengual et al., 2015).

A lack of communication between municipalities and communities, and views that scientific knowledge is superior to non-scientific, local knowledge can also mean that the latter is overlooked in making plans and policies related to UA practice and the provision of growing space. Although it could be argued that a synergistic interaction between governments and citizens is sometimes over-idealised (Collier et al., 2013), the issues of local practitioner groups often cannot be addressed through traditional institutional regulatory instruments (Dezio & Marino, 2018) and measures devised without a sufficient understanding of the local context might not be well-received by the public, or even have unintended negative consequences, like increasing social or spatial inequalities (Baibarac & Petrescu, 2017; Buijs et al., 2016; Jagt et al., 2017; Molnar et al., 2010). For example, top-down approaches to mobilizing citizens can lead to the exclusion of less vocal communities (Buijs et al., 2016; Jagt et al., 2017), and there is evidence that government attempts to make people cultivate abandoned areas may not be effective if these people do not feel attachment to the gardens allocated to them (Calvet-Mir & March, 2019; McMillen et al., 2016).

Another issue is that the science and policy of climate change adaptation, environmental protection, agriculture, food systems, and public health tend to be disconnected across a range of institutions and government departments (Edwards et al., 2011; Scott et al., 2016). This puts UA in a difficult position, since, due to its multifunctional nature, it is not fully in the domain of any particular agency. Instead, its different aspects concern a number of sectors, in all of which it may be given relatively little attention. Complex issues like city resilience and urban agriculture's role in it can also have different understandings, which, combined with limited information sharing and coordination among different government departments, can result in contradicting policies. Current resilience plans often have multiple contrasting goals, overarching city-wide strategies are rare, and possible synergies between different plans (such as opportunities to link green space development with improving urban health and living conditions) are seldom exploited (Crowe et al., 2016; Edwards et al., 2011; Frantzeskaki & Tilie, 2014; James & Friel, 2015; Mabon & Shih, 2018; Plant et al., 2012; Scott et al., 2016). In addition, possible opposition grounded in political differences can make it more difficult to reach a consensus between parties and mean that legislation generally emerges slowly (Collier et al., 2013; Mabon & Shih, 2018; McGrail et al., 2015; Panagopoulos et al., 2018), whilst dominant policy discourses and entrenched urban planning practices can be inhospitable for new frameworks (Frantzeskaki & Tilie, 2014).

Finally, limited knowledge exchange can also be observed within research. For instance, while multi- and interdisciplinary approaches to evaluating ecosystem services are becoming increasingly popular, there is still a shortage of such projects. Multifunctionality is often poorly covered in assessments of urban green spaces (for example, combining green space mapping with related health and wellbeing data), with most studies dealing with only one service from the perspective of one type of stakeholder (Clinton et al., 2018; Collier et al., 2013; Haase et al., 2014). In addition, urban resilience and ecosystem service research rarely involves stakeholders (Hara et al., 2018), and might not focus on the most deprived areas where increased provision of green space, including UA sites, is most needed (Frantzeskaki & Tilie, 2014). Another important problem is that, in many cases, research findings are not communicated sufficiently to relevant planners, policy-makers, and practitioners, or are not directly transferable to real life settings (Ferreira et al., 2013). City resilience and ecosystem service frameworks might also lack specific guidelines or fail to take existing administrative and governance structures as a starting point, which can make them difficult to operationalise (Frantzeskaki & Tilie, 2014).

3.4.5. Contextual diversity

The last underlying challenge identified is the fact that there can be considerable differences between, and even within, cities in key factors affecting urban agriculture and the types of resilience benefits it can provide (Collier et al., 2013). These include geographic constraints on food production (e.g. climate, soil, and groundwater properties) (Monaco et al., 2017; Voskamp & Van de Ven, 2015), landscape features and land cover characteristics (e.g. amount of brown or green vs. grey area, urban built form) (Voskamp & Van de Ven, 2015), land ownership (Monaco et al., 2017; Voskamp & Van de Ven, 2015), costs of key items (e.g. labour, land rent, materials) (Clinton et al., 2018), pressures on land use (Monaco et al., 2017), institutional designs and policies (e.g. tax treatments, subsidies, regulations) (Clinton et al., 2018), cultural factors that affect practice, public perceptions of different forms of UA, and demand for urban produce (Buijs et al., 2016; Calvet-Mir & March, 2019; Faivre et al., 2017; Hara et al., 2018; Kosanović & Fikfak, 2016; Speak et al., 2015). Such wide contextual diversity can limit the transferability of research and policy approaches between different scales and locations, and makes it difficult to find solutions for promoting UA that are appropriate across space (Molnar et al., 2010; Olsson et al., 2016). It also means that the cost and effort of implementing certain measures will likely vary between locations. In addition, the development of locally suitable actions may be hindered by the fact that municipal plans need to conform to larger regional, national, and international policies (Collier et al., 2013).

3.5. Pathways to promoting UA

Based on the reviewed literature, it is proposed that the overall success of UA in increasing city resilience depends on the amount of institutional and public support for it, the presence of a sufficient knowledge base to guide policy and practice, communication and collaboration among different actors, and resourcefulness in finding locally appropriate solutions and alternative ways to use space and other resources efficiently. Figure 5 shows a conceptual diagram illustrating how these factors could promote key aspects of UA through a number of direct and indirect mechanisms.

Figure 5. Pathways to promoting urban agriculture (UA) for increased city resilience: five key aspects of successful UA (top of figure), factors that determine UA's success in increasing city resilience (objects below), and main mechanisms through which these can contribute to different aspects of UA (arrows; all represent promoting effects).

People's ability and motivation to engage in UA and related activities is a crucial factor determining its success. In fact, since a significant portion of space in cities is owned or managed by private individuals and local user groups (Haase et al., 2014), it could be argued that the scale and impact of urban agriculture is ultimately a function of the level of participation from citizens. Nonetheless, the public's contribution is limited without the support of local governments, which have a crucial role in creating enabling policy frameworks and facilitating access to land, funding, and information. It should be noted that there is a bidirectional relationship between public and institutional support for UA. On the one hand, high public demand for growing space and locally grown food can trigger increased attention and support from governments in the form of different policies and urban development plans, which can promote the integration, inclusiveness, and safety of UA. On the other, awareness raising, community engagement, and provision of growing space can increase public interest and participation in UA-related activities, which in turn can increase the scale of the practice. To facilitate such a synergistic relationship, it is important that effective communication takes place between communities and local governments.

Through generating an evidence base to underlie the amount of both institutional and public support and the effectiveness of policy and practical measures, research plays a fundamental role in determining the success of UA, potentially having downstream positive effects on all of its five key aspects. In order to have a real impact, as well as the creation of knowledge, its communication to government administrators, practitioners, and the general public is also crucial. Researchers have a responsibility in increasing key actors' awareness of issues around urban agriculture and resilience, the importance of actions being taken, and how they can contribute. Thus, outreach, education, and good research–policy dialogue are essential. Last but not least, resourcefulness is important for finding effective and locally appropriate solutions, the success of which is greatly dependent on knowledge exchange and collaboration among practitioners and between researchers and communities (Colding & Barthel, 2013; Crowe et al., 2016; Lee & Lee, 2016). Finally, there is a positive feedback relationship between the scale of UA and the amount of knowledge potentially available on it, completing a virtuous cycle of research, science communication, and collaborative action.

4. Discussion

The importance of increasing the resilience of our cities has become clearer than ever after the recent global Covid-19 outbreak. Achieving greater resilience is a complex challenge and, while related research and policy often focus on engineering solutions (Baibarac & Petrescu, 2017; McMillen et al., 2016; Scott et al., 2016), it is arguably as much a social issue as it is a technological one. Despite growing evidence for its various benefits, urban agriculture's contribution to city resilience is a fairly new concept in academia, and our understanding of its role and potential is still limited. At the intersection of multiple dynamic urban systems, UA faces a number of socio-economic, environmental, and technical issues. Thus, increasing its success requires the support of a range of actors (including governments, nongovernmental organisations, researchers, industry, and the general public), as well as holistic, interdisciplinary, and inter-institutional approaches combining knowledge and insights from different areas (Beatley & Newman, 2017; Collier et al., 2013; Crowe et al., 2016; Draus et al., 2019;

Faivre et al., 2017; Lee & Lee, 2016; McMillen et al., 2016; Olsson et al., 2016; Scott et al., 2016; Voskamp & Van de Ven, 2015).

4.1. Directions for policy and practice

In complex urban systems, planners and policy makers have to address a wide range of issues and prioritise different goals (Crowe et al., 2016; De la Sota et al., 2019; Dezio & Marino, 2018; Draus et al., 2019; Edwards et al., 2011; Faivre et al., 2017; Frantzeskaki & Tilie, 2014; McPhearson et al., 2014; Monaco et al., 2017; Panagopoulos et al., 2018; Schuetze et al., 2016; Scott et al., 2016; Voskamp & Van de Ven, 2015). In order to be able to compete for cities' limited resources, UA must receive enough attention and support from governments. City authorities need to recognise agriculture as an important urban land use, devise appropriate policy frameworks, and incorporate UA into their different agendas (such as green space planning, food, wellbeing, and education), paying particular attention to spatial and socio-economic equality (Beatley & Newman, 2017; Collier et al., 2013; Draus et al., 2019; Faivre et al., 2017; Olsson et al., 2016; Schuetze et al., 2016). There is also a need for better integration among sectors and initiatives and more clarity around the responsibilities of different actors (Faivre et al., 2017; James & Friel, 2015; Molnar et al., 2010; Olsson, 2018; Plant et al., 2012; Schuetze et al., 2016; Scott et al., 2016), and for strategic declarations to be complemented with action plans that include specific, measurable objectives (Coppo et al., 2017; Faivre et al., 2017; Jagt et al., 2017).

Local governments should improve access to growing space, information, and funding for UA-related projects (Jagt et al., 2017; James & Friel, 2015; Olsson et al., 2016; Scott et al., 2016), as well as to local produce (e.g. through promotion of farmers' markets (Dezio & Marino, 2018)). Since much potential growing space in urban areas is in the private domain, it is also vital that UA be promoted as a business, social enterprise, or recreational activity among various groups and individuals. Therefore, increased support for local stakeholder-led innovation (Dennis et al., 2016), active citizenship and self-organisation (Baibarac & Petrescu, 2017; Buijs et al., 2016; Colding & Barthel, 2013; Dennis et al., 2016; Jagt et al., 2017; Mabon, 2019), promotion of domestic food production and community farming (Colding & Barthel, 2013), awareness raising and educational programmes (e.g. on healthy and sustainable diets, horticulture, and the environment) (Dennis et al., 2016; Dezio & Marino, 2018; James & Friel, 2015; Lee & Lee, 2016; Sanyé-Mengual et al., 2018; Scott et al., 2016), public engagement (e.g. through hiring "community organisers") (Crowe et al., 2016; Jagt et al., 2017; McMillen et al., 2016; Scott et al., 2016), and development of multi-stakeholder communication and collaboration platforms (Collier et al., 2013; Faivre et al., 2017; Jagt et al., 2017) will be important.

Finally, since the wide contextual diversity that exists between locations may preclude one-size-fits-all solutions, it is important that locally appropriate measures are designed based on a holistic consideration of the environmental, economic, and social setting (Collier et al., 2013; Coppo et al., 2017; Dezio & Marino, 2018; Mabon & Shih, 2018; Monaco et al., 2017). Green Infrastructures and Nature-based Solutions could be appropriate tools to support integrated planning of urban green space (De la Sota et al., 2019; Draus et al., 2019; Faivre et al., 2017; Ferreira et al., 2013; Mabon, 2019; McPhearson et al., 2014; Scott et al., 2016), while Strengths, Weaknesses, Opportunities, and Threats (SWOT)-type assessment frameworks (Berte & Panagopoulos, 2014; Sieber & Pons, 2015) supported by participatory approaches to planning and management (Alvarez et al., 2017; Collier et al., 2013; Crowe et al., 2016; Ferreira et al., 2013; Jagt et al., 2017; Lee & Lee, 2016; Mabon, 2019; McGrail et al., 2015; McMillen et al., 2016; McPhearson et al., 2014; Olsson, 2018; Sanyé-Mengual et al., 2018; Scott et al., 2016) and geospatial information and communication technologies (Collier et al., 2013; Voskamp & Van de Ven, 2015) could be useful in identifying the specific challenges and opportunities that exist in each city and points where interventions might be the most effective.

4.2. Directions for research

Greater institutional support for UA and effective enhancement of its resilience benefits require a better understanding of and larger evidence base for its contribution. More research is needed on the current and potential area of UA in different cities, its ecosystem service provision capacity (including food, climate change mitigation and various social benefits) and how this varies with type of practice (e.g. traditional soil-based vs. technological cultivation methods), and environmental and socio-cultural factors (e.g. acceptance of different forms of UA, motivations to participate in UA-related activities, demand for urban-grown produce). In particular, research taking a whole-system perspective and innovative multidisciplinary approaches will be essential (Collier et al., 2013; Coppo et al., 2017; Scott et al., 2016). Examples of research methods suggested in the reviewed literature include GIS-based models (e.g. for land cover, use, ownership, and ecosystem service provision) (Collier et al., 2013; Haase et al., 2014; Scott et al., 2016; Sieber & Pons, 2015); life cycle analysis (e.g. of alternative food supply chains) (James & Friel, 2015); field surveys (e.g. of soil quality, current cultivated areas, and crop types) (Clinton et al., 2018; Schlecht & Säumel, 2015); computational modelling of different scenarios (Chang & Morel, 2018; Collier et al., 2013); synthesis of interdisciplinary information (Clinton et al., 2018; Schlecht & Säumel, 2015); place-based research (Molnar et al., 2010); surveys and interviews (with both practitioners and the general public) (Clinton et al., 2018; Faivre et al., 2017; Haase et al., 2014; Hara et al., 2018); participatory research (including higher education–community partnerships, bottom-up data collection, and online crowd-sourcing, e.g. for mapping unused spaces in urban areas) (Chang & Morel, 2018; Collier et al., 2013; Hara et al., 2018; McMillen et al., 2016; Molnar et al., 2010); and development of better indicators and tools for measuring both quantitative and qualitative aspects of resilience (Coppo et al., 2017; Haase et al., 2014; McMillen et al., 2016).

As well as filling knowledge gaps, it is equally important to create real-world solutions that can help increase the success of urban agriculture. Therefore, research should also focus on developing communication channels (e.g. digital platforms) and affordable and user-friendly tools to facilitate knowledge- and resource-sharing and different practical aspects of UA projects (Baibarac & Petrescu, 2017), designing alternative solutions for dealing with space and resource constraints (e.g. ponics technologies, green walls and roofs) (Clinton et al., 2018; Molnar et al., 2010), and understanding how institutional actors can best support various initiatives and engage people from different backgrounds in UA-related activities (Crowe et al., 2016; McMillen et al., 2016; Scott et al., 2016). Finally, there needs to be a greater emphasis on effective science–policy dialogue and communicating research findings to different audiences (Faivre et al., 2017; Haase et al., 2014; Mabon & Shih, 2018; McMillen et al., 2016; Molnar et al., 2010; Scott et al., 2016; Sharifi & Yamagata, 2014; Voskamp & Van de Ven, 2015).

4.3. Relevance and limitations of the study

The potential role of UA in increasing city resilience in the developing world has been reviewed by de Zeeuw *et al.* (2011). This study adds to existing knowledge by identifying the factors that determine UA's successful contribution to city resilience in the Global North, using a systematic approach. Furthermore, the conceptual model we present highlights some key pathways to enhancing the resilience benefits of UA, and could serve as a basis for the development of (e.g. SWOT-type) assessment frameworks to assist policy-makers and urban planners in devising locally appropriate and effective strategies. The research and policy directions we identified could further contribute to the success of these efforts.

Nonetheless, some limitations of the study are recognised. First, a single literature database was used to identify relevant publications in English, which means that some potentially important work that was only available elsewhere, in other languages, or which did not include the search terms used here may not have been considered. Second, due to the qualitative nature of the study, some degree of subjectivity might be inevitably present in the interpretation and synthesis of findings.

5. Conclusions

Urban agriculture (UA) could increase city resilience in the Global North against various environmental and socio-economic disturbances, which are expected to increase in frequency and severity in the near future. However, its current and potential contribution to this has been little understood. The aim of this study was to conceptualise the success of UA and identify the pathways through which its resilience benefits can be enhanced. It is proposed that the success of UA in increasing city resilience is determined by five factors: its scale, the extent to which it is integrated into the urban fabric, its inclusiveness, the efficiency of food production, and human and environmental safety of practices. These factors in turn depend on the amount of institutional and public support for UA, the presence of a sufficient knowledge base to guide policy and practice, communication and collaboration among different actors, and resourcefulness in finding alternative ways to use space and other resources efficiently. Increasing its contribution to city resilience requires more research on the current and potential area, ecosystem provision capacity and social factors affecting UA, joined-up thinking and collaboration among governments, researchers and communities, and creative, context-specific solutions based on a comprehensive assessment of local conditions. Despite a number of challenges, through innovative solutions, flexible and integrated approaches to urban planning, and taking collective and local ownership of issues, most apparent space and resource constraints could be overcome, and urban agriculture could form an integral part of the resilient cities of our future. By conceptualising this rather complex topic, identifying some key issues that exist, and providing directions for research, policy, and practical courses of action, it is hoped that this study will contribute to these efforts.

Chapter 3

Measure Your Harvest: insights from a long-term study on the contribution of own-growing to food security in the UK

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Abstract

Urban horticulture is increasingly recognised for its ability to promote food system resilience and the nutritional security of urban populations, however, research quantifying its potential has been limited. Here, we use five years' national scale data from the MYHarvest citizen science project, collecting own crop yields in the UK in combination with regional soil and climate data to determine what factors drive yields of different own-grown crops, estimate yields, and assess national allotment production potential. Average own-grown yield across 39 common crop types was 1.93 kg m^{-2} yr^{-1} ±0.06 (S.E.). Own-grown yields were generally unaffected by growing space type and whether crops were grown organically. Soil type, growing season temperature and growing in protected areas had an effect on some (e.g. broad beans, broccoli, potatoes), but not all, crop types. Yields of several own-grown crops (e.g. cauliflower, courgette, peas, runner beans) were higher than commercial horticultural yields when field-grown, but the majority of crop yields were higher in commercial production, especially when grown under protection. We estimate national allotment food production to be 120.3 thousand tonnes per year ±2.7 (S.E.), which is equivalent to 3.9% of domestic fruit and vegetable (F&V) supply (including potatoes), and could meet the annual '5-a-day' F&V needs of 614 thousand people, and typical potato demand of 874 thousand people. Reconverting suitable former allotment land (approx. 96.8 km^2) could provide another 86.3 thousand tonnes ±1.9 (S.E.) of produce annually, increasing the current level of production by 72%. Small-scale food production by own-growers could play a modest,

but important, role in increasing national self-sufficiency in fresh produce and food system resilience and promote F&V consumption in areas where access to nutritious food is limited, with benefit to urban sustainability, public health and wellbeing.

1. Introduction

Tackling rapid urbanisation, population growth, food insecurity and increasing rates of various forms of malnutrition and related non-communicable diseases are among the greatest challenges we are facing globally (FAO et al., 2020; Loopstra et al., 2015; World Bank, 2022). In addition, our food systems are unsustainable (Dudley & Alexander, 2017; Vermeulen et al., 2012; Yang et al., 2003) and lack resilience against global shocks. For example, the Covid-19 pandemic and war in Ukraine disrupted food supplies, resulting in empty shelves and increased prices (FAO et al., 2022; WFP, 2022), and other food shocks, including ones resulting from climate change, are likely to increase over the coming decades (Béné, 2020; Wheeler & von Braun, 2013). Access to perishable foods like fresh fruits and vegetables (F&V), which are essential components of a healthy diet, is especially vulnerable to such supply disruptions.

Urban horticulture, the practice of growing fruits and vegetables in cities and towns, is increasingly recognised by policy-makers as a mechanism to improve the sustainability and resilience of food systems and improve nutritional security of urban populations (APA, 2019; Milan Urban Food Policy Pact, 2018; Morgan, 2015; Pulighe & Lupia, 2020). Coupled to this, urban horticulture is growing in popularity, particularly in the Global North where the practice had decreased during the 20th century (Dobson et al., 2020a). For example, in the UK public interest in own-growing of F&V on allotments and in domestic gardens has been growing since the turn of the 21st century and rose sharply after the outbreak of the Covid-19 pandemic (Evans & Davies, 2020; Royal Horticultural Society, 2020; Sustain, 2020). There is historical evidence that this practice played an important role in increasing national food security during World War II when food gardening was promoted both in the UK and the USA to aid the war effort (Defra, 2017; Ginn, 2012). Despite this, realistic estimates of current levels of production, based on an understanding of yields achieved by own-growers and their crop preferences, and the potential to expand urban horticulture are unexplored at a national scale (Edmondson et al., 2019).

Understanding current levels of production and potential to expand is important because consuming plenty of F&V is an essential part of a healthy diet that helps prevent a range of non-communicable diseases (WHO, 2003), therefore having a stable supply of a variety of F&V, accessible to all, is a key component of food security. As the UK is heavily reliant on increasingly volatile foreign supplies for its F&V (Defra, 2018), and average F&V intake in the country is already below recommendations (NHS Digital, 2019a; PHE, 2019a), upscaling small-scale own F&V production in urban areas could help increase the resilience of food systems and improve diet-related public health.

Concurrent with the rise in interest in growing food amongst policy-makers and the public has been the growing body of research demonstrating the environmental and health and well-being benefits of urban horticulture. Urban horticultural sites have been found to be pollinator hotspots (Baldock et al., 2019), and support many key ecosystem services, including mitigation of the urban heat island effect (Lin et al., 2015), regulation of stormwater (Goldstein et al., 2016; Lin et al., 2015) and soil carbon storage (Dobson et al., 2021). In addition, the benefits from the physical activity involved in the management of land for urban horticulture are becoming increasingly well understood, providing improved physical and mental health and a sense of community (Andreatta, 2015; Dobson et al., 2021; Genter et al., 2015; Ilieva et al., 2022; Leake et al., 2009; Martin et al., 2016; Opitz et al., 2016; Speak et al., 2015; White & Bunn, 2017).

Despite this, the often-stated goal of expanding urban horticultural production is to increase food security, but the research underpinning this has been lacking in part due to the complexity of producing realistic estimates. Previous important research has estimated food production potential based on commercial horticultural yields (Grewal & Grewal, 2012; Walsh et al., 2022) which provided valuable insight into the potential food security benefits of urban horticulture, however, these yields are likely to vary significantly from urban horticultural yields (Edmondson et al., 2019). Recent city-scale research has started to provide evidence of production in cities based on an understanding of the crops grown by own-growers and the yields they achieve (Edmondson et al., 2020a; Edmondson et al., 2020b). Here, yield data from own-growers in combination with field mapping and geographic information systems (GIS) found that current allotment productivity in the city of Leicester, UK, provides over 3% of the city's population their daily F&V needs (based on a '5-a-day' diet (NHS, 2018a;

WHO, 2003)), while only using 1.5% of urban land (Edmondson et al., 2020a). Allotment production was similar in Sheffield, UK, but when the potential to expand horticultural production was explored it was demonstrated that there was enough land available to feed 122% of the city's population their five daily portions of F&V (Edmondson et al., 2020b). In a more realistic scenario, if just 10% of the additional suitable land in Sheffield was used for growing food, it could still feed 12% of the population (Edmondson et al., 2020b). The link between own-growing, household self-sufficiency and increased consumption of F&V has been further supported by a recent year-long study that found that UK own-grower households were on average 41% self-sufficient in fruits, vegetables, and potatoes, and had F&V intakes 70% higher than the national average (Gulyas & Edmondson, in review). But in order to better assess the significance of own-growing for national food security, we need to understand, at a national scale, how own crop yields are affected by management practices and local environmental conditions, for which it is essential that crop productivity in a wide range of locations and over a longer time period is studied.

The MYHarvest ('Measure Your Harvest') citizen science project, established in 2017, collected F&V yields achieved by own-growers across the UK (Edmondson et al., 2019; *MYHarvest*, 2017). The project has had several hundred participants from across the country submitting harvest data on 44 different types of crops grown on allotments, residential gardens or other spaces (e.g. community gardens), mostly in urban areas, and has resulted in the first comprehensive dataset on own-grown production in the UK. Here we analyse five years' harvest data, combined with previous research exploring the extent of current and former allotment land (Dobson et al., 2020a) and crop preferences (Edmondson et al., 2020a), to answering the following questions:

1) What are the typical yields of common own-grown crops in the UK and how are they affected by production practice and environmental variability?

2) How do urban horticultural F&V yields compare to UK commercial horticulture?

3) What is the total F&V productivity of allotments in the UK and how could potential production be increased?

2. Methods

2.1. Data collection

MYHarvest (Measure Your Harvest: myharvest.org.uk) is a citizen science project collecting F&V crop yield data from UK own-growers. Each participant signed up to the project provided background information about the location of their growing site, whether it was a garden, allotment or other site (e.g. community garden) and also whether they gardened organically. Once signed up, growers were able to submit yield data about one or more crops they were growing. There were 40 key crops the MYHarvest project was collecting data on (see Supplementary Table S1 for full crop list). Here, we use data on 39 crops, excluding loganberries, which had highly variable yields with relatively small sample sizes. Growers could also submit yield data for different crops using an 'other' category. For each crop, participants selected whether the crop was grown outside or inside in a glasshouse or polytunnel. Data collection started in the spring of 2017. The MYHarvest project was granted ethical approval by the Department of Animal and Plant Sciences of The University of Sheffield (project ref. 144905).

2.2. Data processing

Unique identifiers were assigned to each participant and growing site (i.e. a garden, allotment or other type of growing space; in some cases, multiple sites belonging to one participant) and data was anonymised prior to analysis. Location information was provided when participants signed up to the project. Postcode data were provided by garden growers (where possible), allotments and community gardens may not have postcodes and so participants provided the most accurate location data possible. For each site, a British National Grid coordinate was located in a manual search using Google Maps and www.streetmap.co.uk, and corresponding soil and climate data were obtained from www.landis.org.uk and the UK Met Office, respectively, using QGIS. Annual crop yields (kg m^{-2} yr^{-1}) were calculated as the sum of harvested weights of a particular crop type grown at a particular site by a participant over the course of a growing year (March to February) (referred to as 'one harvest') divided by the area in which the crop was planted. For our analyses, we only considered data from five full growing years, from March 2017 to February 2022. Data on failed harvests (i.e. total annual crop weight of zero) were excluded from yield estimations, as we cannot be certain whether all participants were submitting data on these, and due to limitations of sample size, these could have an undue impact on the results. Thus, our estimates of own-grown yields assume that crops did not fail.

2.3. Analysis

2.3.1. Predictors of crop yields

We used R version 4.0.3 (R Core Team, 2013) and lme4 (Bates et al., 2012) to perform a series of linear mixed effects analyses of the relationship between own-grown crop yield (kg m^{-2} yr^{-1}) and characteristics of growing space, management, and local environmental conditions. Twenty-five crops were modelled as they had sufficient sample size for this analysis (Supplementary Table S9). As fixed effects, we entered type of growing space (allotment, garden, or other), growing method (organic or non-organic, and for crops for which greenhouse growing was fairly common (i.e. reported in at least 10 cases), greenhouse or open-air), mean growing season temperature (°C, averaged over 1981-2010, where growing season is defined as April to October; data from the UK Met Office (Met Office, 2017)), and soil type at each site (derived from the 'Soilscapes' database available at www.landis.org.uk (National Soil Resources Institute, 2001)), reduced to six categories: loamy acidic, loamy high groundwater, loamy lime, peat, peaty acidic, and sandy acidic - see Supplementary Table S2) into models, without interaction terms. As random effects, we had intercepts for sites and growing years (i.e. March-February, starting in 2017). To meet the linearity assumption, we used log transformation on the outcome (i.e. crop yields). There was no evidence of multicollinearity between predictors (based on Generalised Variance Inflation Factors (GVIF), using a threshold of 3), and visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity. However, some evidence of non-normality and outliers were present. p-values reported for fixed effects were obtained by likelihood ratio tests (LRT) of the full model with the effect in question against the model without the effect in question. Results of LRTs were verified by cross-checking against F tests with adjusted degrees of freedom. Confidence intervals (95% CI) for model parameters (standard deviations for random effects, estimated effect sizes for fixed effects) were obtained with the 'profile' method. Results of LRTs, F tests and CIs were generally in agreement. To assess the potential influence of outliers, sensitivity analyses were performed by running all regressions on two alternative data sets: one including all non-zero harvest submissions, the other systematically excluding outliers (identified using the interquartile method as values above Q3 + 1.5 x IQR or below Q1 - 1.5 x IQR) in harvest weight and growing area, by crop type. In several cases, results of the two types of analyses were notably different. Therefore, because identified outliers were generally unrealistic values, we report results of analyses carried out on outlier-free data, which we believe to be a more accurate representation of reality (results of analyses using each data set can be found in the Supplementary Tables S10 to S34). To get an estimate of the magnitude of significant fixed effects on crop yields on a linear scale (i.e. difference in mean yield in kg m^{-2} yr^{-1} associated with unit change in the predictor), we used parametric bootstrapping to generate predicted values for each level of the predictor in question between which the significant effect was observed according to mixed models, with all other fixed effects set to a baseline, using 1000 simulations per crop type. As our baseline, we used allotment space type, organic growing method, loamy acidic soil type and 13.3°C mean growing season temperature. Standard errors around mean differences in yield were also obtained from bootstrapped data.

2.3.2. Own-grown crop yields

Adjusted means of own-grown crop yields and uncertainty around these (i.e. standard errors and 95% confidence intervals) were estimated using parametric bootstrapping according to our mixed models, without the random effect of growing year to predict yields in an average year. We used 1000 simulations for each crop type. Our estimates assume that our national scale data on own-grown crop harvests and corresponding information on cultivation methods and soil and climate data are representative of the UK.

2.3.3. National allotment F&V production

To provide a national-scale estimate of F&V production on allotments we used Ordnance Survey Greenspace map (Ordnance Survey, 2017) to obtain the total national area of allotments in combination with the MYHarvest yield data presented herein, and data on allotment site characteristics, including areal coverage of onsite infrastructure and of different commonly grown crop types, as described in Edmondson *et al.* (2020a). Allotments are the primary areas of urban horticulture in UK cities. All allotment sites have communal infrastructure (e.g. roads and paths, on-site communal buildings) and Edmondson *et al*. (2020a) found that these spaces, on average, comprised 18% communal onsite infrastructure by area. In our national-scale estimate, we assumed that the proportion of allotment land used for onsite infrastructure was 18%. The remaining land in each allotment site comprised a group of allotment plots (typical plot size is 250 m^2) managed by an individual or group of people. At a plot level, Edmondson *et al.* (2020a) found that the average proportion of an allotment plot used for F&V cultivation was 51.5% by area. This cultivated area included both areas of active cultivation (90.5%) and areas in cultivation that had recently been harvested and were temporarily bare soil (9.5%). We applied the same ratios to our national-scale estimate. The relative contribution of different crops to national-scale production was estimated using the areal proportions of the twenty most commonly grown crops in Edmondson *et al*. (2020a). This assumption is supported by these crops being among the most frequently reported in the current MYHarvest study. For each of these 20 crop types, we combined an estimate of the areal extent nationally with the MYHarvest yields for each crop reported in this study. For the area of cultivated land without a crop in Edmondson *et al.* (2020a) (9.5% of total) we applied an average yield from across the MYHarvest crops reported in this study. Potential to increase allotment land nationally, and the concurrent increase in F&V production, was approximated based on estimated availability of former allotment land lost throughout the twentieth century that is suitable for reconversion to horticultural use, as determined by Dobson *et al.* (2020a) using a case study of five UK cities.

3. Results

3.1. Data summary

Between March 2017 and February 2022, we received harvest data from 475 growing sites, managed by 452 growers across the UK. Of these, we had sufficient location information to be able to assign site-specific soil type and temperature data for 378 sites (Figure 1). Overall, we had complete data for 8,600 successful harvests, 57% of which were from allotments, 41% from home gardens, and 2% from other types of growing spaces (see Supplementary Tables S3 to S7 for sample characteristics). Over half (57%) of these harvests were produced using organic growing methods. We had sufficient sample sizes to be able to run mixed effects analyses of predictors of crop yields on 25 crop types (Supplementary Table S9), but we provide an estimate of yield for 39 crop types (Supplementary Table S8).

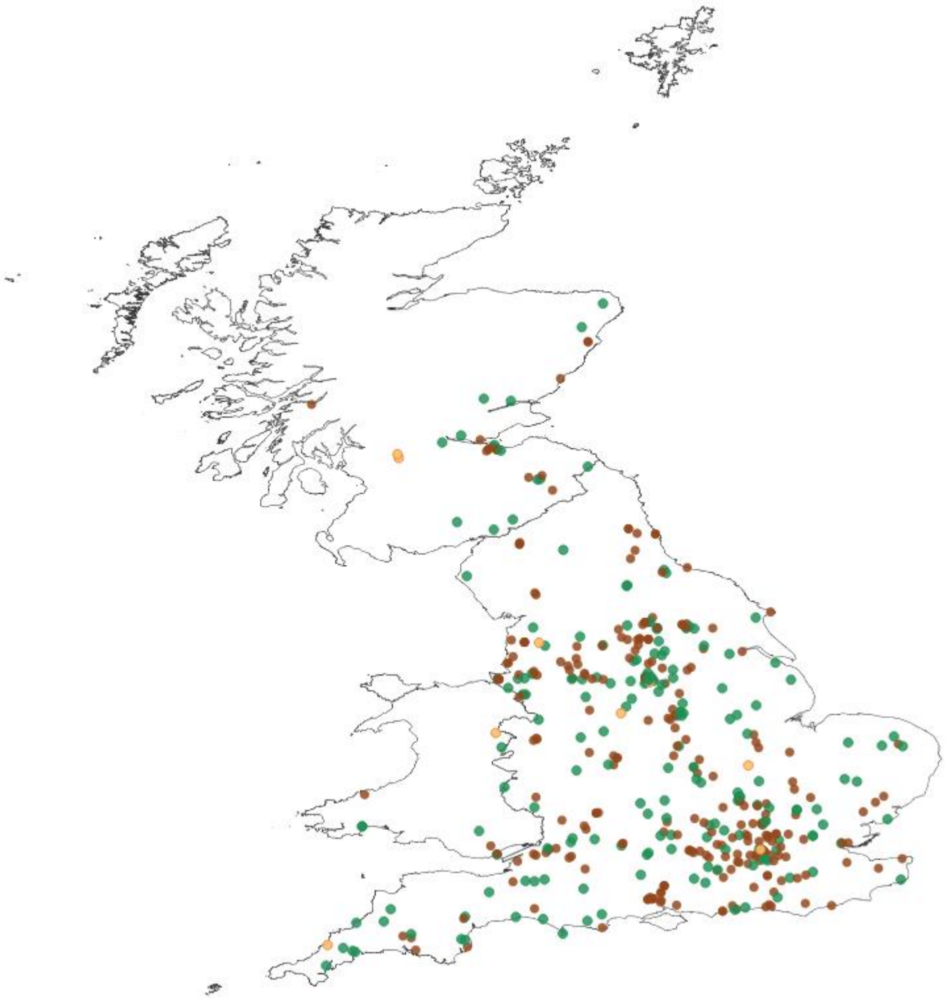


Figure 1. Geographical distribution of growing sites (N=378) contributing own-grown crop data through the MYHarvest project from March 2017 to February 2022. Brown dots represent allotments, green gardens, yellow other types of growing spaces.

3.2. Factors affecting own-grown crop yields

Based on our linear mixed effects analyses and likelihood ratio tests, growing space type (allotment, garden, or other) had no effect on annual crop yields (kg m^{-2} yr^{-1}) in any of the 25 own-grown crop types studied, but all other predictors tested had an effect on the yields of certain crops (see Table 1 for a summary of the significance of each tested predictor in different crop types and Supplementary Tables S10 to S34 for the full results of corresponding likelihood ratio tests). Organic growing had a positive effect on broccoli, associated with an increase of 0.22 kg m^{-2} yr^{-1} ±0.11 (S.E.) in yields compared to non-organic growing. Of the four crops that were relatively commonly grown in a greenhouse (i.e. in at least ten cases), greenhouse growing (compared to open-air) had a positive effect on tomatoes and strawberries, increasing yields by 0.95 kg m^{-2} yr^{-1} ±0.31 (S.E.) and 1.11 kg m^{-2} yr^{-1} ±0.67 (S.E.), respectively, but had no significant effect on cucumbers or lettuce / salad leaves. Mean growing season temperature was associated with increased yields in potatoes and broad beans, increasing yields by 0.38 kg m^{-2} yr^{-1} ±0.13 (S.E.) and 0.53 kg m^{-2} yr^{-1} ±0.21 (S.E.) for an increase of 1°C (from 13 to 14°C) in mean growing season temperature, respectively.

Soil type had a significant effect on the yields of currants, apples, leeks and broccoli. Compared to growing in loamy acidic soils, yields of currants were 0.57 kg m^{-2} yr^{-1} ±0.13 (S.E.) lower in loamy lime soils, yields of tree apples were 0.66 kg m^{-2} yr^{-1} ±0.19 (S.E.) lower in peaty soils, yields of leeks were 0.49 kg m^{-2} yr^{-1} ±0.16 (S.E.) lower in loamy high groundwater soils, while broccoli yields were 0.49 kg m^{-2} yr^{-1} ±0.13 (S.E.) lower in peaty soils. The random effects of growing year were generally very small, but location of growing site explained a considerable amount of variance in the yields of most crop types.

Table 1. Significance (p-values) of predictors of own-grown crop yields (log kg m^{-2} yr^{-1}) according to Likelihood Ratio Tests (LRT) of linear mixed effects models[a, b]

	Predictor / p-value				
Crop	**Organic**	**Space type**	**Greenhouse**	**Soil type**	**Growing season T**
Apple	0.425	0.616	NA	***0.030**	0.224
Beetroot	0.853	0.514	NA	0.736	0.318
Broad beans	0.291	0.648	NA	0.348	***0.043**
Broccoli	***0.034**	0.271	NA	***0.032**	0.312
Cabbage	0.084	0.062	NA	0.118	0.569
Carrot	0.858	0.727	NA	0.738	0.994
Courgette	0.522	0.614	NA	0.730	0.950
Cucumber	0.248	0.410	0.773	0.061	0.774
Currant	0.623	0.942	NA	***0.021**	0.456
French bean	0.773	0.804	NA	0.248	0.630
Gooseberry	0.331	0.320	NA	0.875	0.829
Leek	0.945	0.571	NA	***0.039**	0.368
Lettuce / salad leaves	0.870	0.063	0.672	0.488	0.823
Onion	0.455	0.161	NA	0.796	0.055
Parsnip	0.255	0.153	NA	0.943	0.690
Peas	0.627	0.223	NA	0.648	0.461
Potato	0.856	0.410	NA	0.114	***0.042**
Plum	0.227	0.305	NA	0.998	0.850
Raspberry	0.962	0.524	NA	0.817	0.766
Rhubarb	0.168	0.414	NA	0.870	0.261
Runner beans	0.898	0.405	NA	0.893	0.618
Squash / pumpkin	0.352	0.576	NA	0.669	0.335
Strawberry	0.930	0.833	***0.038**	0.348	0.288
Sweetcorn	0.238	0.167	NA	0.271	0.405
Tomato	0.513	0.635	****0.004**	0.721	0.088

[a] All models include growing year and site as random effects, and growing method (organic or not), space type (allotment, garden, or other), soil type (loamy acidic, loamy high groundwater, loamy lime, peat, peaty acidic, or sandy acidic), and mean growing season temperature (°C) as fixed effects. Models for cucumbers, lettuce / salad leaves, strawberries and tomatoes also include greenhouse growing (yes or no) as a fixed effect. See full results of corresponding LRTs in Supporting Tables S10 to S34.

[b] Figures marked with an asterisk (*) are significant at p<0.05, those marked with two asterisks (**) are significant at p<0.01

3.3. Own-grown crop yields

Mean crop yield ranged between 0.47 kg m^{-2} yr^{-1} ±0.08 (S.E.) (asparagus) and 6.81 kg m^{-2} yr^{-1} ±1.13 (S.E.) (cucumber) (Figure 3; see corresponding data in Supplementary Table S8). Overall mean yield across 39 own-grown crops was 1.93 kg m^{-2} yr^{-1} ±0.06 (S.E.). When compared to commercial horticultural yields, own-grown yield was greater for field-grown asparagus, broad beans, cauliflower, courgette, peas and runner beans, and vice versa for beetroot, broccoli, Brussel sprouts, cabbage, carrots, leek, lettuce / salad leaves, onion, parsnip, potato, raspberry, strawberry, apple and plum (Figure 3a). Yields of own-grown and commercial rhubarb and pear were similar. Defra does not provide commercial field-grown horticultural yields for the rest of the own-grown crop types. For protected crops, commercial yields were higher for all crop types investigated (i.e. cucumber, lettuce / salad leaves, pepper, tomato) (Figure 3b). Data on protected strawberries was not available from Defra.

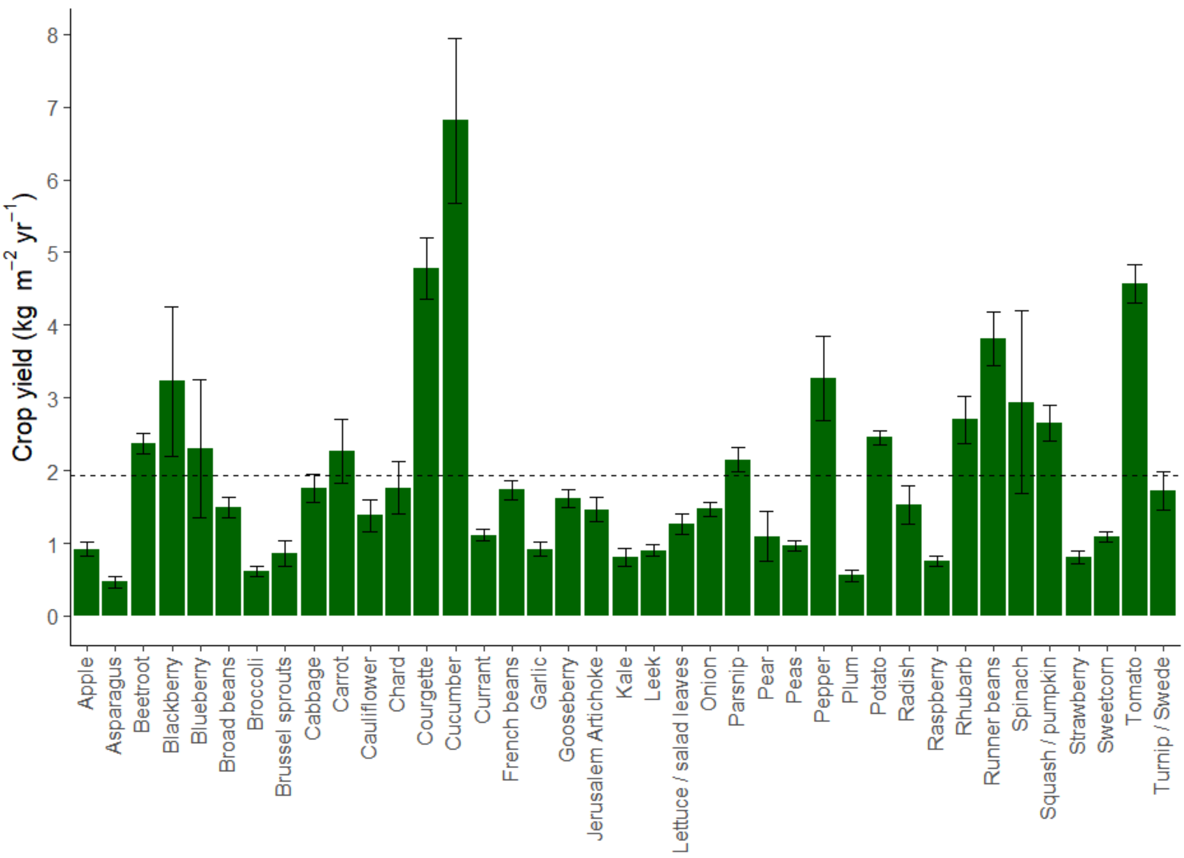
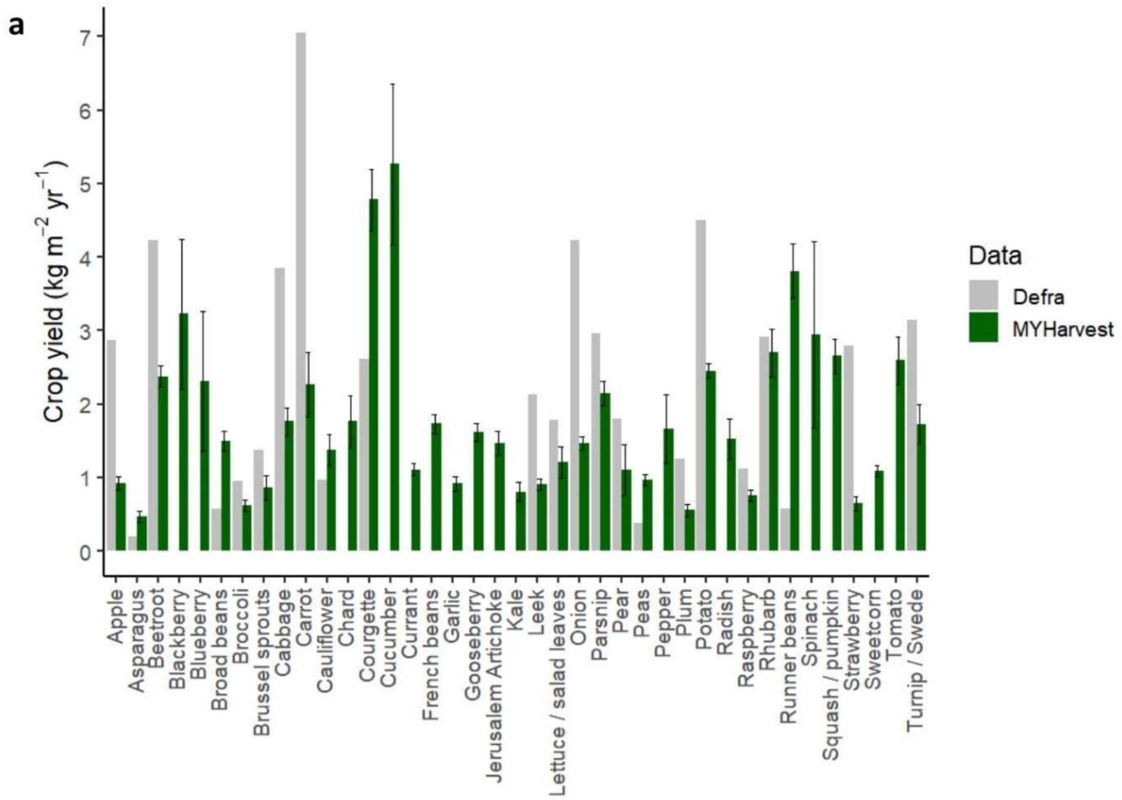


Figure 2. Mean yields of common own-grown crops. Error bars represent ±1 standard error. The dashed line represents overall mean yield across 39 crop types.



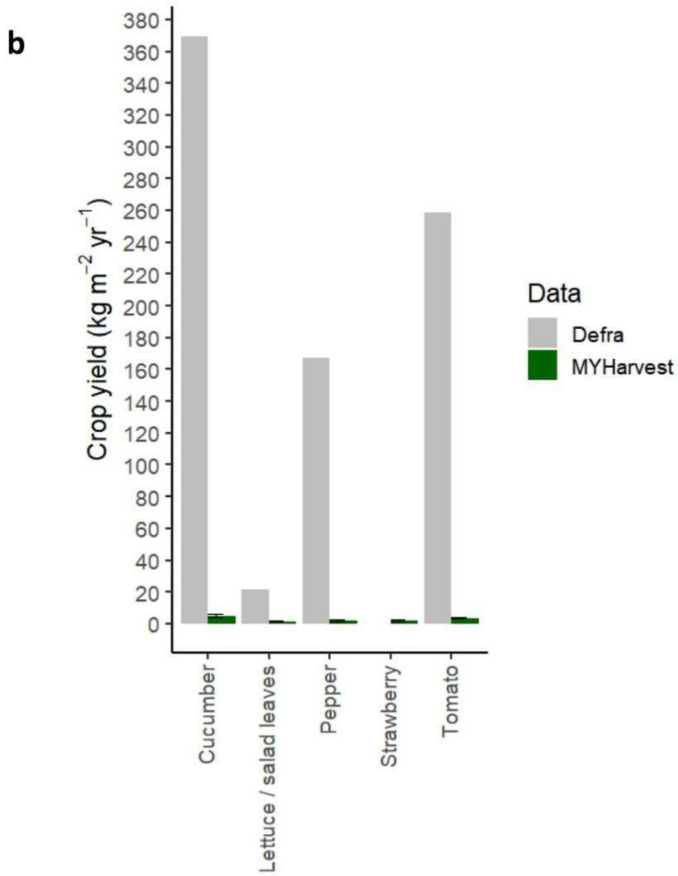


Figure 3. Mean yields of common allotment-grown crops (green bars) and equivalent commercial horticultural yields (grey bars - average over 2017 to 2019 (Defra, 2018)), for (**a**) field-grown and (**b**) protected crops. Error bars represent ±1 standard error.

3.4. Current national allotment fruit and vegetable production

Based on our estimates of yields of different own-grown crops (Figure 2 and Supplementary Table S8) and allotment site and management characteristics at a city-scale as described in Edmondson *et al.* (2020a), weighted mean allotment-grown crop yield adjusted for relative planted area is 2.04 kg m^{-2} yr^{-1} ±0.05 (S.E.) (Table 3). Assuming a total national allotment area of 135 km^2 of which 59.1 km^2 is under active cultivation (Table 3), we estimate national allotment food production to be 120.3 thousand tonnes per year ±2.7 (S.E.), including around 30.7 thousand tonnes ±1.3 (S.E.) of potatoes (26%), 78.4 thousand tonnes ±1.9 (S.E.) of other vegetables (65%), and 11.2 thousand tonnes ±1.4 (S.E.) of fruit (9%). After potatoes, runner beans, tomatoes, squash and courgette make the largest contributions to estimated national allotment food production (Table 3).

Table 3. Estimated national fruit and vegetable productivity of UK allotments[a, b]

Crop	Yield ($kgm^{-2}yr^{-1}$)	SE	Areal proportion (%)	National allotment cultivated area (km^2)	National allotment production (thousand tonnes yr^{-1})	SE
Potato	2.45	0.10	21.17	13.82	30.69	1.29
Onion	1.47	0.09	7.91	5.16	6.86	0.42
Strawberry	0.81	0.08	5.41	3.53	2.57	0.27
Runner beans	3.81	0.37	4.95	3.23	11.15	1.08
Squash / pumpkin	2.65	0.24	4.88	3.18	7.64	0.69
Cabbage	1.76	0.19	4.59	3.00	4.77	0.52
Tomato	4.57	0.27	4.53	2.96	12.23	0.72
Raspberry	0.75	0.07	4.43	2.89	1.97	0.19
Peas	0.97	0.08	4.31	2.81	2.46	0.20
Apple	0.92	0.09	3.43	2.24	1.86	0.19
Brussel sprouts	0.86	0.17	2.91	1.90	1.48	0.29
Beetroot	2.38	0.14	2.86	1.87	4.02	0.24
Sweetcorn	1.09	0.08	2.84	1.86	1.82	0.13
Leek	0.90	0.07	2.72	1.78	1.45	0.12
Carrot	2.27	0.44	2.49	1.63	3.34	0.65
Currant	1.11	0.08	2.44	1.59	1.60	0.12
Courgette	4.78	0.42	2.37	1.55	6.70	0.58
Blackberry	3.23	1.02	2.17	1.42	4.14	1.31
Plum	0.55	0.08	2.09	1.36	0.68	0.10
French/ climbing beans	1.73	0.13	2.04	1.33	2.09	0.16
Other	1.93	0.06	9.47	5.59	10.81	0.34
Total	2.04	0.05	100.00	59.10	120.33	2.70

[a] The 20 allotment-grown crop types with the largest areal coverage in Edmondson et al. (2020a), in decreasing order of coverage. For the 9.5% of the cultivated area that was temporarily bare in that study ('Other' above), we applied the overall mean crop yield across 39 MYHarvest crop types (Supplementary Table S8).

[b] Bootstraps were run using 1000 simulations, on models including site as a random effect, and growing method, space type, soil type, mean growing season temperature, and, for strawberries and tomatoes, also greenhouse growing, as fixed effects.

3.5. Potential for upscaling national allotment fruit and vegetable production

Research looking at changes in allotment provision throughout the twentieth century using a case study of five UK cities has found that by 2016 only 26.7% of original allotment area was still allotment land, but 25.3% remained green space, three quarters of which was suitable for reconversion to horticultural use (Dobson et al., 2020a). Assuming these figures are representative of a nationwide pattern, based on the current national area of allotment land (approx. 135 km^2) there could be around 96.8 km^2 urban green space in the country that may be reconverted to its original use as allotments. Doing so could increase national allotment food production by 86.3 thousand tonnes per year ±1.9 (S.E.), representing a potential 72% increase compared to current estimated allotment production. Potential F&V supply from current and thus reconverted allotments would be 206.6 thousand tonnes per year ±3.3 (S.E.).

4. Discussion

Improving the ability of food systems to provide a stable supply of F&V in the face of environmental and socio-political disturbance is a key priority in the UK (Defra, 2022; Dimbleby, 2021) and globally (*Food Security*). Here, we provide the first comprehensive dataset on F&V yields achieved by households practising small-scale horticulture in allotments and gardens in the UK. This enabled the first national-scale estimate, since the Dig for Victory campaign during World War II, of own-grown F&V production in allotments in the UK and its contribution to the national food supply, as well as an assessment of its potential expansion through reconversion of former allotment sites.

Our results indicate that own-grown crop yields are generally unaffected by growing space type and whether they are grown organically, which is typically associated with decreased yields in conventional agriculture (de Ponti et al., 2012; Seufert et al., 2012). Also surprisingly, the positive effect of growing crops under protection (glasshouse / polytunnel) was only seen in some crops (strawberries and tomatoes) and not others (cucumbers and lettuce / salad leaves). Further, although we found evidence of yield differences associated with regional variation in soil type and growing season temperature in certain crops, most crop types studied were unaffected by these factors. However, there was a large amount of variance in yields associated with individual growing sites that could not be explained by our chosen set of predictors. These findings suggest that, although general soil properties and climate do have an effect on the productivity of certain own-grown crops, some harder to define characteristics of individual growing spaces and practices adopted by growers are also important drivers of own-grown crop yields. For example, practitioners may be using various methods to protect their crop from pests and diseases (e.g. companion planting, bird nets, slug pellets) and enhance soil fertility (e.g. addition of animal manure or compost, crop rotation, 'no-dig' method), or have different growing setups (e.g. raised beds) (Edmondson et al., 2014; National Allotment Society, 2022). In addition, a recent study on household F&V production in the UK has found own-grown crop yields to be positively associated with grower experience, cultivated area, and household size (Gulyas & Edmondson, in review), so these factors might also be contributing to between-site yield variation in our study.

Yields of own-grown crops were different from commercial horticultural yields, with commercial yields being higher for the majority of crop types. However, the relative yields of different crops were dissimilar between own-grown and commercial production, and several crops (i.e. field-grown courgettes, runner beans, asparagus, broad beans, peas, cauliflower) had overall higher yields when own-grown. Even though for the majority of F&V types studied, own-grown yields were lower than those from commercial cultivation, we should bear in mind that around half of our own-grown crop data came from organic growing, which, unlike in conventional agriculture (de Ponti et al., 2012; Seufert et al., 2012), was not associated with decreased yields in own-grown crops. Moreover, research on UH soil quality in the UK has found that allotment soils are generally much higher in organic carbon than surrounding arable or horticultural land, and that allotment gardeners tend to employ management practices conducive to high soil quality (Dobson et al., 2021; Edmondson et al., 2014). Thus, in contrast to conventional horticulture which usually involves practices that contribute to biodiversity loss (Robinson & Sutherland, 2002) and degrade soils (Watts & Dexter, 1997), small-scale UH production can increase F&V supply in a more sustainable way. The stark contrast between yields of protected crops between own-grown and commercial horticulture will be driven by both the controlled environments used in commercial produce (e.g. artificial heat and light), and the year round cropping that this type of production enables (Nemali, 2022).

Our national-scale estimate of allotment-grown crop yield is similar to the mean yield in Leicester allotments found by previous research (2.3 kg m^{-2} yr^{-1} ±0.2 (S.E.)) (Edmondson et al., 2020a). This, combined with our finding that most own-grown crops were unaffected by soil type and growing season temperature, suggests that own crop yields may vary little across the country. This could in part be explained by the use of growing methods best suited to local conditions or the choice of locally adapted crop varieties. Indeed, MYHarvest participants reported data on over 3,000 crop varieties, which also demonstrates that, in contrast to conventional agriculture that relies heavily on monoculture, own-growing can help conserve agrobiodiversity, thereby supporting ecosystem services and sustainable food security (Dudley & Alexander, 2017). This also suggests that own-growing across the UK is likely to adapt and be more resilient to extremes in weather or pests and diseases that can negatively affect commercial horticultural crop yields.

According to our estimate, current allotment F&V production in the UK (120.3 thousand tonnes per year) amounts to around 3.9% of domestic commercial production of F&V (3.1 million tonnes) in 2021 (Defra, 2018). Excluding potatoes, allotment-grown F&V (89.7 thousand tonnes per year) could feed over 614 thousand people (nearly 1% of the population) their 5-a-day F&V (i.e. 400 g per day (WHO, 2003)), while national allotment potato production (30.7 thousand tonnes per year) could meet the typical annual demand (35.1 kg (Defra, 2017)) of 874 thousand people. Estimated current allotment F&V production is notably lower than the historical contribution of own-growing to the UK F&V supply during World War II, when it reached 18% (Defra, 2017; Ginn, 2012). However, our estimate does not include domestic gardens, and importantly, the UK population has grown by around 50 percent since the war (ONS, 2015), while allotment area has decreased by 65% (Dobson et al., 2020).

We estimate that reconverting suitable former allotment land could increase national allotment F&V production by 72% (86.3 thousand tonnes per year). After the exclusion of potatoes, the additional 64.3 thousand tonnes of allotment-grown F&V could provide the annual 5-a-day F&V requirements of over 440 thousand people. Potential F&V supply from current and reconverted allotments would be the equivalent of 6.7% of domestic commercial F&V production (Defra, 2018) and thus represents a potentially important mechanism to decrease our reliance on unsustainably grown F&V within the

UK. Alternatively, putting suitable former allotment land back under cultivation could also decrease our high national dependence on vulnerable foreign F&V supplies (Defra, 2018). Focusing on own production of the highest yielding crop types, especially those that perform relatively better when own-grown than in conventional horticulture, may be especially effective at sustainably increasing food supply. Here, we try to provide a realistic scenario for current and potential production. As such, our estimate of production potential (206.6 thousand tonnes per year) is markedly lower than a recent UK estimate by Walsh *et al.* (2022) which provided an interesting thought exercise focussed on maximum possible production. However, as we have shown here, the yields of many own-grown crop types are quite different from those grown commercially. In addition, in reality, not all urban green spaces may be suitable for food production (e.g. for soil quality or legal reasons), and other types of green spaces also fulfil important social and ecological functions in cities and so should ideally not all be put to horticultural use (Edmondson et al., 2020b).

The potential of other forms of UH, including domestic and community gardens and non-conventional (e.g. rooftop or vertical) growing spaces, to increase food security and resilience is yet to be further explored. For example, domestic gardens cover nearly 30% of urban areas in the UK (Brownbill & Dutton, 2019) and thus have a huge capacity to contribute to the F&V supply, however, we have limited understanding of the extent to which they are currently being used for food production (Grafius et al., 2020), or how, and to what level, this could be increased. Nonetheless, the present research makes an important contribution to the field by determining the yields of common own-grown crops, increasing our understanding of the factors that drive these, and providing the first national-scale estimate of allotment F&V production in the UK.

Promoting own F&V production in urban areas where most of the population lives could help reconnect people with food production and may promote increased consumption of F&V (Alaimo et al., 2008; Barnidge et al., 2013; Demark-Wahnefried et al., 2018; Litt et al., 2011; Nova et al., 2020; Sarti et al., 2017). This in turn could have important public health benefits, as over two thirds of the UK population have insufficient F&V intakes, which is one of the main preventable causes of non-communicable diseases in the country, contributing to around 18,000 premature deaths annually (Afshin et al., 2019). Improving access to fresh F&V could be especially beneficial in more deprived neighbourhoods, which are often characterised by more difficult access to healthy food (Black et al., 2012; PHE, 2019a), lower F&V intake (PHE, 2019b), and worse health status (Stafford & Marmot, 2003). Moreover, strengthening alternative food supplies, including allotment production of F&V, could increase the resilience of the food system by building backup capacity in case of disruptions to conventional supplies, as we have seen during World War II (Defra, 2017; Ginn, 2012). Public interest in grow-your-own has been high and rising, especially since the outbreak of the Covid-19 pandemic (Evans & Davies, 2020; Royal Horticultural Society, 2020; Sustain, 2020), which presents a great opportunity to successfully promote engagement in UH.

5. Conclusion

Our results support the idea that small-scale food production by people could play a modest, but important, role in decreasing reliance on conventional F&V supplies, promoting national self-sufficiency in fresh produce and increasing the resilience and sustainability of the UK food system. Expansion of urban horticulture through increased provision of allotment land and promotion of own-growing would be of particular benefit, as it could improve the availability and consumption of a variety of fresh fruits and vegetables in areas where many people have limited financial or physical access to nutritious food, potentially improving diet quality and related public health.

Chapter 4

The contribution of household fruit and vegetable growing to fruit and vegetable self-sufficiency and consumption

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Abstract

Improving access to, and consumption of, fruits and vegetables (F&V) is crucial to a healthy and food secure population, as current low intakes are linked to high rates of non-communicable diseases, premature death and increased healthcare costs. Household F&V production could improve diet quality and food system resilience, however, quantitative evidence for its potential is limited. We studied year-long F&V production, purchases, donations, and waste in UK food-grower households (N=85) using a food diary approach. Median year-round household self-sufficiency was 51% in vegetables, 20% in fruits, and 50% in potatoes. Median daily per capita F&V intake was 507 g, which is the equivalent of 6.3 portions of F&V, 70% higher than the UK national average. On average, own production accounted for half of each household's annual 5-a-day F&V requirements. F&V waste was negligible, equivalent to 0.12 portions per day and 95% lower than UK average F&V waste. We demonstrate that promoting household F&V production could improve food system resilience, diet-related public health, and sustainability.

1. Introduction

Eating a balanced diet is essential for maintaining health and preventing a range of diseases. The World Health Organisation's (WHO) recommendations for a healthy diet include consuming at least 400 g of a range of fruits and vegetables (F&V) daily (excluding starchy tubers), as well as limiting saturated fat, salt and free sugar intake (WHO, 2020). Sufficient F&V consumption has been shown to reduce the risks of malnutrition, developing obesity and non-communicable diseases, including cardiovascular disease, type 2 diabetes, and certain types of cancer (Bazzano et al., 2003; Wang et al., 2014; WHO, 2003). However, even in developed countries, eating a healthy diet high in F&V can be a challenge for many people due to issues of financial and physical access as well as other factors such as culinary culture (Dimbleby, 2021; FAO et al., 2020).

In the UK, despite national efforts to promote F&V consumption (NHS, 2018), most people do not eat their '5-a-day' (i.e. five 80 g portions), a target set by the UK government informed by the WHO target to consume at least 400 g F&V a day. Although recent years have seen a slight increase, average per capita F&V intake in the country is 26% below recommendations, with only about 8% of teenagers and less than a third of adults meeting the 5-a-day target (BDA, 2020; NHS Digital, 2019; PHE, 2019). The situation is similarly worrying in the US and EU countries, where current guidelines for F&V consumption are met by less than 20% and around 12% of the population, respectively (Eurostat, 2022; USDA, 2020). There are also large and growing socio-economic inequalities in the access to and consumption of F&V, with the poorest 20% of the UK population eating a full portion less a day than the richest 20%, which can be linked to prevailing disparities in health status (PHE, 2019). Significant associations between socio-economic status and F&V intake can be observed in the US and Europe (Ball et al., 2015; Dubowitz et al., 2008; Jack et al., 2013). It is estimated that diets low in F&V contribute to around 18,000 premature deaths in the UK every year (Afshin et al., 2019), and that food-related ill health costs the NHS about £6 billion annually (Rayner & Scarborough, 2005). Globally, diet-related health costs linked to mortality and non-communicable diseases are predicted to exceed USD 1.3 trillion per year by 2030 (FAO et al., 2020). We are facing a diet-related health crisis, with soaring rates of obesity and non-communicable disease placing a heavy burden on both affected individuals and society as a whole (Food Foundation, 2017; NHS Digital, 2020).

In addition, the Covid-19 pandemic and now the rising food prices related to Brexit and the current turbulence in Ukraine have highlighted the fragility of our globalised supply chains and existing issues of food insecurity for growing urban populations (FAO, 2020; FAO et al., 2020; Revoredo-Giha & Costa-Font, 2020; Sweney, 2022). It has become clear that, in order to prepare for further disruptions associated with the unpredictable effects of climate change and political and economic turmoil on global agri-food systems, we must increase the resilience of our food system and reduce inequalities related to diet. The UK government's new food strategy advocates for increasing domestic food production as a key way of providing national resilience against disruptions to foreign supplies, and for adopting longer-term measures to improve access to and affordability of healthy food for all to combat obesity and diet-related illnesses (Defra, 2022). Given the importance of F&V for health, and our relatively low and decreasing national production of these foods, increasing and diversifying domestic F&V production should be a priority (Defra, 2020; Dimbleby, 2021; Ingram et al., 2020; Tendall et al., 2015).

The supply shortages that followed the outbreak of the pandemic drew increased attention to the potential of urban horticulture to improve food security and nutrition (FAO, 2020; Lal, 2020). F&V production on allotments (plots of land approx. 250 m^2 rented to individuals for crop production) and domestic gardens made an important contribution to the UK war effort during World War II, providing 18% of the national F&V supply (Defra, 2017; Ginn, 2012), and now once again it could play a role in improving our food system. Research has demonstrated that own-grown crop yields can be similar to those achieved by conventional production (Edmondson et al., 2020a), and that there is potential in urban areas for horticulture to meet a significant proportion of the F&V demands of its inhabitants (Edmondson et al., 2020b). Moreover, household F&V production could improve diet quality by providing access to F&V as well as potentially triggering healthier food behaviours (Kourmpetli et al., 2022), and while they do not count towards the 5-a-day, potatoes are a nutrient-rich staple in the country and their household production could make an important contribution to food security (Burgos et al., 2020). Although horticultural production potential of urban green spaces has been estimated on the national (Walsh et al., 2022) and city scales (Edmondson et al., 2020b), quantitative data on the level of household self-sufficiency that could be achieved by household food production, and evidence for a relationship between growing F&V and increased household F&V intake in the UK have thus far been lacking. The aim of this research is to quantify the potential contribution of household F&V production to the self-sufficiency and F&V consumption of food-grower households in the UK, as well as to investigate how this may vary with certain characteristics of people's growing practice, to better understand ways in which to increase its potential. We studied year-round crop production, purchases, donations, and crop waste in 85 food-grower households to answer the questions:

1) What levels of year-round production and self-sufficiency can food-grower households achieve in different types of produce, and how does this vary across the year?
2) How much F&V do people in food-grower households eat, and how diverse is their F&V consumption?
3) How do certain aspects of growing practice (i.e. cultivated area, grower experience, gardening effort) and household size affect household food productivity and self-sufficiency?

2. Materials and Methods

2.1. Participants

One hundred and ninety-seven people engaged in food growing (including allotment holders and home gardeners) were recruited on a voluntary basis from across the UK through conventional and social media and via word of mouth in the gardening community (including through collaboration with the National Allotment Society, Royal Horticultural Society, and via the network of the ongoing MYHarvest project (myharvest.org.uk)). Recruitment started in July 2020. Participants kept a year-long record of their fruit and vegetable (including potatoes) production, purchases, foraging, donations and waste. We acknowledge that participants in this study were a self-selecting group of, typically, experienced growers, and that the study period of 2020–2022 was impacted by major COVID-19 lockdowns, which meant that participants likely had more time to tend to their allotments and home gardens than under normal circumstances, so the data may not be fully representative of typical practice. Complete records (i.e. including at least 42 weeks, 80% of the year) were received from 85 participants by February 2022. The project was granted ethical approval by the Department of Animal and Plant Sciences, The University of Sheffield (project ref. 035588).

2.2. Data collection

A diary-based approach was employed as it enabled the collection of the long-term data needed to fully understand the contribution of household food growing to diet across a full year. However, we acknowledge that there are known limitations of diary keeping as a data collection method related to the accuracy and completeness of data (see e.g. Fuller et al., 2017). Volunteers were provided with a diary ('MYHarvest Diary') via post, in which each week they recorded the weights (in grams) of all fruits and vegetables (F&V), including fresh, frozen, tinned, canned, and dried produce, they acquired that week, indicating its source (i.e. their *allotment*, home *garden*, a *shop or market*, gift from *other growers*, or *foraged* in the wild) for a full year, i.e. 52 weeks (data collection started in the summer of 2020, but exact date ranges of records varied among participants). We did not collect data on the consumption of foods acquired before but consumed after the study period, or on the amounts of produce that were recorded then stored and not consumed until after the study period. We made the assumption that amounts of food used from and added to storage would roughly balance out over a year. Ingredients within ready meals/ takeaways or foods otherwise prepared and eaten outside the home were not quantified, but we did collect data on the frequency of eating such meals to ensure that diary records largely reflected participants' total fruit and vegetable consumption. Participants also recorded the approximate number of hours they spent food gardening (including sowing, weeding, watering and harvesting) each week, how much, if any, of their produce they gave away, or went to waste, whether they froze or preserved any produce, or used previously frozen or preserved produce. Additional information collected included household size (indicating the number of people fed by documented amounts of produce), how often participants ate outside the home (takeaways/ restaurant meals), how long they had practised food growing for (number of years), total allotment size, allotment food growing area, garden food growing area, whether participants grew food organically, and what percentage of their total F&V consumption they thought was provided by their own produce (the full list of questions and an example weekly sheet from the diaries can be found in the Supporting Information, Images S11–S13). After 52 weeks, completed diaries were posted back to Sheffield, where their contents were anonymised and entered into a spreadsheet.

2.3. Data processing

Each recorded food item was classified as a fruit, vegetable, potato or nut (potatoes and nuts were excluded from analyses looking at F&V consumption because they do not contribute towards the 5-a-day, but were included in assessments of own produce yields and household self-sufficiency). Fruits and vegetables were differentiated based on their nutritional properties such that more nutrient-dense foods (i.e. higher sugar or fat content), including those typically consumed as a fruit as well as avocados and olives, were classified as a fruit, while those lower in sugar and fat, including most culinary vegetables, legumes, herbs and sweet potatoes, were classified as a vegetable.

Herbs harvested in very small quantities (which participants were not required to weigh), were all assigned a weight of 1 g. In cases where only the number of food items acquired was recorded, weight was estimated based on typical supermarket weight. On a few occasions (i.e. one week per year in three diaries) when participants forgot to record the weights of shop-bought produce but noted that amounts were very similar to the previous week, that week's data was copied to fill in the missing weights. In rare cases (i.e. on average less than three times in a year-long record, with the maximum number of occurrences per diary being 9) when only the type of produce was recorded, it was assumed that either one piece or the amount contained in a typical supermarket pack (e.g. pack of six apples) was harvested or purchased, whichever seemed more realistic based on the type of produce and the participant's previous records. Where 'a few' items were listed, this was assumed to refer to four pieces, while 'a small amount' was assigned an arbitrary weight of 50 g (a list of the exact values used to complete missing data can be found in the Supporting Information, Table S9). In total, 1.4% of our data comprised imputed values according to the above assumptions. To test the effect of using imputed values to complete missing data on our estimates of produce consumption, production and self-sufficiency, we reran these analyses on an alternative version of the data where a weight of 0 g was assigned to all incomplete observations. We found the results of alternative analyses to be very similar (see Supporting Information Tables S4 and S5). We provide results using data including imputed values in the Results.

Recorded weights of dry fruit and juice were converted to equivalent fresh weight based on portion sizes defined by the British Nutrition Foundation (i.e. 30 g dried fruit or 150 ml juice = 80 g fresh weight) and weights of dry pulses were converted to cooked weight (assuming 100 g dry beans or chickpeas = 200 g when cooked, 100 g dry lentils or peas = 250 g when cooked). Jams and chutneys were assumed to have a 50% fruit content by weight. Half a can of vegetable soup was counted as one vegetable portion (i.e. 200 g counted as 80 g). Other vegetable-containing food products (e.g. vegetable burgers) were assumed to have a 10% vegetable content by weight. Due to their high fat and salt content, vegetable crisps, recorded by a few participants, were excluded from estimations of vegetable consumption. Tofu, soy mince and vegetarian meat alternatives not made from whole vegetables were also excluded. Although pulses and fruit juice/smoothies can only count as one portion a day regardless of the amount consumed, where larger quantities of these foods were recorded it was assumed that these were consumed over a period of time, not exceeding the daily maximum, so the full recorded amounts were included in estimations of annual F&V intake.

2.4. Analysis

Household produce consumption, production and self-sufficiency

Total weights of different types of produce consumed in participating households over the course of the year, overall and as acquired from different sources, as well as weights of produce given away and amounts of waste, were calculated by adding up all recorded weight values within each category. Annual self-sufficiency of participating households in all produce, fruits, vegetables and potatoes was calculated as the proportional contribution of own-grown produce to total gross annual consumption.

Fruit and vegetable (F&V) consumption

Mean per capita F&V intake in participating households was estimated by dividing net annual household F&V consumption (i.e. gross consumption minus donations and waste) by the number of people in the household and the number of days for which records were available (i.e. 7 x (52 - number of weeks without records)). F&V weight was converted to number of daily portions such that one portion equals 80 g fresh, canned, tinned or frozen produce, 30 g dried fruit or 150 g pure juice. Dietary diversity in F&V was assessed as the number of types of F&V consumed in participating households over the course of a year. We used a dependent samples t-test to compare the mean number of fruits and vegetables consumed in each household.

Predictors of own food production and self-sufficiency

To investigate the potential effects of a number of factors that could affect own food production (total annual weight and yield per m^2) and household produce self-sufficiency (% by weight), we used multiple linear regression analyses to test associations with food growing area (m^2), gardener experience (number of years growing food), cultivation effort (mean weekly number of food gardening hours and mean number of allotment visits per week), yearly allotment rent (as a possible indicator of the availability of communal resources and services provided by allotment societies) and household size (to indicate the number of people consuming own produce). Models for each outcome were built such that first, all hypothesised predictors (a different set for each outcome, based on hypothesised relationships and inspection of data) were entered simultaneously to create a full model, then, after checking and, if necessary, correcting for the assumptions of linearity (using scatter plots and residual diagnostic plots), multicollinearity (based on Variance Inflation Factors (VIF)) and presence of potential outliers (based on standardised residual distribution) and influential cases (based on Cook's distance and leverage plots), explanatory variables that did not have a significant effect on the outcome were removed one by one, starting with the one with the highest *p*-value. After each removal, the performance of the reduced model was compared to the previous model using the Akaike Information Criterion (AIC), and the model with the lower AIC was selected. The process was repeated until further removal of predictors did not result in improved model fit. Regression parameters were reported for the final, best fit model for each outcome. To assess the generalisability of our best fit models, assumptions of normal standardised residual distribution and homogeneity of residual variance were evaluated. We also assessed the strength of the correlation between calculated levels of F&V self-sufficiency and levels perceived by participants using Pearson's *r*. All analyses were carried out in R (version 4.0.3).

3. Results

3.1. Participants and their growing practice

Over two thirds (67.1%) of participants (N=85) used both an allotment and their home garden to grow food crops, 16.5% used only their allotment, and 16.5% used only their home garden (see Table S1 in the Supporting Information for descriptive statistics on participants' growing practice). Median food growing experience among participants was 20 years, ranging from 6 months to 60 years. The majority of participants fully (75.3%) or mainly (5.9%) adopted organic gardening methods. Median total cultivated area used for food production was 120.5 m^2. On average, participants spent just under four hours food gardening per week and those who had an allotment visited their plot between two and three times a week. Over half of produce recorded (53.9%) was purchased at supermarkets or markets, nearly a third (31.5%) grown on participants' allotments, 12.5% in home gardens, 2.1% received from other growers, and 0.1% acquired by foraging (Table S2). All participants produced vegetables, while fruits and potatoes were each grown by 98% of participants. Participants on average cultivated 37.5 ±1.3 different F&V crops, typically growing around four times more vegetable than fruit crops. Excluding potatoes, the most frequently grown vegetables were tomatoes, courgettes, beetroot, rhubarb, carrots, onions, leeks, lettuce, beans, peas, cucumbers and cabbage, each of which were grown by over two thirds of participants. The most frequently grown fruits were apples, raspberries, strawberries, blackcurrants and gooseberries, each of which were produced by over 50% of participants. Ninety-five percent of participants gave away some of their produce, 72% received produce from other growers, and 19% foraged for food in the wild. Ten participants reported no produce waste during the study year, and several participants noted that they composted or fed their food waste to livestock as a means of sustainable disposal (as data was not specifically collected on composting / livestock feeding, the actual number of participants engaging in such practices is unknown). Nearly all participants froze or preserved some produce during the study year and used their previously frozen or preserved produce (Table S3). Freezing and preservation were more common between June and November than during the rest of the year (Figures 1a and 1b). Using previously frozen or preserved produce was slightly less common in the summer months but was relatively common throughout the year (>60% of participants in every month) (Figures 1c and 1d).

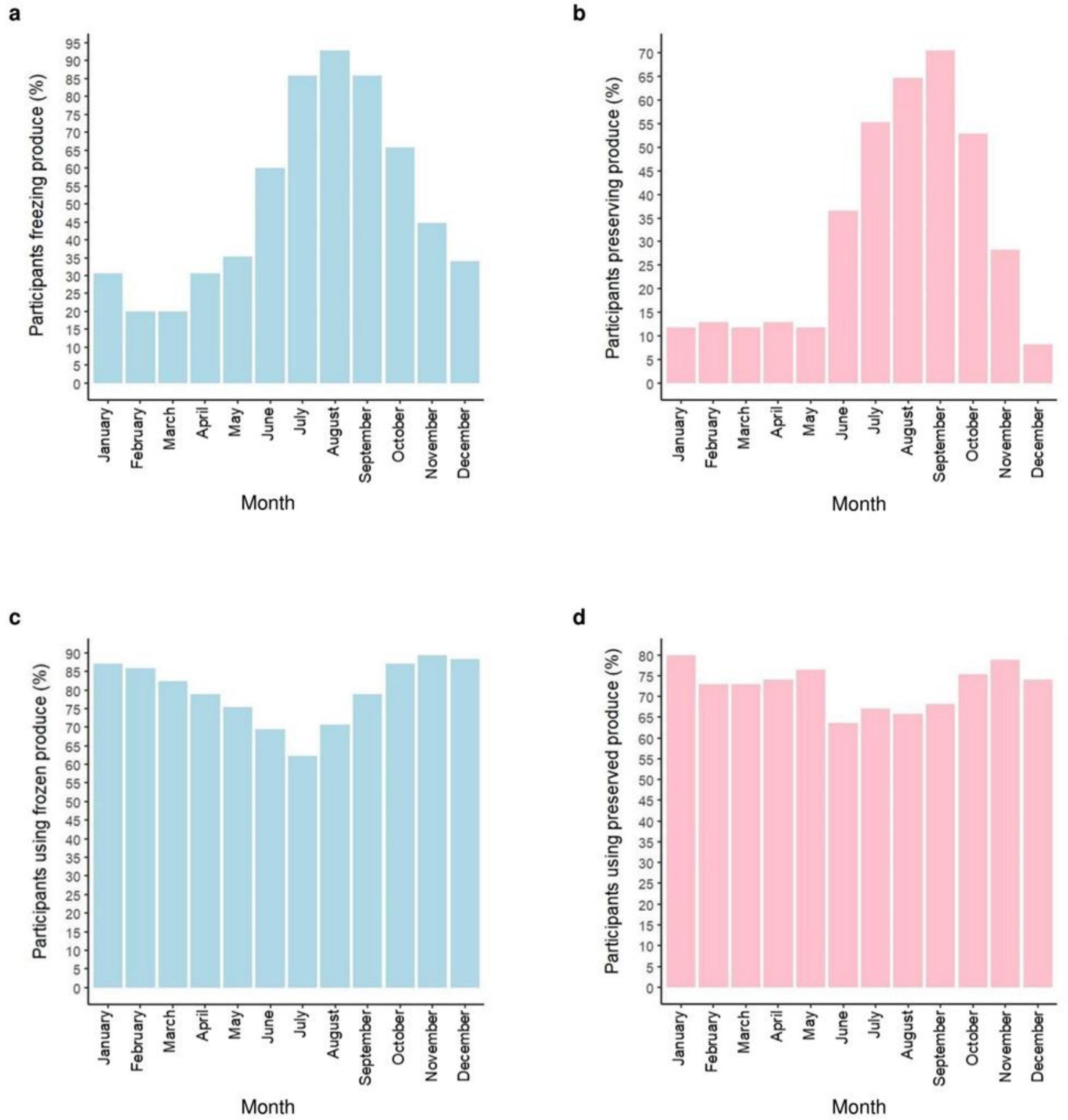

Figure 1 Percentage of participants (N=85) (a) freezing, (b) preserving, (c) using frozen and (d) using preserved produce in different months of the year.

3.2. Annual produce fluxes in food-grower households

Household mean gross produce consumption was 464.1 kg yr^{-1} ±23.6 (S.E.), which comprised 250.3 kg yr^{-1} ±13.1 (S.E.) vegetables, 150.4 kg yr^{-1} ±11.1 (S.E.) fruits, 62.9 kg yr^{-1} ±4.7 (S.E.) potatoes, and 0.8 kg yr^{-1} (median) nuts (recorded by 23.5% of participants) (Supporting Table S4). Participants on average consumed one takeaway or restaurant meal per month (MED=0.25 meal per week), the ingredients of which were not captured by our study. Median weights of fruit, vegetable and potato purchases were 104.5, 116.9 and 28.7 kg yr^{-1}, respectively. Median weights of fruits, vegetables and potatoes grown by participants were 26.6, 107.1 and 24.2 kg yr^{-1}, respectively (Figure 2a). Median weights of produce given away (n=81), and received from other growers (n=72), by participants were 16.1 and 3.8 kg yr^{-1}, respectively. Mean amount of food acquired by foraging among those who foraged during the study year (n=19) was 0.5 kg ±0.2 (S.E.) (across all participants, the contribution of foraging to annual consumption was negligible). Median weight of produce waste was 3.4 kg yr^{-1}, less than 1% of total consumption.

3.3. Own crop yield and household produce self-sufficiency

Median production on allotments was 151.6 kg yr^{-1} (Supporting Table S4). Median production in home gardens was 23.9 kg yr^{-1}. Total household (allotment and garden) crop production ranged between 34.2 and 588.7 kg yr^{-1}, with a median of 163.6 kg yr^{-1} (Figure 2a). Median own-grown produce yield was 1.4 kg m^{-2} yr^{-1}. Median year-round produce self-sufficiency among participants was 41.1%, ranging from 14.9% to 92.3% (Figure 2b). Year-round median self-sufficiency in potatoes was 49.7%, in vegetables, 51.1%, and in fruits, 20.2%. Replacing imputed values of crop weight with 0 g had a small effect on these results; for example, mean annual household F&V self-sufficiency increased from 42.6% ±2.0 to 43.4% ±2.1 (see Supporting Tables S4 and S5). On average, own F&V production accounted for half of participants' annual household 5-a-day requirements (MED=49.8%), providing 1.9 portions of vegetables and 0.5 portions of fruit for each person in the household. Levels of year-round household F&V self-sufficiency calculated from consumption records were strongly correlated with levels of self-sufficiency perceived by participants ($r_{(72)} = 0.70$, $p<0.001$).

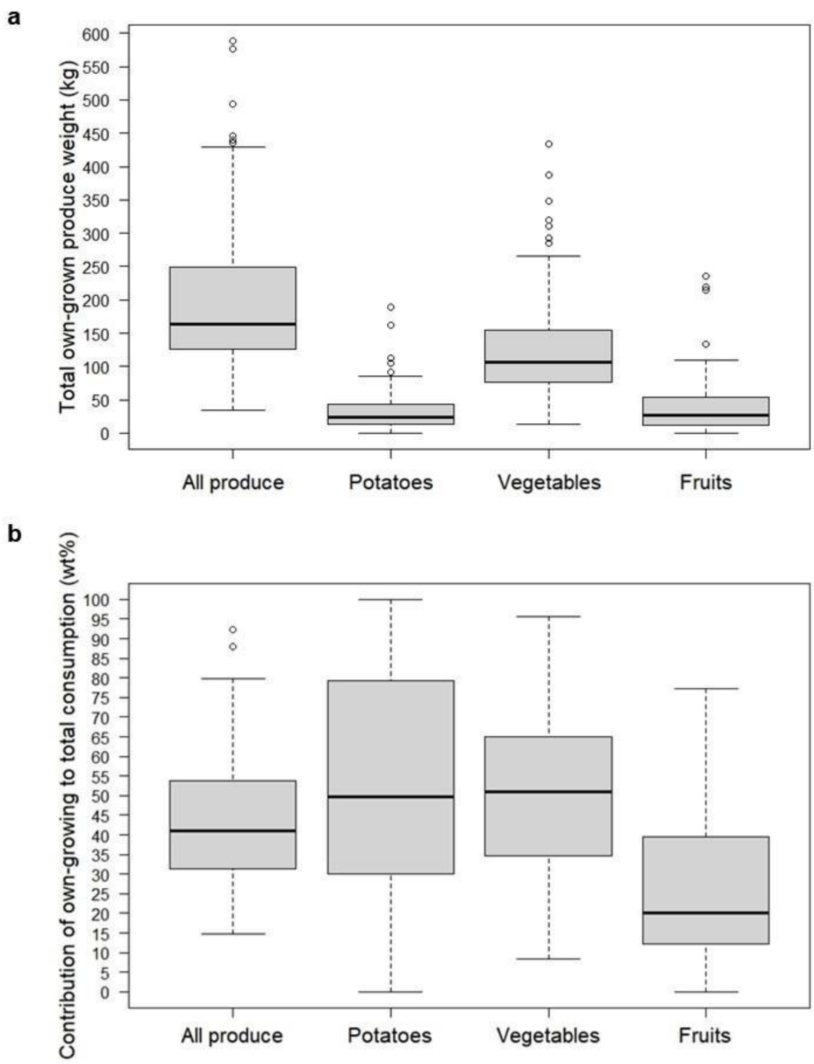

Figure 2 Total weights (kg) of different types of produce grown by participants (N=85) over the course of a year (**a**) and annual household self-sufficiency (percent by weight of total annual household consumption) (**b**) in all produce, potatoes, vegetables and fruits. Boxes represent 25th, 50th and 75th percentiles, circles represent outliers.

Own-grown food production varied across the year (Figure 3a). Median weights of own-grown produce were lowest in February (1.2 kg), increasing gradually to their highest level in August (54.2 kg). Harvest weights from December to May were generally low (i.e. median < 3.8 kg) and much less variable among participants than during the more productive months of the year. Weights of purchased produce varied relatively little across the year, but showed a slight decrease from May to September, then an increase through the winter (Figure 3b). Median weights of monthly produce waste were 0 kg during most of the year, except from July to October, when it increased slightly to up to

0.2 g per month (Figure 3c). Median monthly produce self-sufficiency ranged from 4.8% in February to 77.2% in August, with levels over 50% from July to September (Figure 3d).

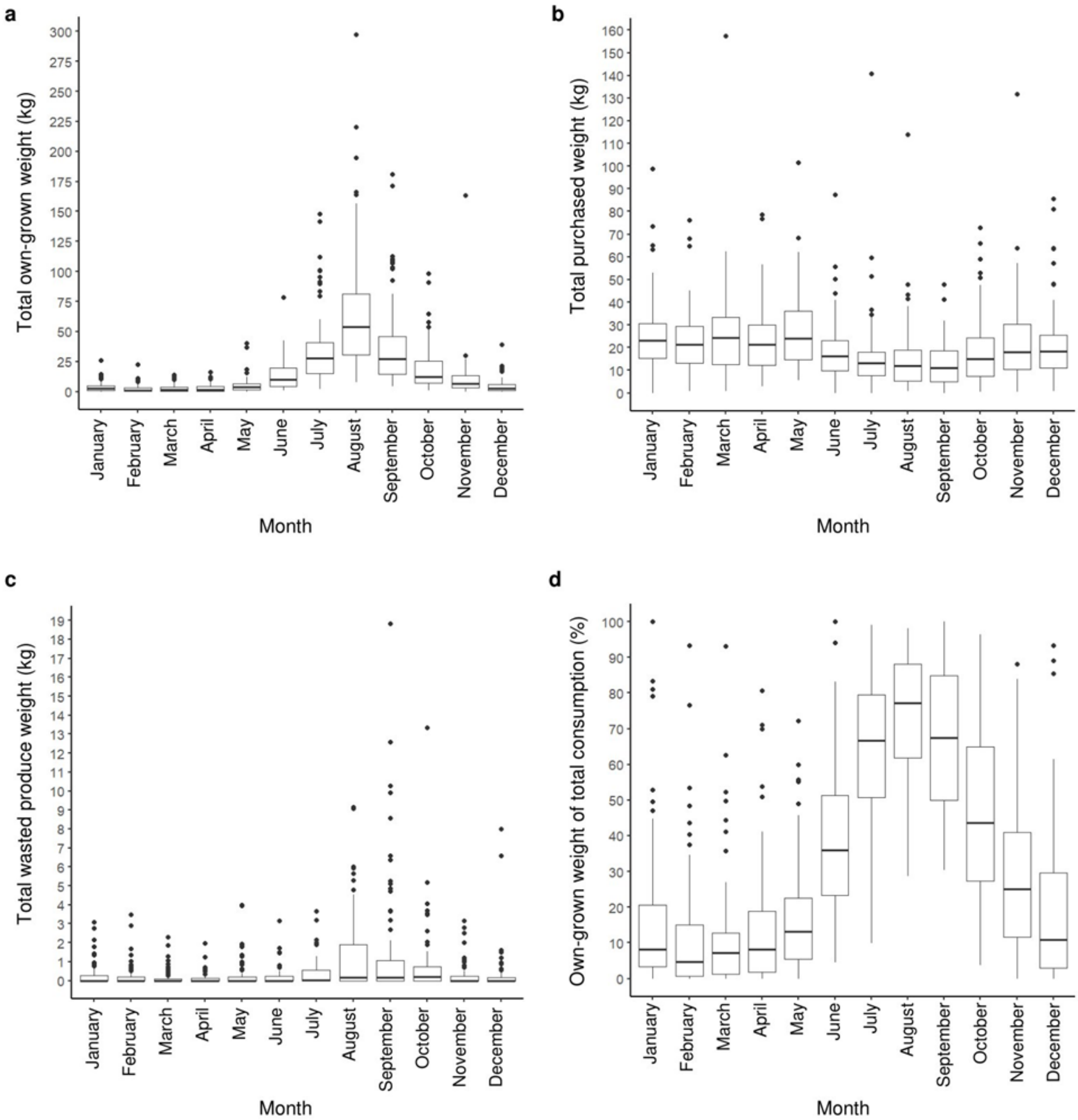

Figure 3 Total weights of (**a**) own-grown, (**b**) purchased, and (**c**) wasted produce, and (**d**) percentage by weight of own-grown produce of total monthly household produce consumption across participant households (N=85) in each month of the year. Boxes represent 25th, 50th and 75th percentiles, dots represent outliers (see Supporting Information Tables S6 to S9 for corresponding data).

3.4. Fruit and vegetable consumption

Median per capita F&V intake in participant households was 507.3 g per day, the equivalent of 6.3 eighty-gram portions (Figure 4 and Supporting Table S4). Replacing imputed values of crop weight with 0 g had a very small effect on these results (see Supporting Table S5). Median per capita fruit and vegetable intakes were 2.3 and 3.9 portions, respectively. The mean number of F&V crop types consumed in households over a year was 69.6 ±2.0 (S.E.), ranging from 32 to 118. Participants typically consumed more than twice as many types of vegetables as fruits (48.4 ±1.4 (S.E.) vs 21.9 ±0.8 (S.E.) respectively (dependent t-test $t(84) = 22.37$, $p<0.001$).

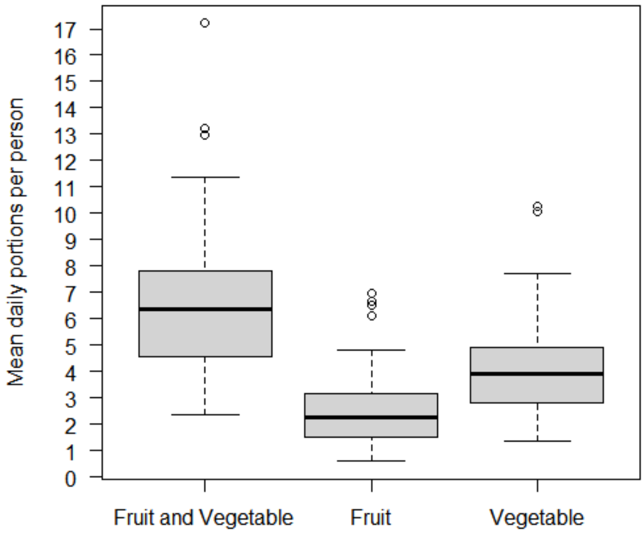

Figure 4 Mean per capita daily fruit and vegetable intakes (number of 80 g portions) in participant households (N=85). Boxes represent 25th, 50th and 75th percentiles, circles represent outliers.

3.5. Predictors of own food productivity

The best fit linear model for annual household crop production (kg yr^{-1}) in the study population included food growing area, frequency of allotment visits, grower experience and household size (Table 1). On average, annual harvest weight increased by 27.2 kg ±6.9 for each additional weekly allotment visit, by 2.6 kg ±0.7 for each additional year of grower experience, and by 0.4 kg ±0.1 for each one m^2 increase in food growing area. The effect of household size was not significant ($p=0.088$). The best fit model for annual produce yield (kg m^2 yr^{-1}) included food growing area, grower experience, household size, mean weekly number of food gardening hours and mean number of weekly allotment visits (Table 2). Produce yield increased by 0.33 kg m^2 yr^{-1} ±0.16 for each additional person in the household, and by 0.02 kg m^{-2} yr^{-1} ±0.01 with each year of grower experience and decreased by 0.005 kg m^{-2} yr^{-1} ±0.001 with each m^2 total cultivated area. The frequency of allotment visits and amount of time spent gardening did not have significant effects (p=0.098 and p=0.170, respectively).

Table 1 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household food crop production (kg yr^{-1})

Predictors	**B (SE)**	***p***
Constant	-61.18 (55.43)	0.274
Total food growing area (m^2)	**0.39** (0.13)	<0.01
Mean allotment visits per week	**27.15** (6.92)	<0.001
Grower experience (years)	**2.59** (0.68)	<0.001
Household size (persons)	31.88 (18.39)	0.088

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). Predictors in the initial full model also included yearly allotment rent and mean weekly number of hours spent food gardening, but these were dropped in the process of improving model fit. Figures in bold are statistically significant at the 5% level (p<0.05). Model R^2 = 0.39, $F_{(4, 60)}$ = 9.6, p<0.0001.

Table 2 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household produce yields (kg m^{-2} yr^{-1})

Predictors	**B (SE)**	***p***
Constant	0.47 (0.49)	0.345
Total food growing area (m^2)	**-0.005** (0.001)	<0.0001
Mean weekly food gardening hours	0.09 (0.05)	0.098
Mean allotment visits per week	0.14 (0.10)	0.155
Grower experience (years)	**0.02** (0.01)	<0.01
Household size (persons)	**0.33** (0.16)	<0.05

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). All predictors included in the initial full model were retained. Figures in bold are statistically significant at the 5% level (p<0.05). Model R^2 = 0.49, $F_{(5, 58)}$ = 11.0, p<0.0001.

Year-round household produce self-sufficiency was best described by a model containing food growing area, grower experience, frequency of allotment visits and household size (Table 3). On average, household produce self-sufficiency increased by 3.6% ±1.1 with each additional weekly allotment visit and by 0.05% ±0.02 with each m^2 total cultivated area. The effects of grower experience and household size were not significant (p=0.058 and p=0.063, respectively). Potato self-sufficiency increased by 0.5% ±0.2 for each additional m^2 total food growing area, by 6.1% ±1.8 with each additional weekly allotment visit, and by 0.2% ±0.1 for each £1 increase in yearly allotment rent, and decreased by 10.8% ±4.6 for each additional person in the household (Table 4). Vegetable self-sufficiency increased by 4.7% ±1.3 with each additional weekly allotment visit, and by 0.05 ±0.02 for each additional m^2 total growing area (Table 5). The model for fruit self-sufficiency included total food growing area and household size, which had a small positive (0.0015% ±0.0007 for each m^2 total growing area) and negative (-0.33% ±0.13 for each additional person in the household) effect, respectively (Table 6).

Table 3 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household produce self-sufficiency (percent by weight of total annual household consumption)

Predictors	**B (SE)**	***p***
Constant	**34.46** (8.55)	<0.001
Total food growing area (m^2)	**0.05** (0.02)	<0.05
Mean allotment visits per week	**3.55** (1.07)	<0.01
Grower experience (years)	0.20 (0.10)	0.058
Household size (persons)	-5.38 (2.84)	0.063

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). Predictors in the initial full model also included yearly allotment rent and mean weekly number of hours spent food gardening, but these were dropped in the process of improving model fit. Figures in bold are statistically significant at the 5% level (p<0.05). Model R^2 = 0.30, $F_{(4, 60)}$ = 6.4, p<0.001.

Table 4 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household potato self-sufficiency (percent by weight of total annual household consumption)

Predictors	**B (SE)**	***p***
Constant	**36.91** (13.07)	<0.01
Yearly allotment rent (£)	**0.24** (0.09)	<0.05
Mean allotment visits per week	**6.12** (1.75)	<0.001
Grower experience (years)	0.48 (0.17)	<0.01
Household size (persons)	-10.80 (4.62)	<0.05

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). Predictors in the initial full model also included total food growing area and mean weekly number of hours spent food gardening, but these were dropped in the process of improving model fit. Figures in bold are statistically significant at the 5% level (p<0.05). Model R^2 = 0.33, $F_{(4, 64)}$ = 7.8, p<0.0001.

Table 5 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household vegetable self-sufficiency (percent by weight of total annual household consumption)

Predictors	**B (SE)**	***p***
Constant	**32.04** (5.99)	<0.0001
Total food growing area (m^2)	**0.05** (0.02)	<0.05
Mean allotment visits per week	**4.70** (1.28)	<0.001

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). Predictors in the initial full model also included yearly allotment rent, household size, grower experience and mean weekly number of hours spent food gardening, but these were dropped in the process of improving model fit. Figures in bold are statistically significant at the 5% level ($p<0.05$). Model R^2 =0 .21, $F_{(2, 62)} = 8.2$, $p<0.001$.

Table 6 Results of multiple regression analysis of the effect of characteristics of food growing practice on annual household fruit self-sufficiency (percent by weight of total annual household consumption)

Predictors	**B (SE)**	***p***
Constant	**3.51** (0.31)	<0.0001
Total food growing area (m^2)	**0.0015** (0.0007)	<0.05
Household size (persons)	**-0.33** (0.13)	<0.05

Note. Predictors and regression coefficients in the table are derived from our best fit model for the outcome based on the Akaike Information Criterion (AIC). Predictors in the initial full model also included yearly allotment rent, grower experience, frequency of allotment visits and mean weekly number of hours spent food gardening, but these were dropped in the process of improving model fit. Figures in bold are statistically significant at the 5% level ($p<0.05$). Model R^2 = 0.16, $F_{(2, 71)} = 6.7$, $p<0.05$.

4. Discussion

Developing the ability of the food system to provide sufficient amounts of healthy food for all and to withstand socio-economic and environmental shocks and pressures from continued rapid urbanisation and climate change is a key priority in the UK (Defra, 2022; Dimbleby, 2021) and globally (*Food Security*, 2022). Here, we report the first long-term study of F&V production and consumption of UK food-grower households over the course of an entire year and demonstrate that promoting household food production could play an essential role in increasing household and national F&V self-sufficiency and improving diet quality as well as reducing waste.

Participants in our study had high levels of year-round self-sufficiency in F&V and potatoes and their perceived levels of self-sufficiency were strongly correlated with levels estimated from their consumption records, which also adds credibility to anecdotal reports of high levels of self-sufficiency in the gardening community (*Allotment Gardening - Grow Your Own*, 2014; Robinson, 2022). Regular freezing and preserving of produce observed among participants could play an important role in this. The relatively higher production of vegetables by participants compared to fruits suggests that household food production may be more effective at providing vegetables. This is in line with recommendations to prioritise increasing vegetable consumption, which may provide a greater health benefit than increasing fruit consumption (EAT, 2019; The Food Foundation, 2021). In addition, food-grower households in our study produced a median of 3.4 kg F&V (including potatoes) waste over a year—since average avoidable household F&V waste in the UK is estimated to be around 68 kg per year (WRAP, 2021), this suggests that household food production may be associated with waste-reducing behaviours. Indeed, giving away, preserving, and freezing excess produce were common practices among participants.

Annual household crop production was positively associated with cultivated area, frequency of allotment visits and grower experience, which suggests that increasing the amount of growing space available and promoting active engagement and skill development are important for maximising the potential of household food production. Crop yields per unit area were also positively associated with household size, which could indicate that larger households were more motivated to make better use of their space, or that sharing tasks among more people improved gardening efficiency.

The list of most frequently grown crops in our study was similar to that found in a case study of allotments in Leicester, likely reflecting general cultural and environmental factors in the country. However, median annual produce yield in our study (1.4 kg m^{-2} yr^{-1}) was lower than mean yield in the Leicester study (2.3 kg m^{-2} yr^{-1}), probably due to differences in management and local environmental conditions. Unlike in the Leicester study, our data came from both allotment holders and home gardeners in various parts of the country, with various levels of engagement with food production. In addition, soil and climatic conditions are known to affect plant growth (McMahon et al., 2011), and our analyses indicate that yields are also influenced by grower experience, cultivated area, and household size, which could explain the difference between the two studies.

Average F&V intake in food-grower households (6.3 portions per person per day) was over 70% higher than the national average (3.7 portions) (PHE, 2019), and included a large variety of F&V. Although we did not collect information on socio-demographic factors that could also affect F&V consumption to be able to directly link observed high F&V intakes to involvement in own production, our results suggest that one mechanism to increase F&V consumption in the UK may be to increase engagement with household level F&V production. Exploring mechanisms to increase F&V consumption, particularly in households with low consumption, is critical, as consuming at least 5 portions of F&V daily is associated with significantly decreased likelihoods of developing obesity, heart disease, type 2 diabetes and certain types of cancer (WHO, 2003), so promoting F&V consumption via improved household availability could have important positive implications for public health. Household F&V production could also help increase dietary intakes of iron, magnesium, potassium, folate, and beta-carotene to prevent and reverse deficiencies (PHE, 2019), as these micronutrients can be found in relatively large amounts in many popular crops grown in our study, including green vegetables, beans and tomatoes (Roe et al., 2013). In addition, home-grown potatoes could provide an important source of carbohydrates, essential amino acids, vitamins B6 and C, potassium, and antioxidants (Burgos et al., 2020), further contributing to household nutritional security.

On a national scale, wide adoption of household food production could considerably reduce reliance on foreign F&V imports. If 2.8 million households, representing about 10% of the UK's population (assuming an average household size of 2.4 (ONS, 2021)), who do not currently grow food started growing on average 163.6 kg produce (including potatoes) annually, the median amount found in our study, their total production would amount to roughly 460 thousand tonnes per year. This would be the equivalent of 5.5% of the total national F&V supply and 8.7% of imports in 2021 (by weight) (Defra, 2020). As a comparison, the level of domestic F&V self-sufficiency (including potatoes) provided by household production following the Dig for Victory campaign was 18% (by value) (Defra, 2017). However, increasing household food production will require greater availability of growing space. Research has demonstrated that there is considerable land suitable for food production in urban areas, where the majority of the population lives (Edmondson et al., 2020b), but only a small proportion of this is currently dedicated to horticulture. Moreover, national provision of allotments has been declining steadily over the decades, and there are important socio-economic inequalities in access to land that put the most deprived neighbourhoods, which could benefit most from better availability of nutritious fresh produce, at a disadvantage (Dobson et al., 2020).

Household food production could contribute to multiple Sustainable Development Goals (SDGs) (Nicholls et al., 2020) and play an important part in increasing the resilience of the UK food system while improving diets and related health outcomes, which could particularly benefit those with limited physical or financial access to F&V (PHE, 2019). Building capacity among the public to produce their own F&V will require increased provision of growing space, as well as promoting access to the skills needed to grow, prepare, cook, and preserve produce to maximise nutritional and self-sufficiency benefits (Lavelle et al., 2020). Crucially, we need to find ways to overcome socio-economic challenges to upscaling household F&V production, especially among those most affected by low F&V intakes, such as low-income families and children (NHS Digital, 2019).

Here, our diary-based approach provides the first long-term evidence of the role household F&V production could play in increasing household F&V self-sufficiency, promoting F&V consumption and potentially reducing food waste. Thus, our study is an important addition to existing literature that provides an evidence base to support policy-decision to expand household level F&V production.

5. Conclusion

Household food production could play an important part in increasing the resilience of the UK food system while at the same time improving diets and related health outcomes, which could particularly benefit those with limited physical or financial access to F&V (PHE, 2019a). Building capacity among the public to produce their own F&V will require increased provision of growing space, as well as promoting access to the skills needed to grow, prepare, cook and preserve produce to maximise dietary and self-sufficiency benefits (Lavelle et al., 2020). Finally, as F&V consumption is known to vary with socio-economic factors (NHS Digital, 2019b), more research is needed on how household F&V production and consumption could be effectively promoted in different settings, especially among low-income families and children.

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Chapter 5

Quantifying the relationship between gardening and health and well-being in the UK: a survey during the covid-19 pandemic

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Abstract

Rates of non-communicable diseases, including cardiovascular disease and type 2 diabetes, and mental health problems, such as anxiety and depression, are high and rising in the urbanising world. Gardening could improve both mental and physical health and help prevent a range of conditions by increasing fruit and vegetable (F&V) consumption, promoting physical activity, and reducing stress. However, good quality quantitative research in the area is scarce, and our understanding of the role of allotments and home gardens, and the effects of the level of engagement in gardening and involvement with food production has thus far been limited. Here, we quantitatively assess the relationship between home and allotment gardening and various indicators and predictors of health and well-being using an online survey of gardeners (n=203) and non-gardeners (n=71) in the UK. After accounting for socio-demographic factors, certain gardening related variables were associated with better self-rated health, higher mental well-being, increased F&V consumption and spending considerable amounts of time outdoors. Higher F&V intake was also associated with better self-rated health and decreased odds of obesity. Our results suggest that multiple mechanisms are involved in delivering different benefits. Improving access to growing space and promoting regular gardening could provide a range of benefits to public health. More research on how socio-economic factors influence the health and well-being benefits of gardening will help policy-makers devise strategies to maximise these benefits.

1. Introduction

Health and well-being are key determinants of both individuals' quality of life and of social and economic development (eurostat, 2021; WHO, 1998). A growing number of people are affected by non-communicable diseases (NCDs), including diabetes, heart disease, stroke and cancer, which are the leading cause of death globally (Forouzanfar et al., 2015; WHO, 2003) and in the UK (Steel et al., 2018). However, while various genetic, socio-demographic and environmental factors increase the risk of developing NCDs, the recent rise in their incidence can be largely attributed to modifiable lifestyle factors, which makes most NCDs preventable (WHO, 2022). Smoking, unhealthy diets, including low fruit and vegetable (F&V) intake (Wang et al., 2021; Wang et al., 2014) and high processed food (Chen et al., 2020; Pagliai et al., 2021) and meat (Battaglia Richi et al., 2015; Papier et al., 2021) consumption, physical inactivity (Lee et al., 2012; Park et al., 2020) and associated hypertension and obesity (Ells et al., 2006; WHO, 2021a) are among the main preventable causes of NCDs. In the UK, nearly two thirds of the adult population are overweight or have obesity (NHS Digital, 2020), and food-related ill health is estimated to cost the National Health Service £6 billion each year (Rayner & Scarborough, 2005). One of the main preventable causes of NCDs in the UK is low F&V consumption—over two thirds of the population do not meet the recommended '5-a-day', which contributes to around 18,000 premature deaths annually (Afshin et al., 2019). In addition, over a third of adults are not active enough for good health, which is associated with 1 in 6 deaths and an annual healthcare cost of £1.2 billion, and rates of insufficient physical activity are growing (British Heart Foundation, 2017; OHID, 2015). Disruptions caused by the recent covid-19 pandemic had further negative impacts on the eating habits and physical activity levels of many people (Theobald & White, 2021).

As well as physical health, poor mental well-being is a major factor reducing quality of life, in the UK and worldwide (Vigo et al., 2016; Vos et al., 2015). Based on a 2007 survey, 1 in 4 people in England experienced a mental health problem, such as depression or anxiety, each year (NHS Digital, 2009), and mental illness is the second-largest source of burden of disease in the country (PHE, 2019b). To exacerbate the problem, the wide-ranging impacts of the covid-19 pandemic brought about a nationwide decline in mental health and a widening of pre-existing inequalities (Abolarin et al., 2020; Helliwell et al., 2021; Pierce et al., 2020). Similar trends could be observed in other parts of the world (Haider et al., 2021; Young et al., 2022). Often devastating on their own, mental health problems also increase the likelihood of unhealthy behaviours and preventable physical health conditions (Naylor et al., 2012; Ohrnberger et al., 2017; Pikkemaat et al., 2022). On the other hand, having poor physical health increases the risk of mental health issues, creating a vicious cycle (Diener & Chan, 2011). But the connection between mental health status and modifiable environmental and behavioural factors also creates opportunities for improvement (Sapranaviciute-Zabazlajeva et al., 2022; Zaman et al., 2019).

Lifestyle changes, including increasing physical activity, improving diet quality, and engaging in activities that reduce stress and provide a sense of well-being, can have positive effects on both mental and physical health. As a form of outdoor exercise and an opportunity to relax and connect with nature, ourselves and others, gardening has been used as a therapeutic tool in different settings (Hefley, 1973; Tereshkovich, 1973), such as care homes and hospitals, and its potential benefits for health and well-being have been increasingly studied in recent decades. Spending time outdoors, especially in natural environments, has been linked to psychological benefits (Gascon et al., 2018; Hartig et al., 2014; Kühn et al., 2021; Pearson & Craig, 2014), and research suggests that gardening is associated with better mental well-being (Alaimo et al., 2016; Chalmin-Pui et al., 2021b; Genter et al., 2015; Hawkins et al., 2011; Machida, 2019; Soga et al., 2017a; Soga et al., 2017b; Wang & MacMillan, 2013; Wood et al., 2016), increased physical activity (Machida, 2019; van den Berg et al., 2010), higher F&V intake (Alaimo et al., 2008; Barnidge et al., 2013; Demark-Wahnefried et al., 2018; Kunpeuk et al., 2020; Litt et al., 2011; Nova et al., 2020; Sarti et al., 2017; Sommerfeld et al., 2010), decreased odds of developing overweight and obesity (Davis et al., 2011; Demark-Wahnefried et al., 2018; Duncan et al., 2015; Kunpeuk et al., 2020; Zick et al., 2013), and improved strength and flexibility in older adults (Wang & MacMillan, 2013). Thus, gardening, particularly F&V growing, may offer a way to simultaneously promote health and well-being through a range of pathways.

However, recent systematic reviews have found that good quality quantitative research on the health and well-being benefits of gardening that use validated tools are still relatively scarce, especially in non-institutionalised settings, and most of these have focused on community gardens in the USA (Audate et al., 2019; Garcia et al., 2018;

Genter et al., 2015; Kunpeuk et al., 2020; Machida & Kushida, 2020; Tharrey & Darmon, 2021). Much less is known about the health-promoting potential of F&V gardening in domestic gardens and allotments, typical sites of gardening in Europe, and how this may be modulated by the level of engagement. A key challenge in studying this is that health and well-being are multifaceted concepts that are not straightforward to assess, and are influenced by a multitude of interrelated socio-economic, environmental, lifestyle and genetic factors (Braveman & Gottlieb, 2014; Buck et al., 2018). For example, income, neighbourhood deprivation and educational attainment, as well as age, gender and ethnicity, are correlated with many health outcomes, including the incidence of different diseases, various measures of physical and mental well-being, and certain risk factors to health, such as smoking, alcohol consumption, diet quality, physical activity level and body mass index (BMI) (WHO, 2022). Therefore, to meaningfully assess the health-promoting effects of gardening, potential confounders must also be considered.

Gardening on allotments (plots of land rented out to individuals for growing fruits and vegetables) and in domestic gardens is a popular recreational activity in the UK that has enjoyed increasing interest in the past 20 years, which grew further during the lockdowns that followed the outbreak of the covid-19 pandemic, motivated by a need to spend time in isolation meaningfully as well as concerns over food shortages (apse, 2022; Lin et al., 2021; Mind, 2022; Statista Research Department, 2022). Qualitative studies have found that home gardens and allotments can hold important emotional, psychological, and spiritual values for people (Dobson et al., 2020b; Dunnett & Qasim, 2000), which may have been a key factor contributing to their rising popularity during a time of great distress and uncertainty. One quantitative study also found that older allotment gardeners in the UK had lower perceived stress levels than similar age participants of indoor exercise classes (Hawkins et al., 2011), suggesting a potential role of allotments in improving well-being. Similarly, a pre-pandemic analysis of a representative survey of the English population revealed an association between access to a private garden and better evaluative well-being (de Bell et al., 2020), while another, more recent, study has found that frequent home gardeners had higher mental well-being and lower stress scores and were more physically active than occasional or never-gardeners (Chalmin-Pui, Griffiths, et al., 2021). Furthermore, research has demonstrated that F&V consumption in UK food-grower households is 70% higher compared to the national average (Gulyas & Edmondson, in review). Although these findings are promising, there is still much we do not know about the contribution of gardening to better health and well-being in the country. In particular, the amount of time spent gardening required to bring about certain benefits, the role of the level of engagement with food production, and potential differences between the benefits of home- and allotment gardening are little understood.

The aim of this research was to quantitatively assess the relationship between gardening and health and well-being in the UK to increase our understanding of the ways in which it can exert its beneficial effects. Specifically, we looked at whether different gardening related variables, namely the amount of time spent gardening in a typical week, self-reported amount of food produced, and having an allotment, were associated with better self-rated general health, higher mental well-being, fewer physical health complaints, or certain predictors of health and well-being, namely obesity, diet quality (in particular, F&V intake and meat avoidance), physical activity level, and the amount of time spent outdoors. Better understanding the associations between these variables will help identify the mechanisms by which gardening could improve different aspects of health and well-being, and provide a foundation for efforts aimed at improving public health and well-being.

2. Methods

2.1. Participants

Data was collected from adults living in the UK, including both regular gardeners and non-gardeners. Participants were recruited by means of social media (i.e. Facebook, Twitter and email newsletter) and word of mouth in the gardening and food-growing community via the network of the ongoing MYHarvest citizen science project (myharvest.org.uk) (Edmondson et al., 2019), in collaboration with the National Allotment Society and the Royal Horticultural Society, and via email through the University of Sheffield's staff and student volunteer lists. The project was granted ethical approval by the Department of Animal and Plant Sciences of The University of Sheffield (project ref. 041219).

2.2. Materials

We used an online survey composed of validated questionnaires and self-defined questions administered to participants via the Qualtrics platform. Data collection ran between 29th July and 30th November 2020. The survey collected data on various aspects of participants' health and well-being, their involvement with gardening, and relevant demographic and lifestyle factors.

2.2.1. Health and well-being measures

General health

General health was assessed with the widely used Self-Rated Health (SRH) question ('*In general, how would you rate your health in the past year? Excellent / Very good / Good / Fair / Poor*') (DeSalvo et al., 2006). The SRH was chosen as a simple yet valid and efficient measure of physical and mental health and predictor of mortality (Baćak & Ólafsdóttir, 2017; Bopp et al., 2012).

Physical health

The Physical Health Questionnaire (PHQ) by Schat & Kelloway 2005 (Schat et al., 2005) (a modified version of Spence *et al.*'s (1987) measure of health) was used as a measure of physical well-being based on the frequency of somatic symptoms experienced by participants, including sleep disturbances, headaches, respiratory illness, and gastrointestinal problems, during the previous month. The PHQ consists of 14 items measured on a seven-point Likert scale. PHQ scores were calculated by totalling responses across all items (with item four reverse scored). Total scores can range from 14 to 98, with higher scores reflecting more frequent physical complaints thus indicating poorer health.

Mental well-being

Mental well-being was measured using the Warwick-Edinburgh Mental Well-being Scale (WEMWBS) (Tennant et al., 2007), a widely used tool developed for the measurement of mental well-being in the general population and the evaluation of projects and policies aimed at improving mental well-being. The WEMWBS focuses on feelings and functioning aspects of positive mental well-being in the past two weeks, and consists of

14 positively scored items measured on a 5-point Likert scale. WEMWBS scores were calculated by adding up points for all 14 items, with total scores thus ranging from 14 to 70. Scores less than 43 are considered to indicate *low*, 43 to 60 *moderate*, and above 60 *high* levels of mental well-being.

Body Mass Index (BMI)

Body Mass Index (BMI) was calculated from reported height and weight of participants using the formula *weight(kg)/height(m)*^{2}, and BMI categories were assigned based on these values (BMI <18.5 – *underweight*, 18.5 to 24.9 – *healthy weight*, 25 to 29.9 – *overweight*, 30 to 39.9 – *with obesity*) (Garrow & Webster, 1985). Having obesity was considered as an indicator of increased health risk.

Diet quality

Diet quality was intended to be measured using the Short Form Food Frequency Questionnaire (SFFFQ) by Cleghorn *et al.* (2016), which assesses fruit, vegetable, fat, oily fish and non-milk extrinsic sugar consumption during a typical week over the previous month and allows the calculation of a Diet Quality Score (DQS) and subsequent classification of individuals into groups with overall *healthy, average* or *unhealthy* dietary habits. However, due to an error in uploading the survey to the online platform that resulted in the omission of one of the questions required for DQS calculation, typical fruit and vegetable (F&V) intake, which is an important predictor of general well-being and the risk of various diseases (Wang et al., 2021) and has been demonstrated to be predictive of overall diet quality (Cleghorn et al., 2016), was used as an indicator of diet quality. We assessed F&V intake both as a numeric outcome (portions per day; 1 portion = approx. 80 g) with higher intakes indicating better diet quality, and as a categorical variable (with three levels *less than 3 portions per day, 3 or 4 portions per day,* and *5 or more portions per day*) with meeting the ‘5-a-day’ target indicating sufficient F&V consumption (WHO, 2003). We also asked if participants followed any meat-avoiding diet, and if so, what type (i.e. vegan, vegetarian, pescatarian or flexitarian), as reduced meat consumption has also been linked to better well-being and lower risk of certain diseases in higher income countries (Battaglia Richi et al., 2015; Papier et al., 2021). Data was also collected on typical alcohol consumption (units per typical week), with more than 14 units per week considered to pose increasing risk to health (DHSC et al., 2021).

Physical activity

Physical activity level was measured using the International Physical Activity Questionnaire (IPAQ) short format (Craig et al., 2003), which forms a part of the SFFFQ. Physical activity levels (*low, moderate,* or *high*) were assigned to participants based on the frequency, intensity and amount of exercise they had done in the previous week. For this, an estimate of their typical energy expenditure, as MET (Metabolic Equivalent of Task) Minutes per week, was calculated from self-reported amounts of exercise of different intensity. Total MET Minutes per week were calculated as the sum of MET Minutes for each exercise type (i.e. *light, moderate* or *vigorous*) undertaken by the participant in the previous week, obtained using the formula: *duration(mins) x frequency(days per week) x MET value (light exercise = 3.3, moderate exercise = 4, vigorous exercise = 8)*. Physical activity levels were assigned as follows: *high* if a) vigorous activity on at least 3 days and achieving a total physical activity of at least 1500 MET Minutes per week OR b) 7 or more days of any combination of light, moderate or vigorous activities achieving a total physical activity of at least 3000 MET Minutes per week; *moderate* if a) 3 or more days of vigorous activity of at least 20 minutes per day OR b) 5 or more days of moderate activity and/or light activity of at least 30 minutes per day OR c) 5 or more days of any combination of light, moderate or vigorous activities achieving a total physical activity of at least 600 MET Minutes per week; *low* if not moderate or high. We used low physical activity level as an indicator of increased risk to physical (Lee et al., 2012; Park et al., 2020) and mental health (Young et al., 2022).

Outdoor time

We used the amount of time participants spent outdoors (focusing on the odds of spending at least 14 hours outdoors in a typical week) as a potential contributor to well-being (Harada et al., 2017; Kondo et al., 2018).

Perceived effects of the pandemic

Participants were asked what kind of effect they felt the covid-19 pandemic had on their physical health, mental health, access to healthy food, and diet quality (individual questions with options *very negative, somewhat negative, neutral, somewhat positive* and *very positive*).

2.2.2. Gardening related variables

Information about participants' gardening habits used as independent variables included the number of hours spent gardening in a typical week (collected as a numerical, but for our analyses we used the categories 1–5 hours, 6–10 hours, 11 hours or more, and 0 hours for those who did not regularly garden), how much food they produced (on a self-rated scale of five, with 1 referring to a very small amount, 5 indicating virtual self-sufficiency in F&V, and 0 assigned to those who did not grow food), and whether they had an allotment.

2.2.3. Demographic information

Socio-demographic information collected in the survey include gender, age, highest level of education, household income, household composition, caring responsibilities, Index of Multiple Deprivation (IMD) quintile (derived from participants' postcodes), whether the participant had any long-term health conditions (assessed with a single *yes/no* type question), BMI (from reported height and weight, focusing on obesity as a risk factor), smoking (current and ex-smokers considered to be at increased risk, those who never smoked more than 100 cigarettes at low risk).

2.3. Analyses

A series of hierarchical regression models were used to test the effects of gardening related variables on our chosen health and well-being measures adjusting for relevant socio-demographic factors, which were selected based on previous research and inspection of our data. Control variables used in the study include gender, age, highest level of education, household income, household composition, caring responsibilities, IMD quintile, whether the participant had any long-term health conditions (*yes/no*), BMI (focusing on obesity as a risk factor), smoking (current and ex-smokers considered to be at increased risk, those who never smoked more than 100 cigarettes at low risk), alcohol consumption (more than 14 units per typical week considered increasing risk drinking), F&V intake (*less than 3 portions per day, 3 or 4 portions per day,* and *5 or more portions per day*), whether any meat-avoiding diet was followed and if so what type (vegan, vegetarian, pescatarian or flexitarian), and physical activity level (IPAQ category). Due to limitations imposed by sample size and the specific characteristics of the study population, the number of levels of certain factors (e.g. age, education level) were reduced. Weekly gardening time and level of food production were treated as categorical rather than numeric variables to allow comparisons with non-gardeners (who were assigned a value of zero for these variables) without violating model assumptions.

To test the effects of gardening related variables on continuous health and well-being outcomes (i.e. WEMWBs score, PHQ score, F&V intake), multiple linear regression models were used. For categorical outcomes (i.e. SRH, WEMWBS level, obesity, IPAQ level, 5-a-day F&V consumption, weekly outdoor time, health-related effects of the pandemic), multiple binary logistic regression models were used. To control for the potential confounding effects of socio-demographic and lifestyle factors, analyses were carried out in a hierarchical way. In the first step of each regression, a model adjusted for gender and age was fitted (Model 1). In step two, other key socio-demographic predictors were added to Model 1 and their significance in predicting the outcome was assessed. If any of these predictors had an associated p value of 0.1 or above, a new model was fitted with the predictor with the highest p value removed, the fit of the two models were compared using their Bayesian Information Criteria (BIC), and the model with the lower BIC was selected. If this model still contained predictors with effects with $p \geq 0.1$, the process was repeated until further removal of predictors did not lead to an improvement in model fit (Model 2). In the third step of the regression, key risk factors to health were added to Model 2 and the above-described method was used to find the best fit model (Model 3). In the final step, variables related to gardening were introduced to Model 3 and the most parsimonious model was identified based on BIC (Model 4). Regression parameters (R^2, B coefficients, standard error (SE), p values and, for logistic regression, χ^2, odds ratios (OR) and 95% confidence intervals (CI)) were reported for the best fit models. We assessed parametric assumptions of no multicollinearity (based on Generalised Variance Inflation Factors (GVIF), using a threshold of 3) and, for linear regression, linearity (using scatter plots and residual diagnostics), and checked for the presence of potential outliers (based on standardised residual distribution) and influential cases (based on Cook's distance and leverage plots) in each regression. To assess their generalisability, normality of standardised residual distribution and homogeneity of residual variance were also evaluated for linear regression models. Analyses were carried out in R (version 4.0.3).

3. Results

3.1. Participants

The study population (N=280) comprised almost entirely (97.5%) white, predominantly female (74.6%) adults (Supplementary Table S1). Nearly three quarters (72.5%) of respondents identified as regular gardeners, representing a similar proportion of both genders. Nearly half of all respondents were aged 55 or over, around 30% between 35 and 54, and 20% under 35 years old. Gardening was most common among people over 55, around 60% of whom were regular gardeners. The majority of respondents (78.2%) had received higher education. Participants were living in neighbourhoods representing all five English IMD quintiles but were predominantly from quintiles 3 to 5. The distribution of participants across IMD quintiles and household income categories was fairly similar among gardeners and non-gardeners. All of those who regularly gardened had a home garden, and around a half of regular gardeners and 36% of all participants had an allotment. Participants spent varying amounts of time gardening and were engaged in different levels of food production (Supplementary Table S2).

3.2. Predictors of health outcomes

3.2.1. Self-rated health (SRH)

According to our best fit logistic regression model, SRH in the study population was positively associated with growing food, and negatively with having obesity or long-term health conditions (Table 1). Participants with obesity were 8 times (OR=7.98, 95%CI=2.49–27.77, $p<0.001$), and those with long-term health conditions over 18 times (OR=18.57, 95%CI=5.52–79.10, $p<0.001$) more likely to have 'not good' health compared to people without obesity and without long-term conditions, respectively. Participants who grew moderate to large amounts of food (i.e. food growing levels 3, 4 and 5) were around 90% less likely (OR=0.14, 95%CI=0.02–0.64, $p<0.05$; OR=0.04, 95%CI=0.00–0.41, $p<0.05$; and OR=0.13, 95%CI=0.01–0.83, $p<0.05$, respectively) to report 'not good' health compared to participants who did not grow food.

Table 1 Odds Ratios (OR) for 'not good health' ('poor' or 'fair') as compared to 'good health' ('good', 'very good' or 'excellent'), adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	-2.04 (0.63)	0.13 (0.03–0.41)	<0.01
Gender (Female)			
Male	-0.46 (0.67)	0.63 (0.16–2.24)	0.49
Age (18-34)			
35-54	0.34 (0.73)	1.40 (0.33–6.00)	0.65
55+	-0.27 (0.83)	0.76 (0.15–3.96)	0.74
Obesity (Without obesity)			
With obesity	2.08 (0.61)	**7.98 (2.49–27.77)**	<0.001
Long-term conditions (No)			
Yes	2.92 (0.67)	**18.57 (5.52–79.10)**	<0.001
Physical activity level (Low)			
Moderate	-1.19 (0.69)	0.30 (0.07–1.08)	0.08
High	-0.70 (0.94)	0.50 (0.06–2.73)	0.46
Food growing level (No food grown)			
1 (very little F&V)	-1.08 (0.91)	0.34 (0.05–1.87)	0.23
2	-1.53 (0.91)	0.22 (0.03–1.17)	0.09
3	-1.99 (0.83)	**0.14 (0.02–0.64)**	<0.05
4	-3.27 (1.37)	**0.04 (0.00–0.41)**	<0.05
5 (nearly self-sufficient in F&V)	-2.07 (1.01)	**0.13 (0.01–0.83)**	<0.05

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, higher education, smoking status, alcohol consumption, F&V intake, time spent gardening, and having allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.39 (Hosmer Lemeshow), 0.30 (Cox and Snell), 0.50 (Nagelkerke); χ^2 (12) = 66.45

[C] Figures in bold are statistically significant at the 5% level (p<0.05)

3.2.2. Mental well-being (WEMWBS)

Mean WEMWBS score in the study population was 49.5±0.5 (S.E.). Mental well-being among survey respondents was positively associated with physical activity level, gardening, and having an allotment, and negatively with neighbourhood deprivation and obesity. On average, those who spent 11 or more hours gardening in a typical week scored 4.57 points ±1.92 (S.E.) higher on the WEMWBS than those who did not regularly garden (Table 2). In addition, participants who had an allotment were 67% less likely (OR=0.33, 95%CI=0.10–0.94, $p<0.05$) to have low mental well-being than those without an allotment, while participants with obesity were 4.5 times more likely (OR=4.46, 95%CI=1.64–12.65, $p<0.01$) to have low mental well-being compared to those without obesity (Table 3). The odds of having high mental well-being were not affected by variables related to gardening, but were positively associated with being male (OR=10.57, 95%CI=2.98–45.32, $p<0.001$) and with having moderate or high, compared to low, physical activity levels (OR=5.33, 95%CI=1.06–31.66, $p<0.05$; and OR=5.55, 95%CI=1.13–32.26, $p<0.05$, respectively) (Supplementary Table S3). Participants' perception of the effect of the covid-19 pandemic on their mental health was negatively associated with having long-term health conditions, and positively with being aged 55 or over and with spending larger amounts of time gardening (Table 4). Those who spent at least 11 hours gardening in a typical week were 78% less likely (OR=0.22, 95%CI=0.07–0.64, $p<0.01$) than non-gardeners to report that the pandemic had a negative effect on their mental health.

Table 2 Hierarchical linear regression analysis of predictors of mental well-being (WEMWBS score) adjusted for demographic and lifestyle factors[a, b, c, d]

Predictor variables (reference)	*Model 1*		*Model 2*		*Model 3*		*Model 4*	
	B (SE)	***p***	**B (SE)**	***p***	**B (SE)**	***p***	**B (SE)**	***p***
Constant	45.50 (1.35)	<0.001	41.08 (2.91)	<0.001	40.87 (3.08)	<0.001	41.52 (3.16)	<0.001
Gender (Female)								
Male	2.51 (1.38)	0.07	2.34 (1.36)	0.09	2.20 (1.35)	0.10	1.66 (1.34)	0.22
Age (18–34)								
35–54	1.79 (1.69)	0.29	1.80 (1.73)	0.30	1.93 (1.81)	0.29	1.09 (1.81)	0.55
55+	**5.96** (1.59)	<0.001	**5.56** (1.77)	<0.01	**5.20** (1.90)	<0.01	3.25 (2.05)	0.11
IMD quintile (First)								
Second			**5.78** (2.76)	<0.05	**6.13** (2.76)	<0.05	**6.14** (2.72)	<0.05
Third			1.14 (2.57)	0.66	1.84 (2.56)	0.47	1.69 (2.52)	0.50
Fourth			2.41 (2.59)	0.35	2.80 (2.57)	0.28	3.27 (2.54)	0.20
Fifth			2.04 (2.55)	0.42	2.09 (2.52)	0.41	2.59 (2.49)	0.30
Household (Alone)								
With partner			**3.91** (1.74)	<0.05	**3.81** (1.70)	<0.05	2.95 (1.71)	0.09
With family			0.55 (2.05)	0.79	0.80 (2.01)	0.69	0.46 (2.00)	0.82
Shared accommodation			4.81 (4.20)	0.25	4.95 (4.20)	0.24	4.37 (4.17)	0.30
Obesity (Without obesity)								
With obesity					-2.98 (1.61)	0.08	-2.45 (1.71)	0.15
Smoking (Non-smoker)								
Current- or ex-smoker					2.26 (1.30)	0.08	2.29 (1.30)	0.08
Daily F&V intake (5+ portions)								
1 or 2 portions					-5.01 (2.57)	0.05	-4.85 (2.55)	0.06
3 or 4 portions					0.29 (1.56)	0.85	-0.50 (1.57)	0.75
Weekly gardening time (0 hours)								
1–5 hours							-0.12 (1.63)	0.94
6–10 hours							-0.28 (1.90)	0.89
11+ hours							**4.57** (1.92)	<0.05
R^2	0.11		0.18		0.23		0.27	
Adjusted R^2	0.09		0.13		0.17		0.20	

[a] Higher WEMWBS scores indicate better mental well-being.
[b] Model 1: adjusted for age and gender; Model 2: adjusted for sociodemographic variables; Model 3: adjusted for sociodemographic variables and health risk and relevant lifestyle factors; Model 4: adjusted for sociodemographic variables, health risk and relevant lifestyle factors and variables related to gardening.
[c] Predictors and coefficients in the table are derived from the best fit models for the outcome based on the Bayesian Information Criterion (BIC) at each stage of the regression. Other explanatory variables tested include household income, having higher education, drinking category, having long-term conditions, physical activity level, food growing, and having an allotment, but these were dropped in the process of improving model fit.
[d] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Table 3 Odds Ratios (OR) for low mental well-being (WEMWBS <43) as compared to moderate mental well-being (WEMWBS 43–59), adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	-0.04 (0.72)	0.96 (0.23–4.03)	0.96
Gender (Female)			
Male	0.22 (0.49)	1.25 (0.47–3.18)	0.65
Age (18–34)			
35–54	-0.19 (0.51)	0.83 (0.30–2.24)	0.70
55+	-1.00 (0.58)	0.37 (0.11–1.12)	0.08
IMD quintile (First)			
Second	-1.51 (0.94)	0.22 (0.03–1.33)	0.11
Third	-0.82 (0.75)	0.44 (0.10–1.98)	0.28
Fourth	-0.48 (0.78)	0.62 (0.13–2.94)	0.54
Fifth	-1.15 (0.77)	0.32 (0.07–1.46)	0.14
Obesity (Without obesity)			
With obesity	1.50 (0.52)	**4.46 (1.63–12.65)**	<0.01
Allotment (No)			
Yes	-1.12 (0.57)	**0.33 (0.10–0.94)**	<0.05

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include household income, household composition, higher education, caring responsibilities, smoking status, alcohol consumption, long-term health conditions, F&V intake, physical activity level, time spent gardening, and growing food, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.16 (Hosmer Lemeshow), 0.15 (Cox and Snell), 0.23 (Nagelkerke); χ^2 (9) = 27.47

[c] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Table 4 Odds Ratios (OR) for negative ('very negative' or 'somewhat negative') as compared to neutral or positive ('neutral', 'somewhat positive' or 'very positive') self-reported effect of the covid-19 pandemic on mental well-being, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-1.22 (0.44)	3.40 (1.50–8.41)	<0.01
Gender (Female)			
Male	-0.48 (0.39)	0.62 (0.28–1.33)	0.23
Age (18–34)			
35–54	-0.75 (0.48)	0.47 (0.18–1.20)	0.12
55+	-1.74 (0.51)	**0.18 (0.06–0.47)**	<0.001
Obesity (Without obesity)			
With obesity	0.77 (0.49)	2.15 (0.84–5.75)	0.11
Long-term conditions (No)			
Yes	0.79 (0.37)	**2.20 (1.09–4.63)**	<0.05
Weekly gardening time (0 hours)			
1–5 hours	-0.53 (0.46)	0.59 (0.24–1.46)	0.25
6–10 hours	-0.92 (0.53)	0.40 (0.14–1.11)	0.08
11+ hours	-1.53 (0.57)	**0.22 (0.07–0.64)**	<0.01

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, higher education, alcohol consumption, smoking status, physical activity level, F&V intake, food growing, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.18 (Hosmer Lemeshow), 0.22 (Cox and Snell), 0.30 (Nagelkerke); χ^2 (8) = 46.94

[C] Figures in bold are statistically significant at the 5% level ($p<0.05$)

3.2.3. Fruit and vegetable (F&V) intake, meat-avoidance, and diet-related effects of the pandemic

Mean typical daily F&V intake (number of 80 g portions) in the study population was 5.76 portions ±0.17 (S.E.). Typical daily F&V intake was positively associated with age, certain meat-avoiding diets, and growing food, and negatively with increasing-risk alcohol consumption (i.e. more than 14 units per typical week) (Tables 5 and 6). Compared to participants under 35, those aged 35–54 consumed on average 1.02

portions ±0.41 (S.E.) more F&V daily, and were 3.6 times more likely (OR=3.64, 95%CI=1.30–10.74, $p<0.05$) to meet the '5-a-day' target (400 g), while those aged 55 or over consumed 1.16 portions ±0.46 (S.E.) more F&V daily, and were 10.2 times more likely (OR=10.22, 95%CI=2.83–41.21, $p<0.001$) to eat at least five portions of F&V on a typical day, genders showing no difference. Those following a flexitarian or pescatarian diet consumed 0.88 portions ±0.34 (S.E.) and 1.87 portions ±0.67 (S.E.), respectively, more F&V compared to regular meat-eaters, and flexitarians were also 2.9 times more likely (OR=2.90, 95%CI=1.10–8.34, $p<0.05$) to meet the 5-a-day target than regular meat-eaters. Participants growing moderate to large amounts of food (i.e. food growing levels 3 and 4) consumed 1.21 portions ±0.58 (S.E.) and 1.68 portions ±0.69 (S.E.), respectively, more F&V daily than those who did not grow food, and those growing moderate amounts of food (i.e. food growing level 3) had 7.5 times higher odds of meeting the '5-a-day' target compared to non-growers (OR=7.47, 95%CI=1.49–43.52, $p<0.05$). The odds of following a meat-avoiding diet were not affected by variables related to gardening, but were positively associated with having higher education (OR=3.61, 95%CI=1.58–8.88, $p<0.01$), and negatively with being male (OR=0.43, 95%CI=0.20–0.87, $p<0.05$), and with living with a partner, compared to living alone (OR=0.34, 95%CI=0.13–0.82, $p<0.05$) (Supplementary Table S4).

Table 5 Hierarchical linear regression analysis of predictors of F&V intake adjusted for demographic and lifestyle factors[a, b, c]

Predictor variables (reference)	*Model 1*		*Model 2*		*Model 3*		*Model 4*	
	B (SE)	***p***	**B (SE)**	***p***	**B (SE)**	***p***	**B (SE)**	***p***
Constant	4.54 (0.32)	<0.001	4.54 (0.32)	<0.001	4.08 (0.35)	<0.001	3.99 (0.41)	<0.001
Gender (Female)								
Male	-0.10 (0.33)	0.77	-0.10 (0.33)	0.77	0.27 (0.33)	0.41	0.15 (0.33)	0.65
Age (18–34)								
35–54	**1.16** (0.40)	<0.01	**1.16** (0.40)	<0.01	**1.24** (0.39)	<0.05	**1.02** (0.41)	<0.05
55+	**1.60** (0.38)	<0.001	**1.60** (0.38)	<0.001	**1.73** (0.37)	<0.001	**1.16** (0.46)	<0.05
Alcohol consumption (Low risk)								
Increasing risk					**-0.84** (0.35)	<0.05	**-0.85** (0.36)	<0.05
Diet (Meat-eater)								
Flexitarian					**0.90** (0.33)	<0.01	**0.88** (0.34)	<0.05
Pescatarian					**1.82** (0.67)	<0.01	**1.87** (0.67)	<0.01
Vegetarian					0.62 (0.44)	0.16	0.63 (0.45)	0.16
Vegan					1.00 (0.64)	0.12	0.98 (0.65)	0.13
Weekly gardening time (0 hours)								
1–5 hours							-0.94 (0.51)	0.06
6–10 hours							-0.51 (0.60)	0.40
11+ hours							-0.44 (0.62)	0.47
Food growing level (No food grown)								
1 (very little F&V)							0.61 (0.56)	0.28
2							1.22 (0.62)	0.05
3							**1.21** (0.58)	<0.05
4							**1.68** (0.69)	<0.05
5 (nearly self-sufficient in F&V)							1.28 (0.67)	0.06
R^2	0.09		0.09		0.19		0.24	
Adjusted R^2	0.07		0.07		0.15		0.17	

[a] Model 1: adjusted for age and gender; Model 2: adjusted for sociodemographic variables; Model 3: adjusted for sociodemographic variables and health risk and relevant lifestyle factors; Model 4: adjusted for sociodemographic variables, health risk and relevant lifestyle factors and variables related to gardening.

[b] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, having higher education, smoking status, physical activity level, long-term health conditions, and having an allotment, but these were dropped in the process of improving model fit.

[C] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Table 6 Odds Ratios (OR) for eating at least 5 portions of F&V daily as compared to eating fewer portions, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-1.95 (0.84)	0.14 (0.03–0.70)	<0.05
Gender (Female)			
Male	-0.49 (0.44)	0.61 (0.26–1.47)	0.27
Age (18-34)			
35-54	1.29 (0.54)	**3.64 (1.30–10.74)**	<0.05
55+	2.32 (0.68)	**10.22 (2.83–41.21)**	<0.001
Household income (£20,000–29,999)			
Under £10,000	2.39 (1.38)	10.93 (0.96–295.67)	0.08
£10,000–19,999	-0.04 (0.77)	0.97 (0.22–4.55)	0.96
£30,000–39,999	0.22 (0.68)	1.25 (0.33–4.89)	0.75
£40,000+	-0.20 (0.61)	0.82 (0.24–2.69)	0.74
Higher education (No)			
Yes	0.96 (0.54)	2.61 (0.92–7.77)	0.07
Diet (Regular meat-eater)			
Flexitarian	1.06 (0.51)	**2.90 (1.10–8.34)**	<0.05
Pescatarian	16.99 (1079.12)	$2.39e^7$ (0.00–NA)	0.99
Vegetarian	0.81 (0.62)	2.25 (0.70–8.05)	0.19
Vegan	1.38 (0.90)	3.98 (0.77–30.68)	0.13
Weekly gardening time (0 hours)			
1–5 hours	-0.58 (0.69)	0.56 (0.14–2.08)	0.40
6–10 hours	-0.80 (0.91)	0.45 (0.07–2.55)	0.38
11+ hours	-1.74 (0.96)	0.18 (0.02–1.05)	0.07
Food growing level (No food grown)			
1 (very little F&V)	0.16 (0.70)	1.17 (0.29–4.71)	0.82
2	0.91 (0.83)	2.49 (0.50–13.54)	0.27
3	2.01 (0.85)	**7.47 (1.49–43.52)**	<0.05
4	2.00 (1.04)	7.38 (1.05–65.33)	0.05
5 (nearly self-sufficient in F&V)	1.84 (0.97)	6.33 (1.00–45.98)	0.06

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household composition, caring responsibilities, alcohol consumption, smoking status, obesity, long-term health conditions, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.25 (Hosmer Lemeshow), 0.26 (Cox and Snell), 0.38 (Nagelkerke); χ^2 (20) = 57.54

[c] Figures in bold are statistically significant at the 5% level (p<0.05)

Participants' perception of the effect of the pandemic on their diet quality or access to healthy food was not affected by gardening related variables but was associated with a number of socio-demographic factors. Respondents aged 55 or over and those with a household income of £30,000–39,999 were 95% less likely (OR=0.05, 95%CI=0.00–0.43 and OR=0.05, 95%CI=0.00–0.67, $p<0.05$) than respondents under 35 and those with a household income of £20,000–29,999, respectively, to report experiencing a negative effect of the pandemic on their access to healthy food (Supplementary Table S5). Participants aged 55 or over were also 92% less likely (OR=0.08, 95%CI=0.02–0.29, $p<0.001$) than under 35s to report that the pandemic had a negative effect on their diet quality, while participants with obesity were around 4 times (OR=4.21, 95%CI=1.52–11.82, $p<0.01$), and those typically consuming 1 or 2 portions of F&V daily were 9 times (OR=9.09, 95%CI=0.08–44.74, $p<0.01$) more likely to report a pandemic-related negative effect on their diet quality when compared to those without obesity and those with a typical daily F&V intake of 5 or more portions, respectively (Supplementary Table S6).

3.2.4. Spending time outdoors

The odds of spending at least 14 hours outdoors in a typical week were positively associated with having higher education, regular gardening and food-growing, and negatively with having long-term health conditions (Table 7). Participants with higher education were 4.5 times more likely (OR=4.47, 95%CI=1.62–13.92, $p<0.01$) than those without higher education, while participants with long-term health conditions were 66% less likely (OR=0.34, 95%CI=0.15–0.75, $p<0.01$) compared to participants without long-term conditions to spend at least 14 hours outdoors weekly. Participants who spent 11 or more hours gardening in a typical week were 5.9 times more likely (OR=5.92, 95%CI=1.11–35.06, $p<0.05$) to spend 14 or more hours outdoors weekly than non-gardeners. In addition, growing small amounts of food (i.e. food growing level 1) was associated with 4.7 times higher odds (OR=4.74, 95%CI=1.09–22.35, $p<0.05$) of spending at least 14 hours outdoors weekly compared to non-growers. Having an allotment had a marginally significant positive association with spending 14 or more hours outdoors (OR=2.61, 95%CI=1.01–7.02, $p=0.05$).

Table 7 Odds Ratios (OR) for spending 14 or more hours outdoors in a typical week as compared to spending less time outdoors, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	-3.41 (0.77)	0.03 (0.01–0.14)	<0.001
Gender (Female)			
Male	0.53 (0.44)	1.70 (0.72–4.03)	0.22
Age (18–34)			
35–54	0.22 (0.57)	1.25 (0.41–3.95)	0.70
55+	0.29 (0.63)	1.34 (0.39–4.67)	0.64
Higher education (No)			
Yes	1.50 (0.54)	**4.47 (1.62–13.92)**	<0.01
Long-term conditions (No)			
Yes	-1.07 (0.41)	**0.34 (0.15–0.75)**	<0.01
Physical activity level (Low)			
Moderate	0.49 (0.42)	1.63 (0.71–3.75)	0.25
High	0.88 (0.53)	2.42 (0.87–6.90)	0.09
Weekly gardening time (0 hours)			
1–5 hours	-0.24 (0.72)	0.78 (0.18–3.20)	0.74
6–10 hours	0.11 (0.82)	1.11 (0.22–5.70)	0.90
11+ hours	1.78 (0.88)	**5.92 (1.11–35.06)**	<0.05
Food growing level (No food grown)			
1 (very little F&V)	1.56 (0.76)	**4.74 (1.09–22.35)**	<0.05
2	0.80 (0.91)	2.23 (0.38–13.88)	0.38
3	0.98 (0.89)	2.67 (0.48–16.23)	0.27
4	0.55 (1.03)	1.74 (0.23–13.47)	0.59
5 (nearly self-sufficient in F&V)	1.10 (1.02)	3.01 (0.41–22.96)	0.28
Allotment (No)			
Yes	0.96 (0.49)	2.61 (1.01–7.02)	0.05

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, obesity, smoking status, alcohol consumption, F&V intake, and meat consumption, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.25 (Hosmer Lemeshow), 0.26 (Cox and Snell), 0.38 (Nagelkerke); χ^2 (20) = 57.54

[C] Figures in bold are statistically significant at the 5% level (p<0.05)

3.2.5. Physical health (PHQ score)

Physical well-being, measured as the frequency of somatic health complaints, was positively associated with age and education level, and negatively with living with a family, having long-term health conditions, and increasing-risk alcohol consumption (i.e. more than 14 units per typical week) (Table 8). Mean PHQ score in the study population was 34.4 ±0.6 (S.E.). Participants aged 35–54 scored 5.70 points ±1.97 (S.E.) lower (i.e. had less frequent health complaints), those aged 55 or over scored 11.11 points ±2.22 (S.E.) lower on the PHQ than under 35s. Respondents with higher education scored 3.89 points ±1.65 (S.E.) lower on the PHQ than those without higher education, while those living with a family scored 4.83 points ±2.24 (S.E.) higher (i.e. had more frequent health complaints) than participants living alone. Participants with long-term health conditions or increasing-risk drinking scored 4.21 points ±1.37 (S.E.) and 4.43 points ±1.73 (S.E.) higher than those without long-term conditions and with low-risk alcohol consumption, respectively. Participants who were aged 55 or over, had higher education or had moderate physical activity levels were less likely to report the pandemic having had a negative effect on their physical health compared to participants under 35, without higher education, and with low physical activity, respectively (Supplementary Table S7). Neither PHQ scores nor the odds of attributing a negative physical health effect to the pandemic was associated with gardening related variables.

Table 8 Hierarchical linear regression analysis of predictors of physical health (PHQ) score adjusted for demographic and lifestyle factors[a, b, c, d]

Predictor variables (reference)	***Model 1***		***Model 2***		***Model 3***		***Model 4***	
	B (SE)	***p***	**B (SE)**	***p***	**B (SE)**	***p***	**B (SE)**	***p***
Constant	41.37 (1.59)	<0.001	48.34 (3.60)	<0.001	45.31 (3.46)	<0.001	45.43 (3.58)	<0.001
Gender (Female)								
Male	-2.36 (1.63)	0.15	-1.64 (1.57)	0.30	-2.85 (1.53)	0.06	-2.69 (1.53)	0.08
Age (18–34)								
35–54	-3.55 (1.99)	0.08	**-4.48** (2.1)	<0.05	**-6.08** (1.92)	<0.01	**-5.70** (1.97)	<0.01
55+	**10.61** (1.86)	<0.001	**-10.85** (2.07)	<0.001	**-12.19** (1.99)	<0.001	**-11.11** (2.22)	<0.001
IMD quintile (First)								
Second			**-6.89** (3.14)	<0.05	-5.21 (3.00)	0.08	-5.13 (3.00)	0.09
Third			-2.11 (2.96)	0.48	-1.41 (2.81)	0.62	-1.10 (2.82)	0.70
Fourth			-4.74 (3.01)	0.12	-2.90 (2.86)	0.31	-2.83 (2.86)	0.32
Fifth			**-6.04** (2.93)	<0.05	-5.11 (2.77)	0.07	-4.94 (2.79)	0.08
Higher education (No)								
Yes			**-4.33** (1.74)	<0.05	**-4.05** (1.64)	<0.05	**-3.89** (1.65)	<0.05
Household (Alone)								
With partner			-0.29 (2.04)	0.89	-0.79 (1.95)	0.69	-0.56 (1.97)	0.77
With family			4.64 (2.36)	0.05	**4.62** (2.24)	<0.05	**4.83** (2.24)	<0.05
Shared accommodation			-5.57 (4.52)	0.22	-5.39 (4.29)	0.21	-6.42 (4.38)	0.14
Obesity (Without obesity)								
With obesity					**3.65** (1.84)	<0.05	3.26 (1.89)	0.09
Long-term conditions (No)								
Yes					**4.42** (1.35)	<0.01	**4.21** (1.37)	<0.01
Alcohol consumption (Low risk)								
Increasing risk					**4.47** (1.70)	<0.01	**4.43** (1.73)	<0.05
Weekly gardening time (0 hours)								
1–5 hours							4.21 (2.23)	0.06
6–10 hours							1.97 (2.63)	0.45
11+ hours							2.89 (2.58)	0.26
Food growing (No)								
Yes							-4.32 (2.34)	0.07
R^2	0.18		0.29		0.38		0.40	
Adjusted R^2	0.17		0.25		0.33		0.34	

[a] Lower PHQ scores indicate fewer health complaints and thus better health.
[b] Model 1: adjusted for age and gender; Model 2: adjusted for sociodemographic variables; Model 3: adjusted for sociodemographic variables and known health risk and relevant lifestyle factors; Model 4: adjusted for sociodemographic variables, health risk and relevant lifestyle factors and variables related to gardening.
[c] Predictors and coefficients in the table are derived from the best fit models for the outcome based on the Bayesian Information Criterion (BIC) at each stage of the regression. Other explanatory variables tested include household income, caring responsibilities, smoking status, physical activity level, F&V intake, and having an allotment, but these were dropped in the process of improving model fit.
[d] Figures in bold are statistically significant at the 5% level ($p<0.05$)

3.2.6. Obesity

Mean BMI in the study population was 25.6±0.31 (S.E.). The odds of having obesity were associated with age, physical activity level, F&V intake, and following a flexitarian diet (Table 9). Participants aged 35–54 were nearly 5 times more likely to have obesity than participants under 35 (OR=4.83, 95%CI=1.19–23.47, $p<0.05$). Those with a moderate physical activity level were 72% less likely to have obesity than those with low activity levels (OR=0.28, 95%CI=0.07–0.91, $p<0.05$), and those typically eating 3 or 4 portions of F&V were 3.9 times more likely (OR=3.94, 95%CI=1.22–13.74, $p<0.05$) to have obesity than participants eating 5 or more portions of F&V daily. Flexitarians were also 87% (OR=0.13, 95%CI=0.03–0.49, $p<0.05$) less likely to have obesity than regular meat-eaters. No gardening related variable had a significant effect on the odds of having obesity.

Table 9 Odds Ratios (OR) for having obesity as compared to being in any other BMI category, adjusted for demographic and lifestyle variables[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-1.99 (0.80)	0.14 (0.03–0.61)	0.01
Gender (Female)			
Male	-1.03 (0.64)	0.36 (0.09–1.16)	0.11
Age (18–34)			
35–54	1.57 (0.75)	**4.83 (1.19–23.47)**	<0.05
55+	0.45 (0.84)	1.56 (0.31–8.66)	0.60
Physical activity (Low)			
Moderate	-1.28 (0.64)	**0.28 (0.07–0.91)**	<0.05
High	-0.51 (0.79)	0.60 (0.11–2.67)	0.52
Daily F&V intake (5+ portions)			
1 or 2 portions	1.35 (0.83)	3.85 (0.72–20.27)	0.11
3 or 4 portions	1.37 (0.61)	**3.94 (1.22–13.74)**	<0.05
Diet (Regular meat-eater)			
Flexitarian	-2.01 (0.73)	**0.13 (0.03–0.49)**	<0.01
Pescatarian	-16.25 (1239.58)	0.00 (NA–1.96e^{34})	0.99
Vegetarian	-1.34 (0.89)	0.26 (0.03–1.25)	0.13
Vegan	-1.49 (1.21)	0.22 (0.01–1.76)	0.22
Weekly gardening time (0 hours)			
1–5 hours	1.17 (0.87)	3.23 (0.62–19.84)	0.18
6–10 hours	1.97 (1.10)	7.17 (0.95–72.37)	0.07
11+ hours	-0.09 (1.25)	0.92 (0.08–11.17)	0.94
Food growing level (No food grown)			
1 (very little F&V)	-1.86 (1.07)	0.16 (0.01–1.10)	0.08
2	-0.43 (1.01)	0.65 (0.08–4.49)	0.67
3	-0.84 (1.03)	0.43 (0.05–3.12)	0.42
4	-0.54 (1.16)	0.59 (0.06–5.58)	0.64
5 (nearly self-sufficient in F&V)	-1.33 (1.24)	0.27 (0.02–2.71)	0.28

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, higher education, household composition, caring responsibilities, smoking status, alcohol consumption, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.26 (Hosmer Lemeshow), 0.20 (Cox and Snell), 0.35 (Nagelkerke); χ^2 (19) = 42.07

[c] Figures in bold are statistically significant at the 5% level (p<0.05)

3.2.7. Low physical activity

The odds of having a low physical activity level were not affected by variables related to gardening, but were associated with age, household income, and having caring responsibilities (Table 10). On average, participants aged 35–54 were 3.6 times more likely (OR=3.56, 95%CI=1.33–10.22, $p<0.05$) to have low physical activity than under 35s. Participants with caring responsibilities were 60% less likely (OR=0.40, 95%CI=0.18–0.85, $p<0.05$) than those without caring responsibilities, while participants with a household income of £40,000 per annum or higher were 64% less likely (OR=0.34, 95%CI=0.13–0.96, $p<0.05$) than those with a household income of £20,000–29,999 to have low physical activity.

Table 10 Odds Ratios (OR) for having low physical activity as compared to higher (moderate or high) physical activity, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	-0.15 (0.63)	0.86 (0.24–2.95)	0.81
Gender (Female)			
Male	0.09 (0.37)	1.10 (0.52–2.28)	0.81
Age (18–34)			
35–54	1.27 (0.52)	**3.56 (1.33–10.22)**	<0.05
55+	-0.01 (0.56)	0.99 (0.33–3.00)	0.98
Household income (£20,000–29,999)			
Under £10,000	0.22 (0.91)	1.25 (0.22–8.53)	0.81
£10,000–19,999	-0.86 (0.58)	0.42 (0.13–1.29)	0.13
£30,000–39,999	-0.58 (0.54)	0.56 (0.19–1.61)	0.29
£40,000+	-1.01 (0.50)	**0.36 (0.13–0.96)**	<0.05
Caring responsibilities (No)			
Yes	-0.91 (0.39)	**0.40 (0.18–0.85)**	<0.05
Diet (Regular meat-eater)			
Flexitarian	0.13 (0.38)	1.14 (0.54–2.44)	0.73
Pescatarian	-1.83 (1.13)	0.16 (0.01–1.05)	0.11
Vegetarian	0.25 (0.51)	1.29 (0.47–3.50)	0.62
Vegan	-0.94 (0.80)	0.39 (0.07–1.75)	0.24
Food growing level (No food grown)			
1 (very little F&V)	-0.05 (0.66)	0.95 (0.25–3.44)	0.94
2	0.38 (0.59)	1.46 (0.45–4.73)	0.52
3	0.45 (0.54)	1.56 (0.55–4.54)	0.41
4	0.93 (0.64)	2.53 (0.73–9.20)	0.15
5 (nearly self-sufficient in F&V)	0.99 (0.59)	2.68 (0.86–8.73)	0.09

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household composition, higher education, smoking status, alcohol consumption, long-term health conditions, obesity, F&V intake, amount of time spent gardening, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.11 (Hosmer Lemeshow), 0.14 (Cox and Snell), 0.19 (Nagelkerke); χ^2 (17) = 28.64

[c] Figures in bold are statistically significant at the 5% level (p<0.05)

4. Discussion

Gardening offers several potential health and well-being benefits, but our understanding of the particular role of allotments and home gardens, and the effects of the level of engagement in gardening and involvement with food production has thus far been limited. Here, we quantitatively assess the relationship between home and allotment gardening in the UK and a range of indicators and predictors of health and well-being to fill some of the knowledge gaps in the field. Specifically, we investigated the effects of the amount of time spent gardening, level of food production, and having an allotment. We provide evidence that, after accounting for several potential confounders, gardening related variables are associated with better self-rated health, higher mental well-being, and certain positive health-related behaviours, including increased fruit and vegetable (F&V) consumption and spending considerable amounts of time outdoors. Higher F&V intake was in turn also associated with better self-rated health and decreased odds of having obesity. Thus, gardening had a positive association with five different aspects of health and well-being, directly or indirectly via increased F&V consumption. Our analyses have also revealed that different aspects of health and well-being are associated with different aspects of gardening, which suggests that a number of distinct mechanisms are involved in delivering benefits.

We found that survey respondents who had an allotment had lower odds of having low mental well-being than those without an allotment, regardless of how much time they spent gardening. The fact that this positive association was observed after accounting for a range of potential confounding variables suggests that having an allotment is likely a predictor of well-being itself, rather than simply an indicator of differences in socio-economic status that impacted on well-being, which may have been expected based on trends of decreasing allotment availability with increasing neighbourhood deprivation (Dobson et al., 2020a). We also found well-being scores to be positively associated with at least 11 hours of weekly gardening, but not with smaller amounts, which suggests that getting a mental well-being benefit, at least in the form measured by the WEMWBS, might require more serious engagement with gardening. Our results indicate that spending larger amounts of time gardening could improve well-being, and having an allotment in particular could help protect against low well-being, but may not be sufficient for achieving high (compared to moderate) well-being, the odds of which were not affected by gardening related variables. This is in line with previous research using the WEMWBS that found the odds of high and low well-being to be determined by different factors, for example, alcohol intake and obesity being associated with low, but not high mental well-being, and F&V intake associated with high well-being (Stewart-Brown et al., 2015; Stranges et al., 2014). In addition, we found 11 or more hours of weekly gardening to be associated with lower odds of attributing a negative mental health effect to the pandemic. This is in agreement with a recent study that found that contact with green spaces helped people cope with the negative mental well-being impacts of the covid-19 lockdowns (Pouso et al., 2021).

Growing moderate to large amounts of F&V was associated with both higher self-reported average F&V intake and increased odds of meeting the 5-a-day target. This is consistent with the results of another piece of recent research in our group, where we studied year-long F&V production, purchases and losses in 85 food-grower households in the UK, and found median daily per capita F&V intake to be 70% higher than the national average (Gulyas & Edmondson, in review). Other studies have also found an association between involvement with gardening and increased F&V intake, but the underlying mechanisms have so far been unclear and research focusing on allotments and domestic gardens in the UK has so far been scarce. The results of the present study suggest that, in this context, gardening contributes to increased F&V intake only if it involves the production of considerable amounts of F&V. This indicates that higher F&V intake is a response to increased availability of F&V through own production, and that engagement in gardening that involves the production of no or only smaller amounts of food may not trigger a dietary change.

Nonetheless, we should not dismiss the idea that close exposure to a variety of F&V through own-growing could build familiarity and promote positive changes in diet, as some research suggests that this could be an effective mechanism for improving food behaviours, especially in children (Heim et al., 2009; Ratcliffe et al., 2011; Sarti et al., 2017). Although the underlying mechanisms are not fully understood, nature relatedness has also been linked to increased F&V intake (Milliron et al., 2022), therefore engaging with natural processes through gardening may be an additional pathway through which food gardening can promote F&V consumption. Although we did not find evidence for a role of F&V gardening in alleviating the potential adverse effects of the pandemic on people's access to healthy food or diet quality associated with temporary store closures and supply shortages (Revoredo-Giha & Costa-Font, 2020), this may be due to the overall relatively small number of participants reporting negative experiences in these areas.

Growing moderate to large amounts of F&V was also associated with considerably lower odds of reporting 'not good' health, which suggests that a health benefit is mediated by increased F&V intake associated with access through own-growing. The importance of sufficient F&V consumption for the prevention of a range of non-communicable diseases is well established (Wang et al., 2014; WHO, 2003). Diets low in F&V are estimated to contribute to 18,000 premature deaths in the UK each year (Afshin et al., 2019), so increasing F&V intake through own production could have important positive implications for public health. As the current cost of living crisis continues, increased availability of F&V through own-growing could particularly benefit people on lower incomes.

Although we did not find a direct association between the odds of having obesity and variables related to gardening, we did find evidence of an inverse relationship between obesity and F&V intake, in agreement with the literature (Bazzano et al., 2003; Buijsse et al., 2009). In addition, while there was no significant association between gardening and the odds of having low physical activity as measured in our study, previous research has established that many gardening tasks require moderate-intensity physical exercise (Park et al., 2011). Combined with a healthy diet, exercise can aid weight loss (Blair, 1993; Donnelly et al., 2004), and evidence of an association between physical activity level and the odds of obesity was also present in our study. Thus, by promoting consumption of F&V and providing physical exercise, food gardening on allotments and in domestic gardens could contribute to the prevention of obesity and lower the risk of associated diseases. Moreover, we found a negative association between obesity and mental well-being, in accordance with previous research (Stranges et al., 2014), suggesting an additional way in which gardening could improve well-being. The potential role of a healthy diet characterised by high consumption of F&V and moderate intake of animal products in improving mental well-being via several biological pathways, including the maintenance of a healthy body weight, has also been proposed in the literature (Firth et al., 2020).

Gardening is an outdoor activity by nature, and our results suggest that both larger amounts of time spent gardening and growing food are associated with higher odds of spending 14 or more hours outdoors in a typical week. Spending time outdoors has been linked to less sedentary time, higher levels of physical activity, better self-rated health and decreased chronic disease risk (Beyer et al., 2018; Harada et al., 2017; Pietilä et al., 2015). Research on the effects of being outdoors and participating in physical activity in natural environments also point to benefits for psychological well-being (Gascon et al., 2018; Kühn et al., 2021; Ohrnberger et al., 2017; Thompson Coon et al., 2011), some evidence of which was also present in our study. Therefore, as a form of green exercise, gardening could improve both physical and mental well-being, which may have been particularly important during the covid-19 lockdowns, which had a negative effect on many people's physical activity levels (Stockwell et al., 2021) and mental well-being (Abolarin et al., 2020).

One somewhat unexpected finding from our study is that older participants had lower, rather than higher, as anticipated based on previous research, odds of reporting 'not good' health (Hatch et al., 2011). This might be related to the fact that in our sample there were notably more gardeners than non-gardeners among those aged 55 or over. However, the age effect persisted even after adjusting for the positive effect of gardening time, which suggests that there are likely some other factors associated with age that positively affect SRH that we did not control for in our analyses. To investigate this further, it would be valuable to repeat the study on a larger and more balanced sample.

Strengths and limitations

Our study adds particular value to existing literature on the benefits of gardening by focusing on the role of allotments and home gardens in the UK, which has been relatively understudied compared to community gardens in the USA, and by examining the effects of the amount of time spent gardening, level of food production, and having an allotment, on a range of health-related outcomes. Nevertheless, because of our moderate sample size, some care should be taken when generalising findings beyond the study population, which is not fully representative of the UK general population. Further work is required to unravel the complex relationships between individual and societal determinants of health and well-being and how the role of gardening may vary with other factors. It is also important to remember that this research was conducted during the covid-19 pandemic while major restrictions were in place in the UK and the lives of people were majorly affected in different ways. While our study offers valuable insight into the links between gardening and health and well-being, these associations may be different under normal circumstances, the specifics of which need further exploration.

5. Conclusion

Good health is an asset that has major impacts on both the individual and societal level. However, rates of mental and physical ill health and unhealthy behaviours that contribute to these are high and rising around the world (WHO, 2022). Our study provides evidence that gardening on allotments and in domestic gardens in the UK could promote physical and mental well-being and help reduce the risk of a number of health conditions via various pathways and may have played a role in protecting against some of the negative impacts of the covid-19 pandemic. However, although gardening is a fairly popular activity in the UK, many people do not have access to a garden (Office for National Statistics, 2020) and the growing demand for allotments is unmet by the dwindling current supply, especially in already deprived neighbourhoods (apse, 2022; Dobson et al., 2020a). Improving access to growing space and promoting regular gardening could therefore provide a range of benefits to public health. There is also a need for more research to determine causal relationships and better understand how the effects of gardening may vary with socio-economic factors to guide policy-makers in devising strategies that help maximise its health and well-being benefits.

Chapter 6

General discussion

1. Introduction

In this PhD research I have investigated some of the ways in which urban horticulture (UH), and particularly small-scale fruit and vegetable (F&V) production by people, could help tackle some of the food security and health challenges faced by today's increasingly urbanised societies, focusing mainly on the United Kingdom. To increase our understanding of the potential benefits of UH in different areas, I used a combination of mostly quantitative research methods, including systematic literature review, online survey, geographic information systems, national-scale online citizen science data collection and food diaries.

In Chapter 1, I provided a general background to the topic, beginning with an overview of some key challenges associated with urbanisation in terms of health, well-being and food security. This was followed by an introduction to UH and a summary of the ways it may promote food system resilience and sustainability, nutritional security, and aspects of health and well-being based on existing literature, and finally identified some key research gaps in the field. In Chapter 2, I explored the role of urban agriculture (UA) in strengthening city resilience in the Global North through a systematic review of the academic literature. I identified factors that determine UA's success in providing resilience benefits, as well as challenges that can limit this, and developed a conceptual model to highlight ways in which its resilience benefits could be enhanced through research, policy, and practice. In Chapter 3, I investigated UH food production in the UK, using five years' own-grown F&V yield data from the national 'Measure Your Harvest' citizen science project, and identified factors driving yields of own-grown crops and provided the first national-scale estimate of own-grown F&V production potential on UK allotments, demonstrating that it could make a modest but important contribution to the national food supply. Chapter 4 assessed the role of own food production in the UK in promoting F&V self-sufficiency and consumption at the household level, using a year-long food diary approach. This research revealed that UK food-grower households can be highly self-sufficient in vegetables, potatoes and fruits, and have considerably higher F&V intake compared to the national average, as well as producing very little

F&V waste. Chapter 5 set out to determine how different aspects of gardening may be associated with a range of health and well-being outcomes in the UK. This online survey of gardeners and non-gardeners identified a number of distinct mechanisms through which regular gardening, having an allotment, and growing F&V might promote physical and mental well-being. In the following sections, I synthesise the key findings of this PhD research, drawing together results from each chapter organised into two principal themes: the role of urban horticulture in food security, and the health and well-being benefits of food gardening. After this, I discuss the implications of this research for policymakers and practitioners and assess the contribution of the thesis to existing research, closing with some suggestions for future work.

2. The role of urban horticulture in food security

The main findings of this PhD research are summarised in Figure 1 below. One of the key themes dealt with in this thesis is the potential role of UH in improving the food security of increasingly urban populations and in increasing urban resilience in the face of socio-political and climatic shocks. To achieve food security, which exists when "*all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" (FAO, 1996), it is not enough to produce enough food for everyone. While increasing food supply to meet the needs of growing populations, from limited resources, already presents a major challenge, our need to do so in a sustainable way and ensure that people have enough to eat and can also access a healthy diet, despite supply disturbances, makes this task even more difficult.

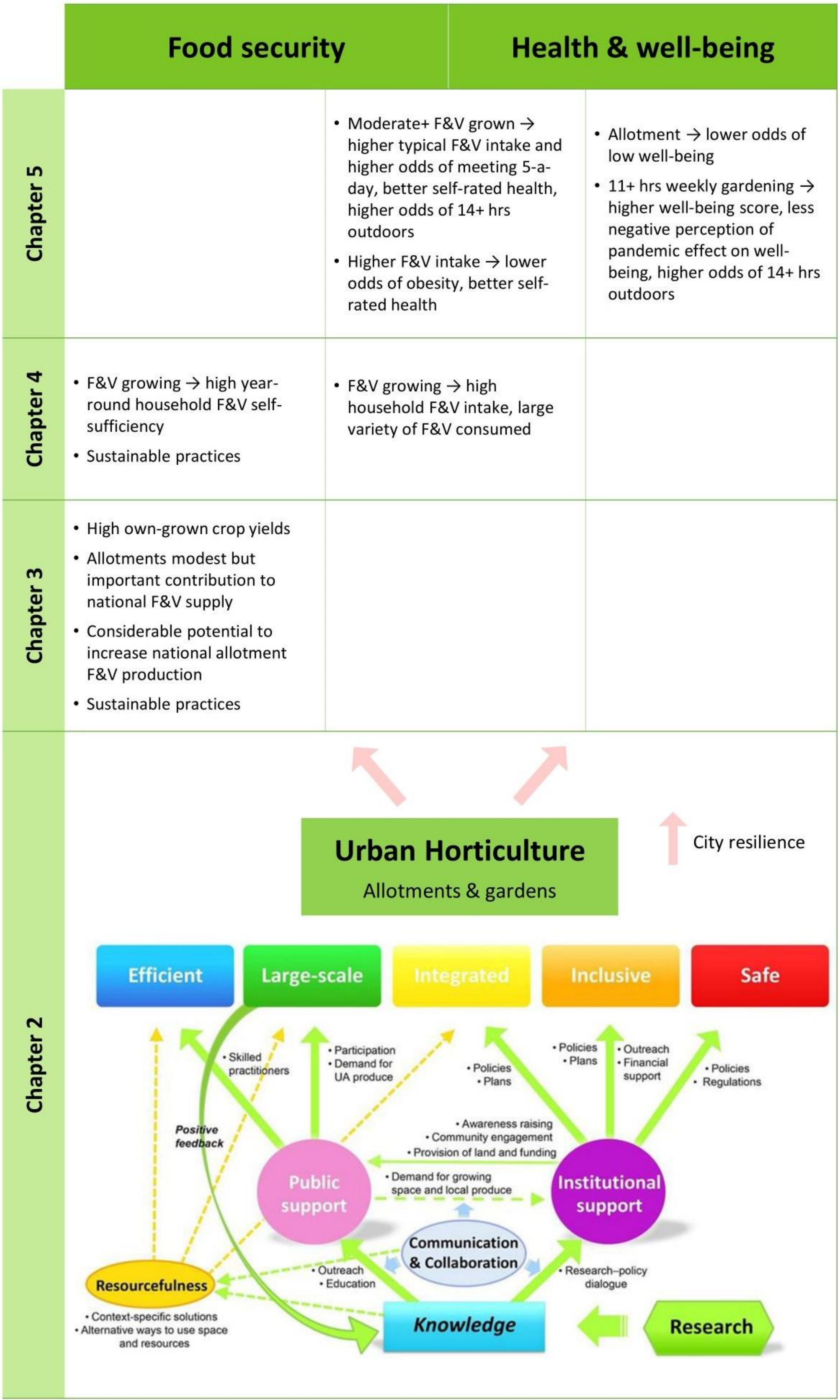

Figure 1. Synthesis of main thesis findings relating to the contribution of urban horticulture to food security, health and well-being and urban resilience in the UK and Global North.

In Chapter 2, I explored the concept of city resilience—the ability of urban systems to absorb shocks of all kinds and their capacity to adapt to changing conditions without losing any of their key functions (Meerow et al., 2016)—and established that one key way in which UA (primarily UH) can support the resilience of cities in the Global North is through improving their food security. By diversifying sources and providing alternative food supplies with shorter supply chains, UH can help build back-up capacity and lessen the repercussions of potential disruptions to conventional supplies. Own food production in allotments and domestic gardens was successfully promoted to aid the war effort during World War II, when it made a significant contribution to the UK national F&V supply (Defra, 2017; Ginn, 2012). Although the challenges we are facing today are different, my results suggest that UH may again play an important role in increasing the food security of urban populations.

In Chapter 3, I examined the contribution of own F&V growing to the national food supply today. I showed that, firstly, own-grown crop yields in the UK can be high (on average 1.93 kg m^{-2} yr^{-1} ±0.06 (S.E.)), in some cases exceeding commercial horticultural yields, and are largely unaffected by growing space type and whether organic methods are used, while greenhouse growing and regional variation in soil type and growing season temperature had an effect on the yields of some, but not all, crop types. Secondly, I estimated that current allotment food production in the country (120.3 thousand tonnes per year ±2.7 (S.E.)) represents around 3.9% of commercial domestic supply of F&V (including potatoes) (Defra, 2018) and provides enough F&V to meet the annual 5-a-day requirements of 614 thousand people, and that reconverting suitable former allotment land could increase allotment F&V production by 72%. Potential F&V production on current and suitable former allotment land (206.6 thousand tonnes per year ±3.3 (S.E.)) would be equivalent to 6.7% of domestic commercial F&V production. While this may be a modest contribution to food supply on the national scale, allotments nonetheless could play an important role in decreasing our reliance on unsustainably grown commercial horticultural produce and vulnerable global supply chains. In addition, UH could improve availability of nutritious food in urban areas where access to healthy diets is increasingly challenging, with benefits to public health.

Taking a different perspective, Chapter 4 focused in part on the contribution of own-growing to food self-sufficiency on the household level, and revealed that food-grower households in the UK were on average 50% self-reliant in potatoes and vegetables, and around 20% in fruits over the course of a year. From a food security point of view, this means that if their access to conventional food sources (i.e. supermarkets and markets) was majorly disrupted, these households would still be able to access considerable amounts of produce (i.e. on average 41% of their total fruit, vegetable and potato consumption) through own-growing. Moreover, since average F&V intake in food-grower households (507 g per person per day) was higher than the recommended minimum 5-a-day (i.e. 400 g per day), own-grown F&V could on average provide 50% of food-growers' household F&V requirements. Additionally, we saw that most food-grower households regularly preserved, froze, or gave away their excess crop, and that they produced considerably less F&V waste than the average UK household. This indicates an association between growing one's own food and waste-reducing behaviours, which could further support food security in the utilisation domain.

The amount of food provided by UH, an important determinant of its potential to improve food security, is essentially determined by two factors: the size of the area devoted to food production in cities, and the amount of produce that can be obtained from unit cultivated area over a certain period of time (i.e. crop yield). I provided estimates of own-grown crop yields in the UK in both Chapters 3 and 4, which, interestingly, are fairly different. My five-year national-scale estimate of yield across 39 common own-grown crops (1.93 kg m^{-2} yr^{-1} ±0.06 (S.E.)) in Chapter 3 is close to the mean yield found in an earlier study of Leicester allotments (2.3 kg m^{-2} yr^{-1} ±0.2 (S.E.) (Edmondson et al., 2020a)), but median household produce yield in Chapter 4 (1.4 kg m^{-2} yr^{-1}) was lower. In Chapter 4, I found that yields were affected by grower experience, cultivated area, and household size, and stipulated that differences in management and local environmental conditions may also be contributing to yield differences. As I found in Chapter 3 that yields of crops grown in different types of growing spaces were not different, we may dismiss the idea that yield differences between these studies are due to data coming from a different proportion of allotments and home gardens. However, I did find, in Chapter 3, that the yields of certain crops were influenced by soil type and growing season temperature, so differences in these factors between the studies could explain some of the observed yield difference. Moreover, as seen in Chapter 3, there could also be considerable variation in crop yields between individual sites that goes beyond what could be explained by the broader drivers of yield examined there. Another likely source of difference lies in the way in which average yield was calculated in the two studies. While in Chapter 3 overall crop yield was calculated as the unweighted mean of the mean yields of 39 different crop types, in Chapter 4 I did not collect data on cultivated area corresponding to individual crops and so yield was derived from total annual produce weight and total cultivated area. We saw in Chapter 3 that yields of different types of fruits and vegetables can be very different, so the relative cultivation of different crops could have had a large effect on estimated average yield in Chapter 4. In addition, while for Chapter 3 participants were given detailed instructions on how to measure their crop weights and cultivated areas, for Chapter 4 the emphasis was more on consistent provision of data for a full year. In addition, for the assessment of average yields in Chapter 3, completely failed crops were excluded, while in Chapter 4 the nature of data did not allow for this and so cultivated area corresponding to total own produce weight also included planted areas that were eventually unproductive, resulting in lower yield estimates.

Although the potential of UH to provide food may seem modest when assessing it on a national scale, ultimately constrained by the availability of growing space in cities, there is another facet to its role in promoting food security. While F&V are generally low in calories, they are a key part of a healthy diet due to their high dietary fibre, essential micronutrient (vitamins and minerals), antioxidant, and in some cases (e.g. beans, peas, broccoli) essential amino acid and overall protein content (FAO et al., 2020; NHS, 2018b). Since being able to eat a varied and nutritionally adequate diet that promotes health is an important part of food security, UH could play a key role in promoting urban food security by improving access to a variety of fresh, nutritious produce where most of the population lives and where accessing these foods is often challenging.

3. Health and well-being benefits of food gardening

The other main focus of the thesis has been on the potential health and well-being benefits of engaging in UH. F&V are an essential constituent of a healthy diet, and their sufficient consumption has been shown to play an important role in preventing a range of diseases (Wang et al., 2021; Wang et al., 2014). Yet, most people in the UK do not eat enough F&V for health (NHS Digital, 2019a; PHE, 2019a), which is among the main preventable causes of non-communicable disease in the country, estimated to contribute to 18,000 premature deaths annually (Afshin et al., 2019). By improving availability and access to F&V, UH, and especially own-growing of F&V, could help promote F&V consumption and improve diet-related health. In addition, as a form of outdoor exercise and a way to relax, gardening could also help improve various aspects of physical and mental wellbeing adversely affected by modern lifestyles (Lee et al., 2012; Park et al., 2020; Vigo et al., 2016).

As well as assessing household self-sufficiency, Chapter 4 also investigated F&V intake and dietary diversity in food-grower households. As already mentioned in the previous section, I found food-grower households to have F&V intakes 70% higher than the national average (PHE, 2019a). Moreover, own-growing households consumed a large variety of F&V (69.6 ±2.0 (S.E.)), many of which (37.5 ±1.3 (S.E.)) were own-grown. Crops grown by participants also included F&Vs that are rarely available in supermarkets (e.g. loganberries, medlars, sorrel, purslane, cucamelon), and they also often grew different varieties of commonly commercially available F&V, further indicating higher than average dietary diversity among own-growers. The importance of sufficient F&V consumption for the prevention of a range of non-communicable diseases is well established (Wang et al., 2021; Wang et al., 2014), and since different types of F&V contain a different set of essential micronutrients and other health-promoting compounds (e.g. antioxidants), eating a more diverse range of F&V is particularly beneficial. This study also found that own-growers produced and consumed more vegetables than fruits. As vegetables are generally lower in sugar and calories than fruits, increasing vegetable consumption may provide greater health benefits, especially in the prevention and management of overweight and obesity and associated health conditions (Davis et al., 2011; Demark-Wahnefried et al., 2018; Zick et al., 2013). Therefore, this research suggests that, in terms of F&V consumption, UK households that are involved in own food production have better diets than the average UK person.

Chapter 5 revealed a number of significant positive relationships between regular gardening and F&V growing in allotments and domestic gardens, and aspects of both physical and mental well-being in the UK, which could be observed even after controlling for a range of potentially confounding socio-demographic and lifestyle factors. Specifically, variables related to food gardening were positively associated with self-rated health, mental well-being, F&V intake and spending time outdoors. In addition, higher F&V intake was associated with better self-rated health and lower odds of obesity, representing further pathways through which food gardening could indirectly benefit health. Importantly, different measures of well-being were linked to different aspects of gardening (i.e. amount of time spent gardening in a typical week, amount of F&V grown, having an allotment). Therefore, this piece of research not only provides evidence that participation in UH could improve health and well-being in multiple ways, but further identifies distinct mechanisms involved in delivering different benefits and determines a minimum 'dose' of gardening and level of food production required for each.

4. Implications for policy and practice

This thesis provides evidence that UH offers a range of benefits on both the individual and societal levels, but in order to make the most of its potential we need to understand how we can increase its positive contribution in different areas. Although the conceptual framework for describing the success of UA presented in Chapter 2 was formulated within the context of urban resilience, it can be argued that many of the same themes and processes would apply when considering how we might promote UH to reach its fullest potential in providing various benefits, resilience-related or otherwise. One of the main messages of Chapter 2 is that, in order to maximise its success, UA needs to be recognised by authorities as an important urban land-use and included in urban planning agendas, ideally integrated with other urban systems. For example, setting up food gardens on school grounds would provide both an educational opportunity and a means of supplementing school meals with fresh, nutritious produce, while doing the same in care homes and greenspaces surrounding hospitals could promote well-being and rehabilitation while helping to enrich the diets of residents and care workers. Further, organic urban wastes, the disposal of which can be problematic, could be recycled to be used as soil amendments to sustainably increase UH crop productivity, while reducing greenhouse gas emissions and costs of waste management (Adhikari et al., 2010; Schröder et al., 2021).

To increase UH's contribution to food security, it is important to make more space available for F&V production and promote the practice, including via policy support for

UH-related small businesses and non-profit initiatives. Increasing the efficiency of food production in urban spaces by promoting related research, knowledge exchange and access to resources needed for effective and sustainable production are also key ways to maximise UH's potential. From a health and well-being perspective, policies aimed at enabling and encouraging wider participation in own F&V growing could have important positive effects. Although public interest in 'grow-your-own' is already on the rise in the UK and other countries (Evans & Davies, 2020; Royal Horticultural Society, 2020; Sustain, 2020), further raising awareness of the various potential benefits of involvement in UH could promote engagement.

Promoting own production to support increased consumption of F&V in urban areas, especially in deprived neighbourhoods where issues of access to healthy food and associated diet quality and related health status are most prevalent (Black et al., 2012; PHE, 2019a; Stafford & Marmot, 2003), could have the greatest public health benefit, and so should be a policy priority. In terms of maximising the food security benefits of UH, focusing on promoting own production of some of the highest yielding own-grown crop types identified in Chapter 3 may be an effective strategy.

Chapter 4 revealed that annual household crop production was positively associated with cultivated area, frequency of allotment visits and grower experience, which further suggests that increasing the amount of growing space available and promoting active engagement and skill development are important for maximising the food security benefits of household food production. Crop yields per unit area were also positively associated with household size, which could indicate that larger households were more motivated to make better use of their space, or that sharing tasks among more people improved gardening efficiency. Therefore, collaboratively managing growing spaces may offer the added benefit of increased productivity as well as having social value.

Chapter 5 provided evidence that regular gardening and growing F&V may provide benefits to various aspects of health and well-being, and so promoting it could have a positive effect on public health. However, many people in the UK do not have access to a home garden and the growing demand for allotments is unmet by the dwindling current supply, especially in already deprived neighbourhoods. Therefore, there is a need to improve access to growing space. Due to potential interactions between socio-economic factors and the benefits of UH, it is important that strategies aimed at promoting provision of land and participation be carefully examined to ensure equity of provision and access in all its forms.

In summary, I make the following general recommendations for policymakers and local authorities regarding UH based on this PhD research:

1. *Protect and provide more growing space*

   One of the key ways to increase the potential of UH in providing various benefits is by making more space available for food production in cities. In doing so, considering spatial mismatches in supply and demand for growing space should be a priority. To help UH withstand pressure from urban development, it is essential that both existing and newly established sites are given legal protection. Despite concerns over the safety of consuming urban-grown produce, research suggests that the risk this poses to growers' health is very low (Crispo et al., 2021; Leake et al., 2009), so considering the benefits of own-growing, it is important that risk assessment tools applied to growing sites are not too prohibitive.

2. *Promote own-growing*

   To maximise both the food security and individual health and well-being benefits of food gardening, it is important that more people engage in this practice. Therefore, promoting participation by raising awareness of the benefits of UH, facilitating access to information on how to get started (e.g. location of nearby allotments and community growing spaces, expected resource requirements), and making renting allotments more easily affordable would be beneficial. Policies aiming to increase participation in UH must be guided by an understanding of the mechanisms to engage different communities.

3. *Facilitate sustainable growing practice and food skills development*

   Maximising the food security and dietary benefits of UH also requires that practitioners know how to properly cook, preserve and store their produce, which novice growers may not have sufficient knowledge of, to minimise waste and ensure continued access to own-grown F&V during the less productive months of the year. In addition, to help maintain soil and ecosystem health while supporting crop productivity, UH sites should be managed using appropriate techniques, such as crop rotation, use of compost and rainfall capture for irrigation. Therefore, information and training (e.g. booklets, workshops or community knowledge exchange sessions provided by local allotment or gardening societies) in these areas would be of benefit.

4. *Focus on equity*

   Importantly, policies aimed at supporting UH should be designed with spatial and socio-economic equity in mind to ensure that everyone has sufficient access to growing space and other resources needed to engage in food growing and benefit from its positive effects. This may involve additional support for underserved neighbourhoods and demographics who would benefit most from better access to F&V, for example in the form of discounted allotment rent or provision of free access to communal tools.

5. Contribution to research and future directions

Contribution to previous research

At the outset of this PhD, research, policy and public interest in the various potential benefits of UH had already been on the rise, and its popularity increased exponentially after the outbreak of the covid-19 pandemic. The work comprising this thesis contributes to our understanding of the ways in which UH can promote urban food security, resilience, and the health and well-being of practitioners, as well as how its beneficial role may be enhanced. The interdisciplinary nature of this investigation has enabled me to answer a range of questions related to the different benefits of UH and thus provide a broader view of the role it could play in addressing some key societal challenges today, with relevance to the wider body of research, including in the areas of urban planning, health promotion, agriculture and social studies.

To fill some key gaps in the literature, the thesis addressed the following objectives:

1. To better understand how urban agriculture in the Global North can increase city resilience and identify some pathways in which its contribution could be maximised.
    - What determines the success of UA in promoting city resilience in the Global North?
    - What challenges does it currently face that might limit its contribution?
    - How could its benefits be maximised through research, policy, and practice?

This objective was addressed in Chapter 2, where, based on a systematic literature review, I identified key aspects of UA (scale, efficiency, integration, inclusiveness, and safety) and challenges it faces in the Global North, including limited availability of suitable growing space, a generational loss of horticultural knowledge, insufficient planning for UA as part of sustainable urban green infrastructure, and socio-demographic inequalities in access to growing space. I also created a conceptual diagram to illustrate the ways in which UA could be made more successful in providing various benefits. The potential role of UA in increasing city resilience in the developing world has already been reviewed by de Zeeuw *et al*. (2011), but the same has been largely unexplored in the context of the Global North. Chapter 2 thus adds to existing knowledge by conceptualising this topic using a systematic approach, highlighting some key pathways to promoting UA that could assist policy-makers and urban planners in devising locally appropriate and effective strategies.

2. To assess the significance of own F&V growing for national food security and understand how own crop yields are affected by management practices and local environmental conditions.
    - What are the typical yields of common own-grown crops in the UK and how are they affected by production practice and environmental variability?
    - How do urban horticultural F&V yields compare to UK commercial horticulture?
    - What is the total F&V productivity of allotments in the UK?

I addressed this objective in Chapter 3, where I studied own-grown crop yields in the UK and provided the first national-scale estimate of own-grown F&V production potential on UK allotments and its contribution to the national food supply. Previous research has found that yields of own-grown crops in the UK can be similar to commercial horticulture, and that allotment production can meet a significant proportion of the F&V needs of the local urban population (Edmondson et al., 2020a). In Chapter 3, I add to this knowledge by providing the first long-term national-scale study of own-grown F&V yields and their drivers in the UK. In addition, although others have recently assessed the horticultural production potential of urban green spaces on a national scale (Walsh et al., 2022), Chapter 3 provides the first estimate of allotment F&V productivity in the UK based on typical cultivation frequency and yields of own-grown crops, which differ from commercial horticulture. I also provided the first estimate of potential expansion of allotment production through reconversion of suitable former allotment land.

3. To quantify the potential contribution of household F&V production to the self-sufficiency and diet quality of food-grower households in the UK.
    - What levels of year-round production and self-sufficiency can food-grower households achieve in different types of produce, and how does this vary across the year?
    - How much F&V do people in food-grower households eat, and how diverse is their F&V consumption?
    - How do certain aspects of growing practice (i.e. cultivated area, grower experience, gardening effort) and household size affect household food productivity and self-sufficiency?

These questions were addressed in Chapter 4, where I investigated the role of own F&V production in the UK in providing food security at the household level and its potential association with increased consumption of F&V. Chapter 4 further increases our understanding of the role of own-growing in increasing food security by assessing its contribution to year-round F&V self-sufficiency on the household level, which has not been addressed in the literature. As well as showing that own-grower households can be highly self-reliant in F&V, this piece of research also provides new evidence that own-grower households have considerably higher average F&V intakes compared to the UK average, meeting dietary recommendations. I also identified certain factors affecting own-grown crop yields, which are still little understood.

4. To quantitatively assess the relationship between different gardening related variables and health and well-being in the UK to increase our understanding of the ways in which it can exert its beneficial effects.

    - Is the amount of time spent gardening in a typical week, self-reported amount of food produced, or having an allotment associated with self-rated general health, mental well-being, frequency of physical health complaints, obesity, diet quality (in particular, F&V intake and meat avoidance), physical activity level, or the amount of time spent outdoors?

This final objective was addressed in Chapter 5, where I used a survey of gardeners and non-gardeners to investigate the associations between different aspects of gardening and measures of health and well-being. While there is growing evidence that gardening can promote health and well-being, the particular role of allotments and home gardens in this, and the effects of the level of engagement in gardening and involvement with food production have been relatively understudied. Chapter 5 adds value to existing literature by focusing on these types of growing spaces in the UK, and by examining the effects of the amount of time spent gardening, level of F&V production, and having an allotment, on a range of health-related outcomes, demonstrating that different pathways facilitate different well-being benefits.

Overall, my results, particularly when considered in the context of the broader literature, also demonstrate that the benefits of UH are complex and wide-ranging. Therefore, when thinking about own-growing, it is important to not just consider a single benefit but understand the breadth of various benefits it may provide.

Future directions

There are a number of directions for further research arising from my results. Firstly, based on the literature reviewed in Chapter 2, more research is needed on the availability of space for UH in different cities, which is an important predictor of its capacity to provide food and various health, social and ecological benefits. In order to better understand UH's potential. However, provision of land in isolation is only part of the solution, it is also crucial to investigate how the provision of different benefits might vary with the type of practice (e.g. soil-based vs. hydro- or aquaponic cultivation), and environmental and socio-cultural factors (e.g. barriers and enablers of participation). Due to the multifaceted nature of this topic, interdisciplinary approaches to studying UH will be essential.

In estimating national own-grown F&V production potential in Chapter 3, I focused on allotments as the most prevalent sites of urban horticulture in the UK. However, other forms of UH, including domestic and community gardens and non-conventional (e.g. rooftop or vertical) growing spaces, could also play a role in improving food system resilience and nutritional security, therefore their potential should be further explored. This study also points to the importance of determining the availability of suitable urban spaces for upscaling UH on a national scale. Although this question has been addressed previously through a case study of Sheffield, which indicated great potential, the extent to which the results of that study could be generalised to other UK cities still needs to be confirmed.

Another key question that needs to be investigated further is whether the higher F&V intake and better well-being outcomes in Chapters 4 and 5 are caused by food gardening, or if the observed relationship is merely correlational. To test this, studies involving growing interventions in non-growing communities will be necessary. In addition, more work is needed to unravel the complex relationships between individual and societal determinants of health and well-being, including how socio-economic context may affect the form and amount of benefits gained from gardening. Finally, it should be noted that research presented in Chapters 4 and 5 was conducted during the covid-19 pandemic while various restrictions were in place in the UK and the lives of people were majorly affected in different ways. While these studies offer valuable insight into the potential benefits of gardening for F&V self-sufficiency and consumption and other aspects of health and well-being, the observed associations may be different under normal circumstances, the specifics of which would be worth exploring further.

6. Conclusions

In this thesis I have demonstrated that UH can provide a multitude of benefits to human wellbeing and sustainable food security, and has an untapped potential that is worth exploring further in the UK and elsewhere. But to make the most of its potential, we must understand how we can best expand UH in a way that encourages wider participation and promotes equal access to its benefits. In a world where, despite all technological advancements, meeting our most basic need of access to a nutritionally adequate diet is threatened by increasingly volatile environmental and socio-economic conditions, and where millions are affected by various ailments of the body or mind that are largely preventable, such a multifaceted practice certainly deserves more attention. Grow-your-own may not be a cure-all to the deeply rooted issues of today's society, but it could play a part in creating a better future, one seed at a time.

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Supplementary information to chapters

Chapter 2

SUPPORTING INFORMATION

Increasing city resilience through urban agriculture: challenges and solutions in the Global North

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CONTENT

Author(s)	Year	Journal	Title	Geographic focus
Alvarez et al.	2017	Sustainable Cities and Society	The role of social network analysis on participation and placemaking.	UK
Baibarac & Petrescu	2017	Procedia Engineering	Open-source Resilience: A Connected Commons-based Proposition for Urban Transformation.	European countries
Barthel et al.	2015	Urban Studies	Food and Green Space in Cities: A Resilience Lens on Gardens and Urban Environmental Movements.	European countries
Beatley & Newman	2013	Sustainability	Biophilic Cities Are Sustainable, Resilient Cities.	USA
Berte & Panagopoulos	2014	International Journal of Urban Sustainable Development	Enhancing city resilience to climate change by means of ecosystem services improvement: a SWOT analysis for the city of Faro, Portugal.	Portugal
Buijs et al.	2016	Current Opinion in Environmental Sustainability	Active citizenship for urban green infrastructure: fostering the diversity and dynamics of citizen contributions through mosaic governance.	European countries
Calvet-Mir & March	2019	European Urban and Regional Studies	Crisis and post-crisis urban gardening initiatives from a Southern European perspective: The case of Barcelona.	Spain
Chang & Morel	2018	Agronomy for Sustainable Development	Reconciling economic viability and socio-ecological aspirations in London urban microfarms.	UK
Clinton et al.	2018	Earth's Future	A Global Geospatial Ecosystem Services Estimate of Urban Agriculture.	global
Colding & Barthel	2013	Ecological Economics	The potential of “Urban Green Commons” in the resilience building of cities.	Germany, Sweden and USA
Collier et al.	2013	Cities	Transitioning to resilience and sustainability in urban communities.	multiple

Coppo et al.	2017	City, Territory and Architecture	Urban food strategies and plans: Considerations on the assessment construction.	multiple
Crowe et al.	2016	Environmental Science and Policy	Operationalizing urban resilience through a framework for adaptive co-management and design: Five experiments in urban planning practice and policy.	European countries
De la Sota et al.	2019	Urban Forestry & Urban Greening	Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain.	Spain
Dennis et al.	2016	Urban Ecosystems	Social-ecological innovation: adaptive responses to urban environmental conditions.	UK
Dezio & Marino	2018	Sustainability	Towards an Impact Evaluation Framework to Measure Urban Resilience in Food Practices.	Italy
Dixon & Richards	2016	Agriculture and Human Values	On food security and alternative food networks: understanding and performing food security in the context of urban bias.	Australia
Draus et al.	2019	Urban Ecosystems	A green space vision in Southeast Michigan’s most heavily industrialized area.	USA
Olsson	2018	Bulletin of Geography	Urban food systems as vehicles for sustainability transitions.	Sweden
Olsson et al.	2016	Sustainability	Peri-Urban Food Production and Its Relation to Urban Resilience.	Sweden, Denmark and Belgium
Edwards et al.	2011	Asia-Pacific Journal of Public Health	Climate change adaptation at the intersection of food and health.	Australia
Faivre et al.	2017	Environmental Research	Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges.	EU
Ferreira et al.	2013	Energy Procedia	Improving Urban Ecosystems Resilience at a City Level the Coimbra Case Study.	Portugal

Frantzeskaki & Tilie	2014	AMBIO	The dynamics of urban ecosystem governance in Rotterdam, the Netherlands.	The Netherlands
Haase et al.	2014	AMBIO	A quantitative review of urban ecosystem service assessments: concepts, models, and implementation.	global
Hara et al.	2018	Sustainability Science	Assessing urban agriculture potential: a comparative study of Osaka, Japan and New York city, United States.	Japan and USA
James & Friel	2015	Public Health Nutrition	An integrated approach to identifying and characterising resilient urban food systems to promote population health in a changing climate.	Australia
Kosanovic & Fikfak	2015	Energy & Buildings	Development of criteria for ecological evaluation of private residential lots in urban areas.	Slovenia and Serbia
Lee & Lee	2016	International Journal of Climate Change Strategies and Management	Evolutionary urban climate resilience: assessment of Seoul's policies.	South Korea
Ling & Chiang	2018	Journal of Cleaner Production	Well-being, health and urban coherence-advancing vertical greening approach toward resilience: A design practice consideration.	Taiwan
Mabon & Shih	2018	World Development	What might "just green enough"urban development mean in the context of climate change adaptation? The case of urban greenspace planning in Taipei Metropolis, Taiwan.	Taiwan
Mabon	2019	Landscape and Urban Planning	Enhancing post-disaster resilience by "building back greener": Evaluating the contribution of nature-based solutions to recovery planning in Futaba County, Fukushima Prefecture, Japan.	Japan
McGrail et al.	2015	Sustainability	Framing Processes in the Envisioning of Low-Carbon, Resilient Cities:	Australia

			Results from Two Visioning Exercises.	
McMillen et al.	2016	Sustainability	Recognizing Stewardship Practices as Indicators of Social Resilience: In Living Memorials and in a Community Garden.	USA
McPhearson et al.	2014	AMBIO	Urban ecosystem services for resilience planning and management in New York City.	USA
Molnar et al.	2010	Environment: Science and Policy for Sustainable Development	Using Higher Education-Community Partnerships to Promote Urban Sustainability.	USA
Monaco et al.	2017	Sustainability	Food Production and Consumption: City Regions between Localism, Agricultural Land Displacement, and Economic Competitiveness.	European countries
Monsson	2015	Local Economy	Resilience in the city-core and its hinterland: The case of Copenhagen	Denmark
Plant et al.	2012	Australian Geographer	The Wild Life of Pesticides: urban agriculture, institutional responsibility, and the future of biodiversity in Sydney's Hawkesbury-Nepean River.	Australia
Privitera et al.	2018	European Planning Studies	Towards lower carbon cities: urban morphology contribution in climate change adaptation strategies.	Italy
Sanye-Mengual et al. a	2018	PLoS One	Social acceptance and perceived ecosystem services of urban agriculture in Southern Europe: The case of Bologna, Italy.	Italy
Sanye-Mengual et al. b	2015	The International Journal of Life Cycle Assessment	An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level.	Spain
Schlecht & Samuel	2015	Environmental Pollution	Wild growing mushrooms for the Edible City? Cadmium and lead content in edible mushrooms	Germany

			harvested within the urban agglomeration of Berlin, Germany.	
Schuetze et al.	2013	Sustainability	Sustainable Urban (re-)Development with Building Integrated Energy, Water and Waste Systems.	Germany
Scott et al.	2016	Planning Theory & Practice	Nature-based solutions for the contemporary city/Re-naturing the city/Reflections on urban landscapes, ecosystems services and nature-based solutions in cities/Multifunctional green infrastructure and climate change adaptation: brownfield greening as an adaptation strategy for vulnerable communities?/Delivering green infrastructure through planning: insights from practice in Fingal, Ireland/Planning for biophilic cities: from theory to practice.	multiple
Sharifi & Yamagata	2014	Energy Procedia	Resilient Urban Planning: Major Principles and Criteria.	multiple
Sieber & Pons	2015	Procedia Engineering	Assessment of Urban Ecosystem Services using Ecosystem Services Reviews and GIS-based Tools.	Singapore
Smith et al.	2017	International Journal of Sustainable Development & World Ecology	Facilitating resilient rural-to-urban sustainable agriculture and rural communities	UK and USA
Speak et al.	2015	Urban Forestry & Urban Greening	Allotment gardens and parks: Provision of ecosystem services with an emphasis on biodiversity.	UK and Poland
Panagopoulos et al.	2018	Urbanism	Urban green infrastructure: the role of urban agriculture in city resilience.	European countries
van der Jagt et al.	2017	Environmental Research	Cultivating nature-based solutions: The governance of communal urban gardens in the European Union.	EU
Voskamp & Van de Ven	2015	Building and Environment	Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events.	multiple

Winiwarter et al.	2014	Current Opinion in Environmental Sustainability	A European perspective of innovations towards mitigation of nitrogen-related greenhouse gases.	European countries

Chapter 3

SUPPORTING INFORMATION

Measure Your Harvest: insights from a long-term study on the contribution of own-growing to food security in the UK

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CONTENT

Table S23	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual onion yields (kg m^{-2} yr^{-1}).**
Table S24	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual parsnip yields (kg m^{-2} yr^{-1}).**
Table S25	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual pea yields (kg m^{-2} yr^{-1}).**
Table S26	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual plum yields (kg m^{-2} yr^{-1}).**
Table S27	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual potato yields (kg m^{-2} yr^{-1}).**
Table S28	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual raspberries yields (kg m^{-2} yr^{-1}).**
Table S29	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual rhubarb yields (kg m^{-2} yr^{-1}).**
Table S30	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual runner bean yields (kg m^{-2} yr^{-1}).**
Table S31	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual squash / pumpkins yields (kg m^{-2} yr^{-1}).**
Table S32	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual strawberry yields (kg m^{-2} yr^{-1}).**
Table S33	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual sweetcorn yields (kg m^{-2} yr^{-1}).**
Table S34	**Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors on annual tomato (kg m^{-2} yr^{-1}).**

Table S1 List of MYHarvest crops with scientific names

Common name	Scientific name
Apple	*Malus domestica*
Asparagus	*Asparagus officinalis*
Beetroot	*Beta vulgaris (variety rubra)*
Blackberry	*Rubus fruticosus*
Blueberry	*Vaccinium meridionale*
Broad beans	*Vicia faba*
Broccoli	*Brassica oleracea (variety italica)*
Brussel sprouts	*Brassica oleracea (variety gemmifera)*
Cabbage	*Brassica oleracea (variety capitata)*
Carrot	*Daucus carota*
Cauliflower	*Brassica oleracea (variety botrytis)*
Chard	*Beta vulgaris (variety cicla)*
Courgette	*Cucurbita pepo*
Cucumber	*Cucumis sativus*
Currant	*Ribes nigrum*
French beans	*Phaseolus vulgaris*
Garlic	*Allium sativum*
Gooseberry	*Ribes uva-crispa*
Jerusalem Artichoke	*Helianthus tuberosus*
Kale	*Brassica oleracea (variety sabellica)*
Leek	*Allium porrum*
Lettuce	*Lactuca sativa*
Loganberry	*Rubus loganobaccus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*
Pear	*Pyrus communis*
Peas	*Pisum sativum*
Pepper	*Capsicum annuum*
Plum	*Prunus domestica*
Potato	*Solanum tuberosum*
Radish	*Raphanus sativus*
Raspberry	*Rubus idaeus*
Rhubarb	*Rheum rhabarbarum*
Runner beans	*Phaseolus coccineus*
Spinach	*Spinacia oleracea*
Squash / Pumpkin	*Cucurbita pepo (also C. moschata; C. maxima)*
Strawberry	*Fragaria ananassa*
Sweetcorn	*Zea mays*
Tomato	*Solanum lycopersicum*
Turnips / Swedes	*Brassica rapa / Brassica napus (variety napobrassica)*

Table S2 Soil type categories used as predictors of own-grow crop yield, derived from the 'Soilscapes' database[a]

'SOILSCAPE' description	Soil type group
Fen peat soils	Peat
Freely draining acid loamy soils over rock	Loamy acidic
Freely draining floodplain soils	Loamy lime
Freely draining lime-rich loamy soils	Loamy lime
Freely draining slightly acid but base-rich soils	Loamy acidic
Freely draining slightly acid loamy soils	Loamy acidic
Freely draining slightly acid sandy soils	Sandy acidic
Freely draining very acid sandy and loamy soils	Sandy acidic
Lime-rich loamy and clayey soils with impeded drainage	Loamy lime
Loamy and clayey floodplain soils with naturally high groundwater	Loamy high groundwater
Loamy and clayey soils of coastal flats with naturally high groundwater	Loamy high groundwater
Loamy and sandy soils with naturally high groundwater and a peaty surface	Loamy high groundwater
Loamy soils with naturally high groundwater	Loamy high groundwater
Naturally wet very acid sandy and loamy soils	Sandy acidic
Shallow lime-rich soils over chalk or limestone	Loamy lime
Slightly acid loamy and clayey soils with impeded drainage	Loamy acidic
Slowly permeable seasonally wet acid loamy and clayey soils	Loamy acidic
Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils	Loamy acidic
Slowly permeable wet very acid upland soils with a peaty surface	Peaty acidic
Very acid loamy upland soils with a wet peaty surface	Peaty acidic
water	*NA*
NA	*NA*

[a] from www.landis.org.uk

Table S3 Descriptive statistics of MYHarvest data subsets[a] across five growing years[b]

	n			
	All data	**Non-zero harvest data**	**All model data**	**Outlier-free model data**
Participants	452	452	360	329
Growing sites	475	475	378	346
Harvests	10737	10638	8600	6371
Crop types	44	44	44	44
Crop varieties	3998	3976	3317	2618

[a] 'All data' includes all harvest data submitted by participants during the study period; 'Non-zero harvest data' includes all data except submissions with a harvest weight of 0 g; 'All model data' includes all non-zero harvests for which corresponding information on all four predictors of yields tested (i.e. space type, organic growing, greenhouse growing, soil type, growing season temperature) was available; 'Outlier-free model data' includes non-zero harvests after systematic removal of outliers in weight and cultivated area by crop type for which corresponding information on all four predictors was available

[b] From March 2017 to February 2022

Table S4 Descriptive statistics of MYHarvest data subsets used in mixed model analyses[a] across five growing years[b]

	Harvests (n)			
	All model data		Outlier-free model data	
Predictor	**n**	**%**	**n**	**%**
Space type				
Allotment	4928	57.30	3485	54.70
Garden	3508	40.79	2770	43.48
Other space	164	1.91	116	1.82
Method				
Organic	4882	56.77	3669	57.59
Non-organic	3718	43.23	2702	42.41
Greenhouse				
Greenhouse	545	6.34	414	6.50
Open air	8055	93.66	5957	93.50
Soil type				
Loamy acidic	6275	72.97	4734	74.31
Loamy high groundwater	556	6.47	396	6.22
Loamy lime	1226	14.26	918	14.41
Peat	144	1.67	59	0.93
Peaty acidic	34	0.40	29	0.46
Sandy acidic	365	4.24	235	3.69

[a] 'All model data' includes all non-zero harvests for which corresponding information on all four predictors of yields tested (i.e. space type, organic growing, greenhouse growing, soil type, growing season temperature) was available; 'Outlier-free model data' includes non-zero harvests after systematic removal of outliers in weight and cultivated area by crop type for which corresponding information on all four predictors was available

[b] From March 2017 to February 2022

Table S5 Descriptive statistics of MYHarvest data subset used in mixed model analyses including outliers in crop weight and cultivated area, in each growing year

	Growing year										
	2017-2018		2018-2019		2019-2020		2020-2021		2021-2022		
	n	%	n	%	n	%	n	%	n	%	Total
Participants	179	31.57	193	34.04	90	15.87	56	9.88	49	8.64	567
Growing sites	187	31.59	202	34.12	92	15.54	59	9.97	52	8.78	592
Harvests	2392	27.81	2960	34.42	1139	13.24	1110	12.91	999	11.62	8600
Crop types	40	90.91	44	100.00	44	100.00	43	97.73	44	100.00	44
Varieties	1195	36.03	1441	43.44	731	22.04	683	20.59	649	19.57	3317
Space type											
Allotment	1408	58.86	1821	61.52	585	51.36	646	58.2	468	46.85	
Garden	945	39.51	1040	35.14	535	46.97	457	41.2	531	53.15	
Other	39	1.63	99	3.34	19	1.67	7	0.6	0	0.00	
Method											
Organic	1424	59.53	1545	52.20	622	54.61	677	61.0	614	61.46	
Non-organic	968	40.47	1415	47.80	517	45.39	433	39.0	385	38.54	

Table S6 Descriptive statistics of MYHarvest data subset used in mixed model analyses excluding outliers in crop weight and cultivated area, in each growing year

	Growing year										
	2017-2018		2018-2019		2019-2020		2020-2021		2021-2022		
	n	%	n	%	n	%	n	%	n	%	Total
Participants	157	30.08	184	35.25	84	16.09	52	9.96	45	8.62	522
Growing sites	164	30.26	192	35.42	85	15.68	54	9.96	47	8.67	542
Harvests	171	3.54	2189	45.31	835	17.28	846	17.51	790	16.35	4831
Crop types	40	90.91	44	100.00	44	100.00	43	97.73	44	100.00	44
Varieties	893	34.11	1141	43.58	584	22.31	562	21.47	550	21.01	2618
Space type											
Allotment	951	55.58	1329	60.71	400	47.90	458	54.14	347	43.92	
Garden	736	43.02	791	36.14	419	50.18	381	45.04	443	56.08	
Other	24	1.40	69	3.15	16	1.92	7	0.83	0	0.00	
Method											
Organic	1035	60.49	1179	53.86	486	58.20	522	61.70	447	56.58	
Non-organic	676	39.51	1010	46.14	349	41.80	324	38.30	343	43.42	

Table S7 Sample sizes of different own-grown crops in data subsets used in mixed model analyses[a], across five growing years[b]

Crop	Participants growing	Sites growing	Harvests	
			All model data	Outlier-free model data
Apple	134	136	288	206
Asparagus	33	33	62	53
Beetroot	199	201	264	182
Blackberry	54	54	59	42
Blueberry	31	31	49	41
Broad beans	208	212	274	212
Broccoli	104	104	157	121
Brussel sprouts	59	59	90	68
Cabbage	133	133	235	173
Carrot	152	155	238	169
Cauliflower	36	36	48	44
Chard	51	52	67	54
Courgettes	259	263	387	247
Cucumber	101	102	152	117
Currant	176	177	278	229
French beans	227	229	367	243
Garlic	73	74	108	79
Gooseberry	158	159	217	169
Jerusalem Artichoke	10	10	11	6
Kale	50	52	89	73
Leek	145	145	234	183
Lettuce / salad leaves	183	187	283	225
Loganberry	13	13	19	16
Onion	207	210	375	280
Other	229	236	861	673
Parsnip	90	90	164	128
Pear	25	25	45	30
Peas	211	215	297	220
Pepper	48	48	82	64
Plum	74	76	125	96
Potato	292	299	612	465
Radish	40	41	42	34
Raspberry	209	215	277	171
Rhubarb	104	105	122	95
Runner beans	197	203	260	160
Spinach	42	42	55	35
Squash / Pumpkin	131	132	213	170
Strawberry	208	210	270	185
Sweetcorn	132	132	175	140
Tomato	219	223	480	335
Trained Apple	20	20	47	39
Trained Pear	8	8	13	13

Trained Plum	8	8	11	9
Turnip / Swede	64	64	98	77
TOTAL	452	475	8600	6371

[a] 'All model data' includes all non-zero harvests for which corresponding information on all four predictors of yields tested (i.e. space type, organic growing, greenhouse growing, soil type, growing season temperature) was available; 'Outlier-free model data' includes non-zero harvests after systematic removal of outliers in weight and cultivated area by crop type for which corresponding information on all four predictors was available

[b] From March 2017 to February 2022

Table S8 Bootstrapped mean yields (kg m^{-2} yr^{-1}), standard errors (SE) and 95% confidence intervals (2.5% and 97.5% CI) of own-grown crop types[a] based on our mixed effects models[b]

Crop	Yield (kg m^{-2} yr^{-1})	SE	2.5% CI	97.5% CI
Apple	0.92	0.09	0.76	1.11
Asparagus	0.47	0.08	0.35	0.63
Beetroot	2.38	0.14	2.12	2.67
Blackberry	3.23	1.02	2.00	5.93
Blueberry	2.30	0.95	1.18	4.90
Broad beans	1.49	0.14	1.26	1.79
Broccoli	0.62	0.07	0.49	0.79
Brussel sprouts	0.86	0.17	0.63	1.30
Cabbage	1.76	0.19	1.46	2.17
Carrot	2.27	0.44	1.82	3.20
Cauliflower	1.38	0.21	1.02	1.85
Chard	1.76	0.36	1.21	2.55
Courgette	4.78	0.42	4.04	5.72
Cucumber	6.81	1.13	5.22	9.59
Currant	1.11	0.08	0.96	1.28
French beans	1.73	0.13	1.51	2.01
Garlic	0.92	0.10	0.75	1.14
Gooseberry	1.61	0.12	1.39	1.87
Jerusalem Artichoke	1.46	0.17	1.16	1.82
Kale	0.81	0.13	0.60	1.11
Leek	0.90	0.07	0.77	1.06
Lettuce / salad leaves	1.26	0.14	1.03	1.60
Onion	1.47	0.09	1.30	1.64
Parsnip	2.14	0.17	1.84	2.51
Pear	1.10	0.35	0.64	1.93
Peas	0.97	0.08	0.83	1.13
Pepper	3.27	0.57	2.40	4.57
Plum	0.55	0.08	0.43	0.73
Potato	2.45	0.10	2.27	2.68
Radish	1.53	0.27	1.08	2.12
Raspberry	0.75	0.07	0.63	0.91
Rhubarb	2.70	0.32	2.10	3.39
Runner beans	3.81	0.37	3.18	4.67
Spinach	2.94	1.26	1.30	6.12
Squash / pumpkin	2.65	0.24	2.20	3.15
Strawberry	0.81	0.08	0.67	1.00
Sweetcorn	1.09	0.08	0.94	1.23
Tomato	4.57	0.27	3.90	5.01

[a] Own-grown crop types on which data was collected in the MYHarvest project, excluding loganberries and 'Other' crops

[b] Bootstraps were run using 1000 simulations, on models including site as a random effect, and growing method, space type, soil type, mean growing season temperature, and, for cucumber, lettuce / salad leaves, pepper, strawberry and tomato, also greenhouse growing, as fixed effects

Table S9 List of crops with sufficient sample sizes for mixed effects analyses[a] of predictors of yields

	Harvests	
Crop	**All model data**	**Outlier-free model data**
Potato	612	465
Tomato	480	335
Onion	375	280
Courgette	387	247
French / climbing beans	367	243
Currant	278	229
Lettuce / salad leaves	283	225
Peas	297	220
Broad beans	274	212
Apple	288	206
Strawberry	270	185
Leek	234	183
Beetroot	264	182
Cabbage	235	173
Raspberry	277	171
Squash / Pumpkin	213	170
Carrot	238	169
Gooseberry	217	169
Runner beans	260	160
Sweetcorn	175	140
Parsnip	164	128
Broccoli	157	121
Cucumber	152	117
Plum	125	96
Rhubarb	122	95

[a] 'All model data' includes all non-zero harvests for which corresponding information on all four predictors of yields tested (i.e. space type, organic growing, greenhouse growing, soil type, growing season temperature) was available; 'Outlier-free model data' includes non-zero harvests after systematic removal of outliers in weight and cultivated area by crop type for which corresponding information on all four predictors was available

Table S10 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of apples

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	4.521	1	0.034	4.628	0.034	0.638	1	0.425	0.641	0.426
Space type	0.134	2	0.935	0.067	0.935	0.252	1	0.616	0.257	0.614
Soil type	9.695	4	0.046	2.549	0.043	10.692	4	0.030	2.820	0.029
Growing season T (˚C)	4.255	1	0.039	4.352	0.039	1.478	1	0.224	1.523	0.221

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S11 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of beetroots

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.058	1	0.809	0.058	0.809	0.034	1	0.853	0.034	0.854
Space type	0.951	2	0.622	0.477	0.621	1.330	2	0.514	0.669	0.514
Soil type	1.090	5	0.955	0.220	0.954	2.766	5	0.736	0.558	0.732
Growing season T (˚C)	0.202	1	0.653	0.202	0.654	0.996	1	0.318	1.005	0.318

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S12 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of broad beans

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.904	1	0.342	0.905	0.343	1.116	1	0.291	1.120	0.292
Space type	3.249	2	0.197	1.643	0.196	0.867	2	0.648	0.435	0.648
Soil type	1.474	4	0.831	0.369	0.830	4.455	4	0.348	1.126	0.347
Growing season T (˚C)	0.965	1	0.326	0.967	0.327	4.085	1	0.043	4.128	0.044

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S13 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of broccoli

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.038	1	0.846	0.038	0.847	4.490	1	0.034	4.574	0.034
Space type	0.801	2	0.670	0.402	0.671	2.609	2	0.271	1.319	0.271
Soil type	6.261	4	0.181	1.633	0.181	10.554	4	0.032	2.757	0.031
Growing season T (˚C)	0.003	1	0.960	0.003	0.960	1.021	1	0.312	1.026	0.313

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S14 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of cabbage

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	2.687	1	0.101	2.754	0.100	2.980	1	0.084	3.065	0.084
Space type	1.244	2	0.537	0.628	0.536	5.564	2	0.062	2.899	0.059
Soil type	3.328	5	0.650	0.687	0.635	8.779	5	0.118	1.869	0.107
Growing season T (˚C)	0.992	1	0.319	0.994	0.321	0.325	1	0.569	0.338	0.562

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S15 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of carrots

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.037	1	0.847	0.037	0.847	0.032	1	0.858	0.032	0.858
Space type	0.980	2	0.613	0.491	0.613	0.639	2	0.727	0.327	0.722
Soil type	3.847	5	0.572	0.779	0.567	2.753	5	0.738	0.558	0.732
Growing season T (˚C)	0.794	1	0.373	0.797	0.374	0.000	1	0.994	0.000	0.994

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S16 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of courgettes

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.091	1	0.763	0.091	0.763	0.410	1	0.522	0.411	0.523
Space type	0.083	2	0.959	0.042	0.959	0.098	2	0.614	0.489	0.614
Soil type	4.664	5	0.458	0.960	0.445	2.034	4	0.730	0.511	0.728
Growing season T (˚C)	0.436	1	0.509	0.436	0.510	0.004	1	0.950	0.004	0.950

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S17 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of cucumbers

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.085	1	0.771	0.085	0.771	1.337	1	0.248	1.377	0.245
Space type	1.732	2	0.421	0.875	0.421	1.783	2	0.410	0.906	0.409
Soil type	1.017	1	0.313	1.033	0.311	0.083	1	0.773	0.084	0.773
Greenhouse	3.135	5	0.679	0.644	0.667	10.554	5	0.061	2.284	0.059
Growing season T (˚C)	1.459	1	0.227	1.468	0.230	0.082	1	0.774	0.083	0.775

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), greenhouse growing (yes or no), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S18 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of currants

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.319	1	0.572	0.320	0.572	0.242	1	0.623	0.244	0.622
Space type	0.168	2	0.919	0.084	0.919	0.120	2	0.942	0.060	0.942
Soil type	1.026	5	0.960	0.206	0.959	11.508	3	0.021	2.956	0.023
Growing season T (˚C)	0.204	1	0.651	0.205	0.652	0.557	1	0.456	0.559	0.456

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S19 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of French beans

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.023	1	0.881	0.023	0.881	0.084	1	0.773	0.083	0.773
Space type	2.330	2	0.312	1.173	0.312	0.436	2	0.804	0.218	0.804
Soil type	11.001	5	0.051	2.272	0.049	6.646	5	0.248	1.354	0.245
Growing season T (˚C)	0.264	1	0.607	0.265	0.607	0.232	1	0.630	0.237	0.627

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S20 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of gooseberries

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	3.624	1	0.057	3.670	0.058	0.945	1	0.331	0.952	0.332
Space type	0.051	1	0.821	0.051	0.821	0.990	1	0.320	0.994	0.321
Soil type	0.751	5	0.980	0.151	0.979	1.810	5	0.875	0.364	0.871
Growing season T (˚C)	1.259	1	0.262	1.264	0.264	0.047	1	0.829	0.047	0.829

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S21 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of leeks

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.153	1	0.696	0.153	0.696	0.005	1	0.945	0.005	0.946
Space type	0.376	2	0.829	0.191	0.826	1.119	2	0.571	0.571	0.567
Soil type	10.120	4	0.039	2.641	0.038	10.105	4	0.039	2.684	0.036
Growing season T (˚C)	0.520	1	0.475	0.512	0.476	0.812	1	0.368	0.814	0.369

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S22 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of lettuce / salad leaves

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.033	1	0.857	0.033	0.857	0.027	1	0.870	0.027	0.869
Space type	4.592	2	0.101	2.337	0.100	5.529	2	0.063	2.849	0.061
Soil type	0.034	1	0.854	0.034	0.854	0.180	1	0.672	0.181	0.671
Greenhouse	2.750	4	0.600	0.691	0.600	2.429	4	0.488	0.815	0.488
Growing season T (˚C)	0.021	1	0.886	0.021	0.886	0.050	1	0.823	0.051	0.822

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), greenhouse growing (yes or no), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S23 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of onions

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.065	1	0.799	0.065	0.799	0.557	1	0.455	0.572	0.452
Space type	2.352	2	0.309	1.191	0.307	3.660	2	0.161	1.920	0.154
Soil type	10.120	5	0.072	2.105	0.069	2.371	5	0.796	0.513	0.766
Growing season T (˚C)	1.702	1	0.192	1.723	0.191	3.675	1	0.055	3.887	0.052

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S24 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of parsnips

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	3.141	1	0.076	3.195	0.079	1.294	1	0.255	1.304	0.259
Space type	1.801	2	0.406	0.918	0.405	3.759	2	0.153	2.023	0.143
Soil type	1.156	4	0.885	0.296	0.880	0.767	4	0.943	0.196	0.940
Growing season T (°C)	2.497	1	0.114	2.571	0.114	0.159	1	0.69	0.160	0.690

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S25 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of peas

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	1.054	1	0.305	1.061	0.304	0.237	1	0.627	0.237	0.627
Space type	1.314	2	0.518	0.659	0.519	2.998	2	0.223	1.519	0.223
Soil type	2.782	5	0.734	0.562	0.729	3.337	5	0.648	0.675	0.643
Growing season T (°C)	0.674	1	0.412	0.678	0.411	0.543	1	0.461	0.547	0.461

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S26 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of plums

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.497	1	0.481	0.500	0.482	1.457	1	0.227	1.533	0.223
Space type	3.958	2	0.138	2.033	0.138	1.052	1	0.305	1.087	0.303
Soil type	5.647	3	0.130	1.983	0.126	0.036	3	0.998	0.012	0.998
Growing season T (˚C)	5.993	1	0.014	6.270	0.015	1.036	1	0.850	0.036	0.850

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S27 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of potatoes

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.108	1	0.743	0.108	0.743	0.033	1	0.856	0.033	0.856
Space type	0.175	2	0.916	0.088	0.916	1.784	2	0.410	0.901	0.408
Soil type	3.432	4	0.488	0.863	0.487	5.945	3	0.114	2.014	0.114
Growing season T (˚C)	3.858	1	0.050	3.883	0.050	4.121	1	0.042	4.145	0.043

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Table S28 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of raspberries

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.499	1	0.480	0.502	0.480	0.002	1	0.962	0.002	0.962
Space type	0.446	2	0.504	0.366	0.694	1.294	2	0.524	0.649	0.524
Soil type	1.433	4	0.839	0.361	0.836	0.935	3	0.817	0.314	0.815
Growing season T (˚C)	0.674	1	0.412	0.447	0.505	0.089	1	0.766	0.090	0.765

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S29 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of rhubarb

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.183	1	0.669	0.184	0.669	1.900	1	0.168	1.928	0.169
Space type	0.295	2	0.863	0.148	0.863	1.762	2	0.414	0.890	0.415
Soil type	1.035	4	0.905	0.262	0.902	1.249	4	0.87	0.317	0.866
Growing season T (˚C)	0.565	1	0.452	0.584	0.447	1.264	1	0.261	1.323	0.254

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S30 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of runner beans

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.020	1	0.886	0.020	0.887	0.017	1	0.898	0.017	0.898
Space type	0.530	2	0.767	0.265	0.767	1.809	2	0.405	0.913	0.405
Soil type	2.244	5	0.815	0.452	0.811	1.668	5	0.893	0.336	0.890
Growing season T (˚C)	0.896	1	0.344	0.897	0.345	0.249	1	0.618	0.249	0.619

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S31 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of squash / pumpkins

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.238	1	0.626	0.242	0.624	0.866	1	0.352	0.903	0.346
Space type	0.691	2	0.708	0.354	0.702	1.102	2	0.576	0.554	0.577
Soil type	2.499	4	0.645	0.641	0.635	2.365	4	0.669	0.602	0.662
Growing season T (˚C)	0.683	1	0.409	0.685	0.410	0.931	1	0.335	0.955	0.332

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S32 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of strawberries

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.950	1	0.330	0.956	0.330	0.008	1	0.930	0.008	0.930
Space type	1.621	2	0.445	0.813	0.445	0.366	2	0.833	0.183	0.833
Soil type	2.123	1	0.145	2.136	0.146	4.319	1	0.038	4.378	0.038
Greenhouse	1.389	5	0.926	0.279	0.924	5.595	5	0.348	1.138	0.343
Growing season T (˚C)	0.380	1	0.538	0.381	0.538	1.130	1	0.288	1.135	0.289

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), greenhouse growing (yes or no), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S33 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of sweetcorn

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	0.166	1	0.684	0.166	0.684	1.395	1	0.238	1.490	0.225
Space type	4.893	2	0.087	2.489	0.088	3.574	2	0.167	1.827	0.167
Soil type	1.279	4	0.865	0.323	0.862	5.159	4	0.271	1.401	0.240
Growing season T (˚C)	2.051	1	0.152	2.065	0.153	0.695	1	0.405	0.723	0.397

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)
[b] On the log scale

Table S34 Results of mixed effects analysis of the effect of characteristics of growing practices and soil and climate factors[a] on annual yields[b] (kg m^{-2} yr^{-1}) of tomatoes

	All model data					Outlier-free model data				
	LRT			F test		LRT			F test	
Predictor	**chi**	**df**	**p**	**F**	**p**	**chi**	**df**	**p**	**F**	**p**
Organic growing	1.002	1	0.317	1.004	0.318	0.427	1	0.513	0.428	0.514
Space type	0.005	2	0.997	0.003	0.997	0.909	2	0.635	0.457	0.634
Soil type	8.034	1	0.005	8.228	0.004	8.546	1	0.003	8.735	0.003
Greenhouse	2.080	5	0.838	0.420	0.835	2.079	4	0.721	0.524	0.718
Growing season T (˚C)	1.448	1	0.290	1.453	0.230	2.914	1	0.088	2.976	0.087

[a] Fixed effects included organic growing (yes or no), growing space type (allotment, garden, or other), greenhouse growing (yes or no), soil type (see Table S2), and mean growing season temperature (averaged over 1981-2010; data from the UK Met Office); for the random effects we had intercepts for individual sites and growing years (i.e. March-February, from March 2017 to February 2022)

[b] On the log scale

Chapter 4

SUPPORTING INFORMATION

The contribution of household fruit and vegetable growing to fruit and vegetable self-sufficiency and consumption

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CONTENT

Image S11 **Weekly recording sheet from the 'MYHarvest Diary'.**

Image S12 **Questions about participants from the 'MYHarvest Diary'.**

Image S13 **Questions about participants' growing spaces from the 'MYHarvest Diary'.**

Table S1 Descriptive statistics across participants (N=85) for household size, food growing experience, characteristics of growing spaces and food gardening effort over a year

	Mean	Median	Min	Max	SE
Household size	2.1	2.0	1.0	5.0	0.1
Food growing experience (yrs)	23.5	20.0	0.5	60.0	2.0
Allotment size (m^2)	204.1	150.0	35.0	650.0	14.3
Allotment rent (£ yr^{-1})	45.4	37.0	5.0	170.0	3.6
Allotment food growing area (m^2)	143.8	110.3	40.2	480.6	9.6
Garden food growing area (m^2)	57.1	8.0	0.8	714.5	14.1
Total food growing area (m^2)	168.9	120.5	19.0	714.5	14.0
Mean allotment visits (times wk^{-1})	2.8	2.3	0.5	10.8	0.2
Mean food gardening time (hrs wk^{-1})	5.0	3.8	1.4	16.2	0.4

Note. Statistics specific to allotments or gardens only were calculated for the subset of participants who had that type of growing space.

Table S2 Total weights (kg) of produce recorded in participant households (N=85) from different sources over the course of a year, with corresponding percentage of the grand total

	Total weight (kg)	Percent of total
TOTAL	39,445.3	100.0
Shop/Market	21,265.2	53.9
Allotment	12,339.1	31.3
Garden	4,928.1	12.5
Other growers	830.7	2.1
Foraged	45.1	0.1
Given away	*2,459.3*	*6.2*
Wasted	*494.6*	*1.3*

Note. Italicised rows (i.e., *Given away* and *Wasted*) refer to negative produce fluxes and should be interpreted as amounts of the grand total not consumed within participant households.

Table S3 Number (n) and percentage of all participants (N=85) freezing, preserving, using frozen and using preserved produce in each month of the year

	Freezing		Preserving		Using frozen		Using preserved	
Month	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
January	26	30.6	10	11.8	74	87.1	68	80.0
February	17	20.0	11	12.9	73	85.9	62	72.9
March	17	20.0	10	11.8	70	82.4	62	72.9
April	26	30.6	11	12.9	67	78.8	63	74.1
May	30	35.3	10	11.8	64	75.3	65	76.5
June	51	60.0	31	36.5	59	69.4	54	63.5
July	73	85.9	47	55.3	53	62.4	57	67.1
August	79	92.9	55	64.7	60	70.6	56	65.9
September	73	85.9	60	70.6	67	78.8	58	68.2
October	56	65.9	45	52.9	74	87.1	64	75.3
November	38	44.7	24	28.2	76	89.4	67	78.8
December	29	34.1	7	8.2	75	88.2	63	74.1

Table S4 Descriptive statistics across participant households (N=85) for food production and consumption over the course of a year

	Mean	**Median**	**Min**	**Max**	**SE**
Total household produce consumption (kg yr^{-1})	464.06	433.16	160.96	1564.53	23.63
Total household F&V consumption (kg yr^{-1})	400.73	370.44	126.13	1501.84	21.81
Total household potato consumption (kg yr^{-1})	62.90	51.64	2.00	258.95	4.70
Total allotment produce (kg yr^{-1})	171.38	151.57	10.44	534.74	11.25
Total allotment F&V (kg yr^{-1})	137.42	121.41	1.32	422.48	9.41
Total garden produce (kg yr^{-1})	65.71	23.88	0.01	493.30	11.06
Total garden F&V (kg yr^{-1})	60.66	23.42	0.01	421.64	9.84
Total own-grown produce (kg yr^{-1})	203.15	163.64	34.21	588.65	13.30
Total own-grown F&V (kg yr^{-1})	169.21	142.82	25.40	521.49	11.47
Total own-grown fruit (kg yr^{-1})	40.16	26.57	0.00	235.41	4.89
Total own-grown vegetables (kg yr^{-1})	129.05	107.12	12.74	433.51	9.17
Total own-grown potatoes (kg yr^{-1})	33.90	24.17	0.00	189.59	3.64
Own-grown produce yield (kg m^{-2} yr^{-1})	1.59	1.41	0.18	7.34	0.12
Total purchased produce (kg yr^{-1})	250.18	221.76	28.49	1154.99	17.99
Total purchased F&V (kg yr^{-1})	221.40	187.23	25.99	1129.57	17.05
Total purchased F (kg yr^{-1})	104.53	86.05	2.94	549.50	9.07
Total purchased V (kg yr^{-1})	116.87	100.32	6.46	580.06	9.34
Total purchased potatoes (kg yr-1)	30.61	28.70	0.74	135.55	2.87

Total produce from other growers (kg yr^{-1})	9.77	3.79	0.00	109.69	1.82
Total F&V from other growers (kg yr^{-1})	9.26	3.32	0.00	94.44	1.67
Total foraged produce (kg yr^{-1})	0.53	0.00	0.00	6.97	0.15
Total foraged F&V (kg yr^{-1})	0.49	0.00	0.00	6.97	0.15
Total produce given away (kg yr^{-1})	*28.93*	*16.05*	*0.00*	*181.38*	*3.87*
Total F&V given away (kg yr^{-1})	*25.87*	*15.46*	*0.00*	*164.28*	*3.43*
Total produce waste (kg yr^{-1})	*5.82*	*3.39*	*0.00*	*33.09*	*0.75*
Total produce waste (% of total consumption)	*1.26*	*0.85*	*0.00*	*6.12*	*0.15*
Total F&V waste (kg yr^{-1})	*5.17*	*3.13*	*0.00*	*33.09*	*0.67*
Total F&V waste (% of total consumption)	*1.34*	*0.93*	*0.00*	*7.57*	*0.17*
Year-round produce self-sufficiency (own-grown % of total consumption)	43.70	41.06	14.87	92.33	1.93
Year-round F&V self-sufficiency (own-grown % of total consumption)	42.56	40.26	12.02	91.83	1.99
Year-round fruit self-sufficiency (own-grown percent of total consumption)	26.48	20.20	0.00	77.21	2.12
Year-round vegetable self-sufficiency (own-grown percent of total consumption)	51.22	51.05	8.42	95.52	2.33
Year-round potato self-sufficiency (own-grown percent of total consumption)	53.16	49.69	0.00	100.00	3.21
F&V types consumed in household*	69.64	68.00	32.00	117.00	1.96
F&V types grown*	37.52	38.00	13.00	72.00	1.34
Fruit types consumed in household*	21.86	22.00	6.00	38.00	0.78
Fruit types grown*	7.68	8.00	1.00	14.00	0.37
Vegetable types consumed in household*	48.35	48.00	24.00	87.00	1.42
Vegetable types grown*	30.14	31.00	9.00	69.00	1.17
Mean per capita F&V intake (g d^{-1})**	520.92	507.25	189.24	1376.06	23.23
Mean per capita F&V intake (portions d^{-1})**	6.51	6.34	2.37	17.20	0.29
Mean per capita fruit intake (g day^{-1})**	195.72	182.24	47.22	555.63	11.71
Mean per capita fruit intake (portions day^{-1})**	2.45	2.28	0.59	6.95	0.15
Mean per capita vegetable intake (g day^{-1})**	325.20	310.85	107.47	820.44	15.26
Mean per capita vegetable intake (portions day^{-1})**	4.06	3.89	1.34	10.30	0.19
Mean per capita own F&V (portions day^{-1})**	3.07	2.49	0.53	11.70	0.22
Own percent of annual household '5 a day'	61.47	49.81	10.65	233.26	4.33
Mean per capita own fruit (portions day^{-1})**	0.73	0.45	0.00	4.42	0.09

Mean per capita own vegetable (portions day^{-1})**	2.35	1.93	0.18	9.80	0.17

Note. 'F&V' stands for fruits and vegetables (excluding potatoes), 'produce' includes potatoes and nuts as well as F&V. Italicised rows refer to negative produce fluxes. Statistics specific to allotments or gardens only were calculated for the subset of participants who had that type of growing space. Statistics for produce or F&V received from other growers, foraged, given away, or wasted were calculated for all participants including those who did not have records in that category.

* Number of F&V types grown and consumed are based on recorded names of crops (e.g., red cabbage and savoy cabbage are counted as different types of vegetables), but the same crops spelt in different ways were counted as one (e.g., mange tout = mangetout).

** Mean per capita household F&V intake was calculated by dividing net F&V consumption (= total household F&V consumption - (total F&V donations + total F&V waste)) by household size and number of days for which records were available, and thus assumes equal F&V consumption among household members.

Table S5 Key statistics across participant households (N=85) for food production and consumption over the course of a year (without imputing values for missing weight data)

	Mean	Median	Min	Max	SE
Total household produce consumption (kg yr^{-1})	459.09	430.64	160.96	1564.00	23.85
Total household F&V consumption (kg yr^{-1})	395.80	366.54	122.59	1501.31	22.02
Total household potato consumption (kg yr^{-1})	62.86	51.64	2.00	258.95	4.70
Year-round produce self-sufficiency (own-grown % of total consumption)	44.29	41.30	14.90	92.33	1.97
Year-round F&V self-sufficiency (own-grown % of total consumption)	43.35	41.72	12.27	92.46	2.08
Year-round fruit self-sufficiency (own-grown percent of total consumption)	27.65	20.75	0.00	77.21	2.22
Year-round vegetable self-sufficiency (own-grown percent of total consumption)	51.39	51.05	8.42	95.65	2.36
Year-round potato self-sufficiency (own-grown percent of total consumption)	53.22	50.55	0.00	100.00	3.20
Mean per capita F&V intake (portions day^{-1})*	6.42	6.07	2.40	17.20	0.29
Mean per capita fruit intake (portions day^{-1})*	2.39	2.14	0.39	6.94	0.15
Mean per capita vegetable intake (portions day^{-1})*	4.04	3.87	1.34	10.30	0.19

Note. 'F&V' stands for fruits and vegetables (excluding potatoes), 'produce' includes potatoes and nuts as well as F&V. Italicised rows refer to negative produce fluxes. Statistics specific to allotments or gardens only were calculated for the subset of participants who had that type of growing space. Statistics for produce or F&V received from other growers, foraged, given away, or wasted were calculated for all participants including those who did not have records in that category.

* Mean per capita household F&V intake was calculated by dividing net F&V consumption (= total household F&V consumption - (total F&V donations + total F&V waste)) by household size and number of days for which records were available, and thus assumes equal F&V consumption among household members. One portion = 80 g.

Table S6 Descriptive statistics across participant households (N=85) for weights of own-grown produce harvested in each month of the year

	Total own-grown produce weight (kg)				
Month	**Mean**	**Median**	**Min**	**Max**	**SE**
January	3.8	2.6	0.0	26.0	0.5
February	2.4	1.2	0.0	22.8	0.4
March	2.5	1.5	0.0	14.0	0.3
April	2.9	1.7	0.0	16.2	0.4
May	5.2	3.7	0.0	40.2	0.7
June	12.9	9.8	0.9	78.5	1.3
July	35.3	27.4	2.0	148.1	3.2
August	64.0	54.2	7.6	297.3	5.4
September	40.0	26.8	4.2	180.9	3.9
October	19.0	12.2	0.7	98.3	2.0
November	10.5	6.4	0.0	163.3	2.0
December	4.5	2.7	0.0	39.1	0.6

Table S7 Descriptive statistics across participant households (N=85) for weights of purchased produce harvested in each month of the year

	Total purchased produce weight (kg)				
Month	**Mean**	**Median**	**Min**	**Max**	**SE**
January	24.9	23.0	0.0	98.9	1.8
February	23.3	21.1	0.8	76.2	1.6
March	26.5	24.3	0.8	157.3	2.2
April	22.7	21.2	2.9	78.6	1.5
May	27.0	24.0	5.6	101.6	1.8
June	18.7	16.0	0.0	87.4	1.5
July	16.1	13.1	0.0	140.8	1.9
August	14.9	11.9	0.8	114.1	1.6
September	12.6	11.1	0.0	47.8	1.1
October	18.6	15.0	0.5	73.0	1.6
November	23.5	17.8	0.4	131.6	2.1
December	21.3	18.3	0.8	85.7	1.8

Table S8 Descriptive statistics across participant households (N=85) for weights of wasted produce harvested in each month of the year

	Total produce waste weight (kg)				
Month	**Mean**	**Median**	**Min**	**Max**	**SE**
January	0.3	0.0	0.0	3.1	0.1
February	0.2	0.0	0.0	3.5	0.1
March	0.2	0.0	0.0	2.3	0.0
April	0.1	0.0	0.0	2.0	0.0
May	0.3	0.0	0.0	4.0	0.1
June	0.2	0.0	0.0	3.2	0.1
July	0.4	0.0	0.0	3.7	0.1
August	1.2	0.2	0.0	9.2	0.2
September	1.5	0.2	0.0	18.8	0.3
October	0.8	0.2	0.0	13.4	0.2
November	0.3	0.0	0.1	3.2	0.1
December	0.3	0.0	0.1	8.0	0.1

Table S9 Descriptive statistics across participant households (N=85) for percentage of own-grown produce of total household produce consumption in each month of the year

	Own-grown percent of total monthly produce consumption				
Month	**Mean**	**Median**	**Min**	**Max**	**SE**
January	16.0	8.2	0.0	100.0	2.2
February	11.4	4.8	0.0	93.4	1.8
March	11.2	7.2	0.0	93.1	1.7
April	14.1	8.1	0.0	80.7	1.8
May	16.8	13.2	0.0	72.2	1.7
June	40.0	35.9	4.6	100.0	2.6
July	64.0	66.7	9.9	99.2	2.4
August	73.9	77.2	28.6	98.2	1.9
September	67.2	67.4	30.5	100.0	2.2
October	46.1	43.7	3.7	96.3	2.6
November	29.6	25.1	0.0	88.1	2.4
December	19.7	10.8	0.0	93.3	2.3

Table S10 Values used to complete missing data on produce weights

Produce (type, amount)	Estimated weight (g)	Source
Apples (Braeburn, one)	134	tesco.com
Apples (pack of six)	804	tesco.com
Apricot (halves in juice)	234	tesco.com
Apricot (one)	53	cookipedia.co.uk
Artichoke (one)	120	recipeland.com
Asparagus (one stem)	16	traditionaloven.com
Aubergine (one)	350	shopappy.com
Avocado (Gem, one)	160	tesco.com
Baked beans (tin)	420	tesco.com
Banana (one)	150	tesco.com
Beans (borlotti, tin)	246	tesco.com
Beans (cannellini, tin)	246	tesco.com
Beans (green, tin)	235	tesco.com
Beans (kidney, tin)	220	tesco.com
Beetroot (bunch of three)	450	tesco.com
Beetroot (one)	150	tesco.com
Blackberries (tray)	150	tesco.com
Blueberries (tray)	150	tesco.com
Broccoli (one)	375	tesco.com
Cabbage (white, one)	908	howmuchisin.com
Carrot (bunch of four)	244	whatthingsweigh.com
Carrot (one)	61	whatthingsweigh.com
Cauliflower (one)	588	whatthingsweigh.com
Celery (one)	320	tesco.com
Chard (rainbow, pack)	200	tesco.com
Chickpeas (tin)	240	tesco.com
Chillies (one)	22	tesco.com
Chillies (pack of three)	65	tesco.com
Clementine (one)	50	tesco.com
Clementine (pack)	600	tesco.com
Corn on the cob (one ear)	180	Measured by participant
Courgette (one)	167	tesco.com
Courgette (pack of three)	500	tesco.com
Cucumber (one)	201	whatthingsweigh.com
Fennel (one)	250	tesco.com
Fig (one)	50	traditionaloven.com
Garlic (one head)	105	big-garlic.com
Ginger (one)	63	tesco.com
Grapefruit (one)	374	tesco.com
Grapes (tray)	150	tesco.com
Herbs ('Great for roasting', bunch)	30	tesco.com
Jalapeno (one)	20	cooksinfo.com
Kale (curly, pack)	180	tesco.com
Kale (one leaf)	57	smoothie-handbook.com
Kalette (pack)	200	sainsburys.co.uk
Kiwi (one)	75	tesco.com

Kiwi (pack of six)	450	tesco.com
Leek (pack of four)	500	tesco.com
Lemon (one)	70	whatthingsweigh.com
Lentils (tin)	235	tesco.com
Lettuce (average head)	300	befreshproduce.com
Lettuce (small head)	200	Own measurement
Lime (one)	67	healthline.com
Mango (one)	336	mango.org
Marrow (one)	1250	cooksinfo.com
Melon (Cantaloupe, one)	1500	cooksinfo.com
Mixed veg (frozen pack)	1000	tesco.com
Mushroom (chestnut, tray)	250	tesco.com
Mushroom (Portobello, one)	85	howmuchisin.com
Nectarine (one)	80	tesco.com
Olives (black pitted, jar)	163	tesco.com
Onion (brown, pack of three)	385	tesco.com
Onion (large bag)	1000	tesco.com
Onion (one)	128	tesco.com
Orange (one)	131	reference.com
Orange (pack of five)	655	tesco.com
Parsnip (one)	100	tesco.com
Parsnip (pack of five)	500	tesco.com
Passion fruit (pack of three)	40	tesco.com
Peach (one)	150	weightofstuff.com
Pear (one)	102	tesco.com
Pepper (one)	170	tesco.com
Persimmon (one)	168	healthline.com
Pineapple (one)	1775	cbi.eu
Pineapple (slice)	175	whatthingsweigh.com
Plum (one)	50	tesco.com
Pomegranate (one)	282	myfitnesspal.com
Potatoes (bag)	2500	tesco.com
Radish (red, bunch)	240	tesco.com
Radish (red, one)	11	tesco.com
Raisins (pack)	500	tesco.com
Raspberries (tray)	150	tesco.com
Rhubarb (pack of four stalks)	400	tesco.com
Runner beans (bunch)	180	tesco.com
Salad leaves (bowl)	90	eatthismuch.com
Salad leaves (handful)	40	Own measurement
Salad leaves (mixed, bag)	120	tesco.com
Satsuma (one)	100	tesco.com
Satsuma (pack)	600	tesco.com
Spring onions (bunch)	100	tesco.com
Sprouts (on stalk, one stalk)	125	cookipedia.co.uk
Sprouts (washed, bag)	400	tesco.com
Squash (butternut, one)	1004	waitrose.com
Squash (patty pan, one)	196	recipeland.com
Squash (summer, one)	196	recipeland.com

Stir fry vegetables (mixed, bag)	320	tesco.com
Strawberries (handful)	70	Own measurement
Strawberries (one)	12	strawberryplants.org
Strawberries (tray)	227	tesco.com
Swede (one)	400	tesco.com
Sweet potato (one)	130	en.wikipedia.org
Sweetcorn (tin)	260	tesco.com
Tangerine (one)	50	tesco.com
Tangerine (pack)	600	tesco.com
Tomato (cherry, pack)	330	tesco.com
Tomato (chopped, tin)	400	tesco.com
Tomato (large, one)	198	cuisinevault.com
Tomato (passata, carton)	500	tesco.com
Tomato (puree, tin)	142	tesco.com
Tomato (salad, one)	60	tesco.com
Tomato (salad, pack of six)	360	tesco.com
Tomato (sauce, jar)	500	tesco.com
Tomato (sun dried, jar)	145	tesco.com
Water chestnuts (tin)	140	tesco.com
Watermelon (one small)	1500	tesco.com

Note. Where available, weight data was obtained from Tesco, Sainsbury's or Waitrose UK (in this order). Otherwise, a general internet search was employed and, where this was not conclusive, average sized produce was weighed in person in Tesco (the validity of data from sources other than British supermarkets was also checked by weighing). If the source was not specified, bananas and other exotic fruit were assumed to all come from a shop. Otherwise, where the source of produce was uncertain and could not be confirmed by contacting participants, this information was left incomplete.

Image S11 Weekly recording sheet from the 'MYHarvest Diary'

Week commencing: ____ / ____ / _______

Fruit / Vegetable	Weight (weekly total in grams)			
	Allotment	Garden	Other growers	Shop / Market

Did you give away any of your harvest? What and how much?

Did anything go to waste? What and how much?

Did you freeze any of your produce?	Yes / No
Did you preserve any of your produce?	Yes / No
Did you use any of your frozen produce?	Yes / No
Did you use any of your preserved produce?	Yes / No
Do you think everyone in your household mostly ate their 5-a-day?	Yes / No

How many times did you visit your allotment this week? ____ times

How much time did you spend food gardening in total this week? Around ____ hours

Image S12 Questions about participants from the 'MYHarvest Diary'

About you

How long have you been growing food for? _____ years

Number of people over 18 in your household: _____

Number of people retired in your household: _____

Number of under 18s in your household: _____

Is anyone in your household shielding (i.e. identified as being at high risk from covid-19 and taking extra measures to self-isolate)? Yes / No

Do children in your household get school meals? Yes / No / Not applicable

Where do adults in your household normally get their lunch from?
mostly pack at home / mostly buy at work / each about half of the time

How often do you eat ready meals/takeaway or eat out in your household?
_____ times a week (on average)

Anything else we need to know:

Image S13 Questions about participants' growing spaces from the 'MYHarvest Diary'

About your allotment

Note: if you don't have an allotment, you can ignore the questions that are specific to allotments, and only answer the ones that apply to your growing space

Name of your allotment site: ___________________________________

What is the yearly rent for your plot? £ _____

Approximate size of your plot: _____ square metres

How long have you had your plot for? _____ years

Number of households using your allotment (including yours): _____

Do you grow food in your home garden? Yes / No

Area used for food growing in your garden: _____ square metres

Do you grow organically? Yes / No

How much of your total fruit and vegetable consumption do you think comes from own-growing? Around _____ %

Anything else we need to know:

Chapter 5

SUPPORTING INFORMATION

Quantifying the relationship between gardening and health and well-being in the UK: a survey during the covid-19 pandemic

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CONTENT

Table S1 Socio-demographic characteristics of survey respondents (N=280), for gardeners and non-gardeners

	Gardening		Non-gardening		TOTAL	
	n	**%**	**n**	**%**	**n**	**%**
TOTAL	203	72.5%	71	25.4%	280	100.0%
Gender						
Male	49	23.4%	21	29.6%	71	25.4%
Female	154	73.7%	50	70.4%	209	74.6%
Age						
18–34	24	11.8%	34	47.9%	59	21.1%
35–54	54	26.6%	28	39.4%	83	29.6%
55+	125	61.6%	9	12.7%	138	49.3%
Education						
A levels or lower	44	21.7%	15	21.1%	61	21.8%
Postgraduate degree	159	78.3%	56	78.9%	219	78.2%
Household composition						
Alone	33	16.3%	7	9.9%	41	14.6%
With partner	122	60.1%	31	43.7%	156	55.7%
With family	45	22.2%	27	38.0%	73	26.1%
In shared accommodation	2	2.5%	6	8.5%	9	3.2%
Caring responsibilities						
Yes	60	29.6%	25	35.3%	85	30.4%
No	142	70.0%	46	64.8%	194	69.3%
Household income						
Under £10,000	7	3.5%	3	4.2%	10	3.6%
£10,000–19,999	29	14.3%	3	4.2%	32	11.4%
£20,000–29,999	47	23.2%	11	15.5%	61	21.8%
£30,000–39,999	34	16.3%	11	15.5%	47	16.8%
£40,000+	76	37.4%	42	59.2%	119	42.5%
IMD quintile						
1	11	5.4%	4	5.6%	16	5.7%
2	22	10.8%	8	11.3%	30	10.7%
3	46	22.7%	12	16.9%	59	21.1%
4	36	17.7%	7	9.9%	45	16.1%
5	47	23.2%	22	31.0%	70	25.0%

Table S2 Characteristics of survey respondents (N=280) related to gardening

	n	%
TOTAL	280	100.0%
Weekly gardening time		
0 hours	72	25.7%
1–5 hours	75	26.8%
6–10 hours	56	20.0%
11+ hours	66	23.6%
Food growing level		
No food grown	65	23.2%
1 (very little F&V)	25	8.9%
2	30	10.7%
3	67	23.9%
4	30	10.7%
5 (nearly self-sufficient in F&V)	54	19.3%
Allotment		
Yes	102	36.4%
No	172	63.6%

Table S3 Odds Ratios (OR) for high mental well-being (WEMWBS 60+) compared to moderate mental well-being (WEMWBS 43–59), adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-5.01 (1.47)	0.01 (0.00–0.08)	<0.001
Gender (Female)			
Male	2.36 (0.68)	**10.57 (2.98–45.32)**	<0.001
Age (18–34)			
35–54	-0.12 (1.38)	0.89 (0.07–23.16)	0.93
55+	1.16 (1.17)	3.20 (0.43–67.07)	0.32
Household income (£20,000–29,999)			
Under £10,000	-15.51 (1828.10)	0.00 (NA–$1.48e^{+75}$)	0.99
£10,000–19,999	-1.35 (1.07)	0.26 (0.02–1.83)	0.21
£30,000–39,999	0.11 (0.84)	1.11 (0.20–5.88)	0.90
£40,000+	-0.73 (0.84)	0.48 (0.09–2.47)	0.39
Smoking (Non-smoker)			
Current- or ex-smoker	1.31 (0.69)	3.71 (0.99–15.36)	0.06
IPAQ category (Low)			
Moderate	1.67 (0.85)	**5.33 (1.06–31.66)**	<0.05
High	1.71 (0.84)	**5.55 (1.13–32.26)**	<0.05

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household composition, caring responsibilities, higher education, obesity, alcohol consumption, long-term health conditions, F&V intake, time spent gardening, food growing level, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.31 (Hosmer Lemeshow), 0.19 (Cox and Snell), 0.38 (Nagelkerke); χ^2 (10) = 30.84

[c] Figures in bold are statistically significant at the 5% level (p<0.05)

Table S4 Odds Ratios (OR) for following a meat-avoiding diet as compared to having a regular diet including meat, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-0.49 (0.65)	0.62 (0.17–2.21)	0.46
Gender (Female)			
Male	-0.85 (0.37)	**0.43 (0.20–0.87)**	<0.05
Age (18-34)			
35-54	-0.06 (0.46)	1.06 (0.43–2.62)	0.90
55+	0.47 (0.47)	1.60 (0.64–4.12)	0.32
Higher education (No)			
Yes	1.28 (0.44)	**3.61 (1.58–8.88)**	<0.01
Household (Alone)			
With partner	-1.09 (0.46)	**0.34 (0.13–0.82)**	<0.05
With family	-0.29 (0.54)	0.75 (0.26–2.13)	0.59
Shared accommodation	1.85 (1.29)	6.33 (0.65–152.12)	0.15

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, alcohol consumption, smoking status, obesity, long-term health conditions, time spent gardening, food-growing level, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.09 (Hosmer Lemeshow), 0.12 (Cox and Snell), 0.16 (Nagelkerke); χ^2 (7) = 24.27

[C] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Table S5 Odds Ratios (OR) for negative ('very negative' or 'somewhat negative') as compared to neutral or positive ('neutral', 'somewhat positive' or 'very positive') self-reported effect of the covid-19 pandemic on participants' access to healthy food, adjusted for demographic and lifestyle variables[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	0.64 (1.42)	1.89 (0.11–31.78)	0.65
Gender (Female)			
Male	-0.61 (0.78)	0.54 (0.10–2.26)	0.44
Age (18–34)			
35–54	-0.06 (0.70)	0.95 (0.24–3.90)	0.94
55+	-3.03 (1.23)	**0.05 (0.00–0.43)**	<0.05
IMD quintile (First)			
Second	-1.18 (1.17)	0.31 (0.03–3.16)	0.31
Third	-1.81 (1.23)	0.16 (0.01–1.89)	0.14
Fourth	-169 (1.27)	0.19 (0.01–2.21)	0.18
Fifth	-1.09 (1.17)	0.34 (0.03–3.77)	0.35
Household income (£20,000–29,999)			
Under £10,000	-18.06 (1844.17)	0.00 (NA–9.36e^{37})	0.99
£10,000–19,999	-0.29 (1.13)	0.75 (0.07–6.78)	0.80
£30,000–39,999	-3.07 (1.55)	**0.05 (0.00–0.67)**	<0.05
£40,000+	-0.94 (0.99)	0.39 (0.05–2.87)	0.34
Higher education (No)			
Yes	-1.06 (0.96)	0.35 (0.05–2.33)	0.27
Obesity (Without obesity)			
With obesity	1.16 (0.66)	3.19 (0.85–11.82)	0.08
Daily F&V intake (5+ portions)			
1 or 2 portions	0.69 (1.02)	2.00 (0.22–14.05)	0.50
3 or 4 portions	1.29 (0.69)	3.62 (0.94–14.84)	0.06

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include household composition, caring responsibilities, smoking status, alcohol consumption, physical activity level, having long-term health conditions, amount of time spent gardening, food growing level, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.28 (Hosmer Lemeshow), 0.14 (Cox and Snell), 0.33 (Nagelkerke); χ^2 (15) = 30.66

[C] Figures in bold are statistically significant at the 5% level (p<0.05)

Table S6 Odds Ratios (OR) for negative ('very negative' or 'somewhat negative') as compared to neutral or positive ('neutral', 'somewhat positive' or 'very positive') self-reported effect of the covid-19 pandemic on participants' diet quality, adjusted for demographic and lifestyle variables[a, b, c]

Variable (reference category)	B (SE)	OR (95% CI)	*p* value
Constant	-1.40 (0.48)	0.25 (0.09–0.61)	<0.01
Gender (Female)			
Male	-0.72 (0.58)	0.49 (0.14–1.42)	0.21
Age (18–34)			
35–54	-0.31 (0.52)	0.73 (0.26–2.04)	0.54
55+	-2.56 (0.73)	**0.08 (0.02–0.29)**	<0.001
Obesity (Without obesity)			
With obesity	1.44 (0.52)	**4.21 (1.52–11.82)**	<0.01
Daily F&V intake (5+ portions)			
1 or 2 portions	2.21 (0.77)	**9.09 (0.08–44.74)**	<0.01
3 or 4 portions	0.73 (0.51)	2.07 (0.75–5.68)	0.14

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, higher education, smoking status, alcohol consumption, physical activity level, having long-term health conditions, amount of time spent gardening, food growing level, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.28 (Hosmer Lemeshow), 0.22 (Cox and Snell), 0.38 (Nagelkerke); χ^2 (6) = 49.54

[c] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Table S7 Odds Ratios (OR) for negative ('very negative' or 'somewhat negative') as compared to neutral or positive ('neutral', 'somewhat positive' or 'very positive') self-reported effect of the covid-19 pandemic on physical health, adjusted for demographic and lifestyle factors[a, b, c]

Variable (reference category)	**B (SE)**	**OR (95% CI)**	***p* value**
Constant	1.09 (0.64)	2.98 (0.87–10.82)	0.09
Gender (Female)			
Male	0.50 (0.48)	1.66 (0.65–4.24)	0.29
Age (18–34)			
35–54	-0.60 (0.57)	0.55 (0.17–1.67)	0.29
55+	-1.31 (0.66)	**0.27 (0.07–0.97)**	<0.05
Higher education (No)			
Yes	-1.27 (0.51)	**0.28 (0.10–0.76)**	<0.05
Obesity (Without obesity)			
With obesity	1.46 (0.53)	**4.31 (1.54–12.69)**	<0.01
Long-term conditions (No)			
Yes	0.73 (0.43)	2.08 (0.90–4.94)	0.09
Physical activity level (Low)			
Moderate	-1.95 (0.58)	**0.14 (0.04–0.41)**	<0.001
High	-1.13 (0.69)	0.32 (0.07–1.16)	0.10
Food growing level (No food grown)			
1 (very little F&V)	-1.40 (0.83)	0.25 (0.04–1.13)	0.09
2	0.15 (0.66)	1.16 (0.32–4.26)	0.82
3	-0.35 (0.62)	0.70 (0.20–2.39)	0.57
4	-1.57 (0.96)	0.21 (0.02–1.18)	0.10
5 (nearly self-sufficient in F&V)	-1.25 (0.76)	0.29 (0.06–1.24)	0.10

[a] Predictors and regression coefficients in the table are derived from the best fit model for the outcome based on the Bayesian Information Criterion (BIC). Other explanatory variables tested include neighbourhood deprivation, household income, household composition, caring responsibilities, alcohol consumption, smoking status, F&V intake, amount of time spent gardening, and having an allotment, but these were dropped in the process of improving model fit.

[b] Model R^2 = 0.28 (Hosmer Lemeshow), 0.28 (Cox and Snell), 0.40 (Nagelkerke); χ^2 (13) = 60.52

[c] Figures in bold are statistically significant at the 5% level ($p<0.05$)

Published versions of chapters

Chapter 2

Systematic Review

Increasing City Resilience through Urban Agriculture: Challenges and Solutions in the Global North

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Abstract: Cities, which now host the majority of the global population, are vulnerable to environmental and socio-economic disturbances, which are likely to increase in number and severity in the near future. Urban agriculture (UA) could help increase the resilience of cities to a range of pressures and acute shocks by improving food security and public health, building social capital, and promoting circular economies. However, comprehensive assessments of its potential are still lacking. Here, we use a systematic review of the literature on UA in the global North to identify factors that determine its success in providing resilience benefits, explore challenges that can limit this, and develop a conceptual model to highlight the ways in which it could be enhanced through research, policy, and practice. We define the success of UA in increasing city resilience as determined by five factors, which in turn depend on the amount of institutional and public support for UA, the presence of a sufficient knowledge base, communication and collaboration among different actors, and resourcefulness in finding alternative ways to use space and other resources efficiently. We close with a discussion of specific directions for research and practice based on the conceptual model developed here.

Keywords: food system; urban horticulture; food security; sustainable urban development; global change; urbanisation; sustainability

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1. Introduction

1.1. City Resilience

Hosting the majority of the world's population, today urban areas are facing an unprecedented number of threats, including natural disasters, pandemics, terrorism, water scarcity, poverty, and food insecurity. These risks are exacerbated by climate change, population growth, and continued rapid urbanisation, and are expected to increase in number and severity in the near future [1–4]. In addition, most cities' dependence on global resources has made them highly vulnerable to shocks that can disrupt their current supply systems, the fragility of which has become obvious following the recent outbreak of the Covid-19 pandemic [5–10]. Therefore, to prevent an imminent disaster, cities must take prompt measures to better prepare for future crises.

The term resilience—often defined as "the ability of a system to absorb shocks of all kinds, and its capacity to adapt to changing conditions without losing any of its key functions" [11]—has become a buzzword in urban planning, used to describe cities that can withstand and recover from various disturbances, including those caused by climate change and socio-economic crises [12–14]. Resilient cities are proposed to be reflective, resourceful, flexible, redundant, robust, and integrated, characteristics which make them "safe to fail" (rather than fail-safe) in the face of challenges [15,16]. Since urban areas are complex, dynamic socio-ecological systems, city resilience is a concept that spans multiple dimensions and involves various systems and actors [13,17–19]. Appropriate institutional frameworks with equitable rights and decision-making processes are also argued to be an important aspect of systems resilience [19].

1.2. Urban Agriculture and Resilience

As well as serving to meet basic needs, the food system is a key determinant of the health and wellbeing of society, with poor diets being a main cause of noncommunicable diseases and related deaths worldwide [20–22]. Thus, securing access to sufficient amounts of nutritious food for urban populations in the face of disturbance is a fundamental part of resilience [19,23]. Most cities in the developed world are currently highly dependent on globalised supplies, which are vulnerable to environmental, economic, social, and geopolitical stresses [10,24,25]. As a result, supply disruptions and increasing food prices can severely impact consumers in urban areas, especially the urban poor [9,26,27]. Increasing local production and developing shorter supply chains could decrease the likelihood of disruption to food supplies, enable the development of circular systems, reducing dependency on external inputs, while diversifying sources can provide "back-up" capacity and, thus, improve the ability of food systems to react and adapt to shocks [19,24,26,28–30]. There is growing evidence that urban agriculture can increase city resilience through a number of mechanisms, including, but not only, through increasing the resilience of food systems.

Urban agriculture (UA)—the production of food, mostly fruit and vegetables, within urban areas [31,32]—is increasingly recognized for its multiple social and ecological benefits by city governments around the world [10,33–36]. During World War II, UA played an important role in increasing food security and boosting national morale in Britain and the USA, where household fruit and vegetable production was promoted through the Dig for Victory and Victory Garden campaigns, respectively [7,37]. Following a period of decline in post-war years, urban agriculture is now enjoying a resurgence of interest in the global North, which has recently spiked during the Covid-19 lockdowns [6,38–44]. Today, UA takes various forms, from vegetable plots in private gardens, through allotments and community farms, to rooftop gardens and edible walls using technologically advanced, soil-free cultivation methods [45,46]. While peri-urban agriculture (PUA)—the production of food on the outskirts of cities—is sometimes treated as a separate phenomenon from UA, the distinction between the two is not always clear-cut [32,47]. For the purposes of this study, the term UA will be used to refer to all forms and scales of growing food in both urban and peri-urban areas.

Perhaps the most obvious way in which UA can contribute to city resilience is by increasing household and citywide food security, especially in terms of micronutrient requirements, through the provision of fresh produce locally [6,32,34,35,41,46,48–52]. Own-growing, in particular, can play an important role in supplementing the diets of more disadvantaged groups who have limited physical or financial access to fresh food [9,23,26,27,53]. However, importantly, UA can also increase the sustainability of the food system on a larger level, by enabling the recycling of organic urban wastes as fertiliser and reducing reliance on mineral fertilisers, which have considerable environmental costs globally [26,30,54–56]. In addition, making use of spare space in urban areas can increase food production without devoting more scarce land to agriculture, while certain forms of UA can help protect crops from adverse weather effects and enable stable year-round production [39,48,56].

Several potential resilience benefits of UA also go beyond the food system. For example, promoting public health through improving access to fresh produce and providing a form of regular exercise [34,57] could reduce the incidence of noncommunicable disease within the urban population, making cities better able to cope during crises caused by pandemics, terrorism, or natural disasters. Furthermore, the practice of food growing can play an important role in building social capital, fostering proactive attitudes, and collaboration, which are key determinants of the ability of communities to get through challenging times [15,34,42,52,57–60]. Urban farms can also create jobs and help fight unemployment and poverty [26,61]. Last but not least, vegetation cover provided by urban agricultural sites could improve air quality and decrease the urban heat island effect (UHI), potentially mitigating some of the acute effects of climate change [6,26,62,63].

However, despite growing evidence for UA's various benefits and increasing recognition of its potential to increase city resilience, it is still unclear how UA's success in providing these benefits could be enhanced. While previous research on UA has predominantly focused on issues in developing countries, the urgent need to increase the resilience of cities in the developed world is now also clear. The aim of this study is, therefore, to assess and conceptualise the success of UA in the global North in order to answer to the following questions:

1. What determines the success of UA in promoting city resilience in the global North?
2. What challenges does it currently face that might limit its contribution?
3. How could its benefits be maximised through research, policy, and practice?

2. Methods

To gain a comprehensive understanding of urban agriculture in the context of city resilience in the global North, a review of the academic literature was carried out. In order to minimise bias and improve replicability, a systematic approach was taken based on predefined criteria for the selection of relevant studies. An overview of the selection process is shown in Figure 1 below. Articles were identified using a combination of keywords connected by Boolean operators (i.e., AND, OR, and NOT), which could appear anywhere in the title, abstract, topic, or keywords of papers. Studies focusing on issues in the developing world and for which full-text was not available in English were excluded. To control for the quality of sources, only publications in peer-reviewed journals were considered. In order to ensure that issues are considered from a range of perspectives, no restrictions on article type, publication date, or journal title were applied.

The following literature database search was carried out in July 2019 through the University of Sheffield's StarPlus catalogue:

> "urban agriculture" OR "urban farming") AND ("city resilience" OR "urban resilience") NOT ("africa" OR "developing countries" OR "developing world" OR "middle east" OR "latin america"

Abstracts of all 73 returned articles were read and any nonrelevant search hits (i.e., articles not related to the keywords) were manually removed. The remaining 53 papers were read in full and information related to the specific questions addressed by the study (i.e., 1. factors determining the success of UA in providing city resilience benefits; 2. current challenges for UA; 3. ways in which UA and its benefits could be promoted) was extracted and organised into emerging themes to characterise the success of UA in terms of the amount of resilience benefits it can provide, and was used as the basis for the development of a conceptual framework to illustrate potential pathways through which it could be promoted.

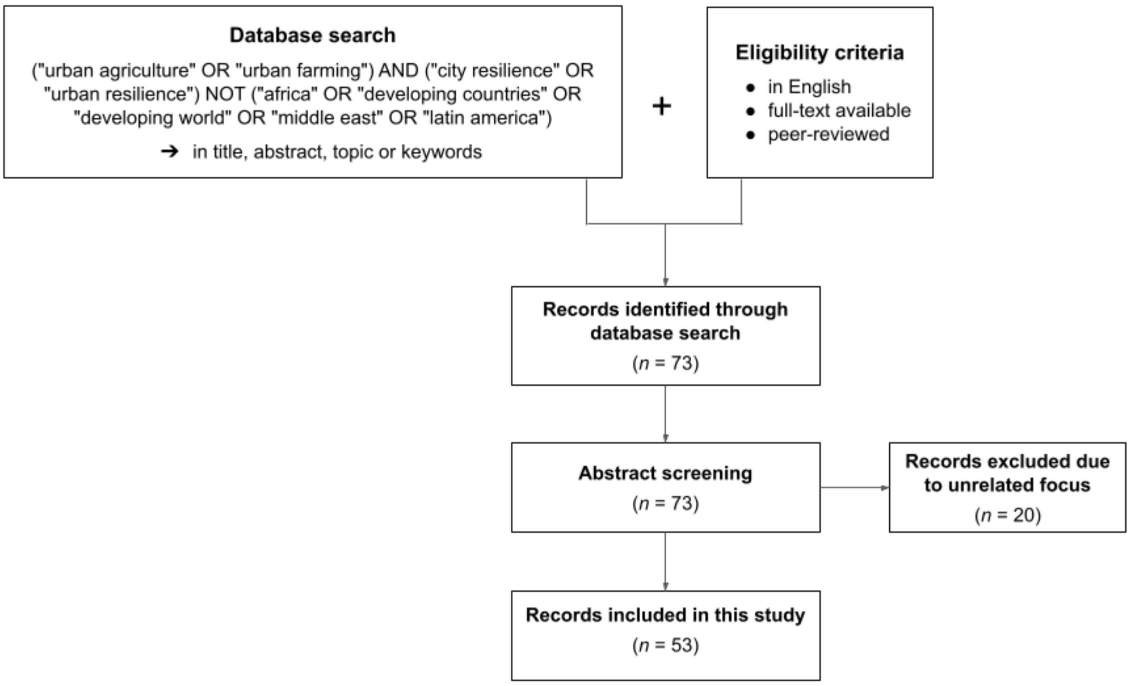

Figure 1. Study selection strategy for the systematic literature review.

3. Results

3.1. Bibliometrics

Applying all selection criteria and an initial screening of 73 abstracts (see Methods) resulted in 53 papers to be reviewed for this study. All reviewed papers were published after 2010 (most between 2013 and 2018) (Figure 2), in 39 different journals with focal subjects covering a range of topics (mostly related to sustainability, environmental science, and urban planning and policy, but also public health, geography, architecture, and engineering) (Figure 3). This reflects the novelty and inherently multidisciplinary nature of this research area, and also demonstrates the breadth of research that fed into the conceptual model we present in this study.

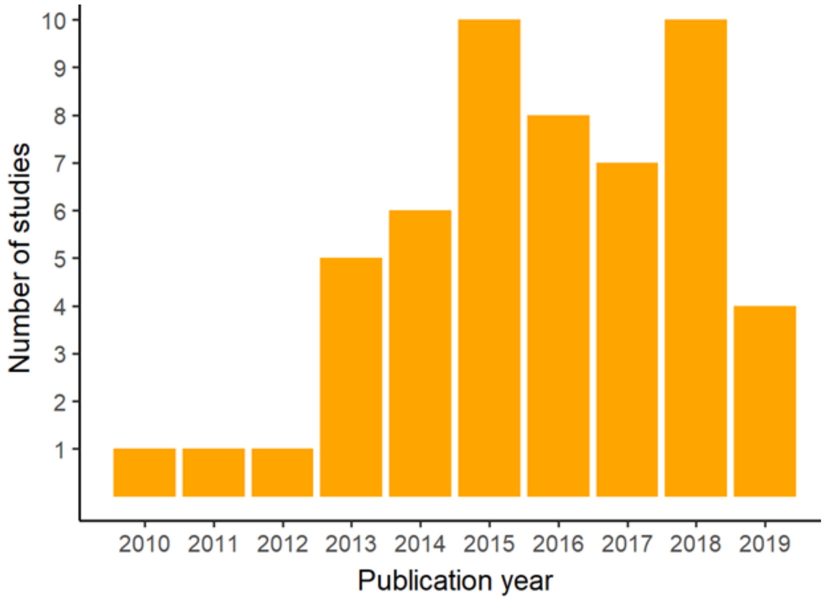

Figure 2. Distribution of reviewed studies by publication date.

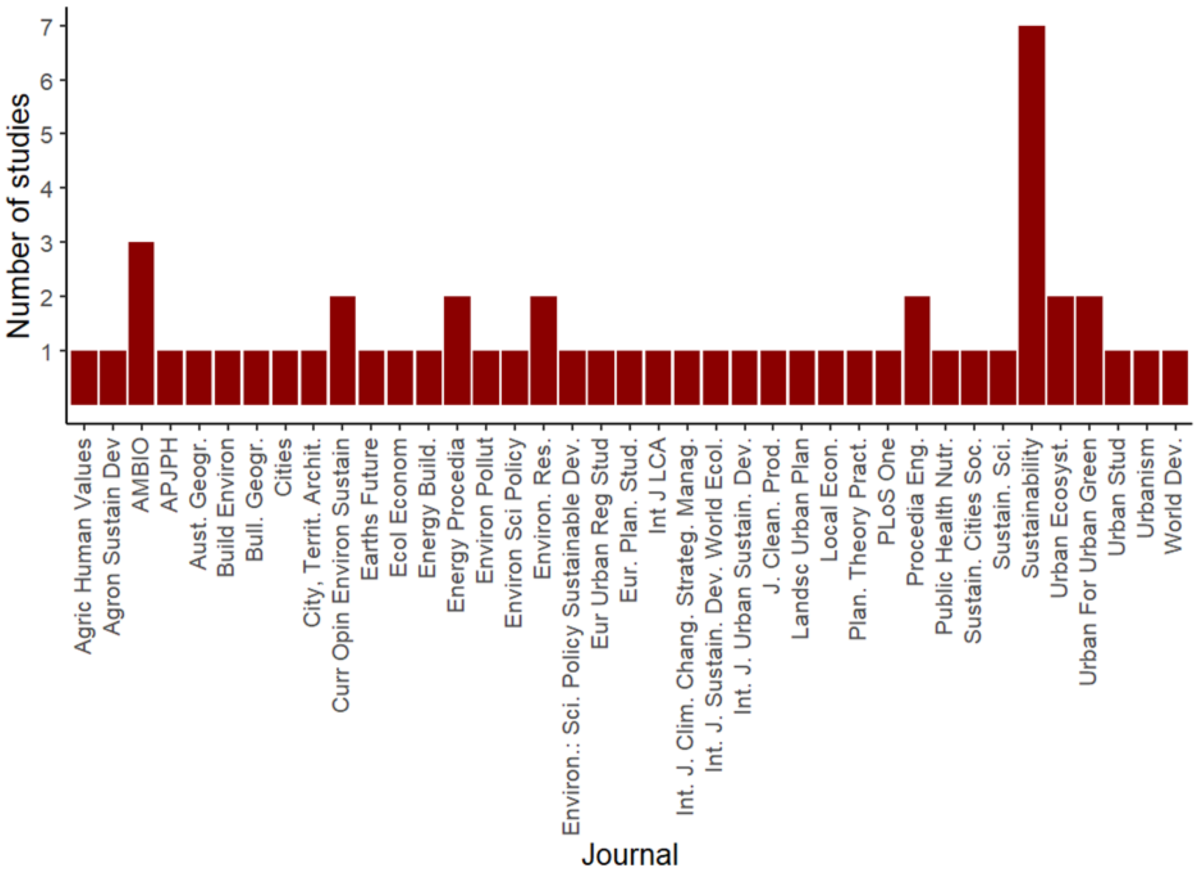

Figure 3. Distribution of reviewed studies by journal.

3.2. What Makes UA Successful?

Based on the reviewed literature, it is proposed that the provision of resilience benefits by UA in the global North is determined by five factors (Figure 4): its scale (i.e., the amount of space dedicated to, and number of people engaged in food production in a city); the efficiency of production (i.e., crop yields per unit cultivated area and resource input); the extent to which it is integrated into the urban fabric (i.e., links with different urban systems including food, waste, and education), inclusiveness (i.e., equitable access to growing space and other resources needed to engage in UA, and to urban-grow food); and human and environmental safety (i.e., urban-grown produce is safe to consume and practices do not pollute the city's water supplies or cause harm to surrounding ecosystems). A range of potential issues related to the five key aspects of successful UA as proposed here (i.e., Scale, Efficiency, Integration, Inclusiveness, and Safety) was identified. The aim of the following section is not to provide an exhaustive list of these, but rather an overview of the different kinds of challenges that need to be addressed if UA is to play a more significant role in increasing city resilience.

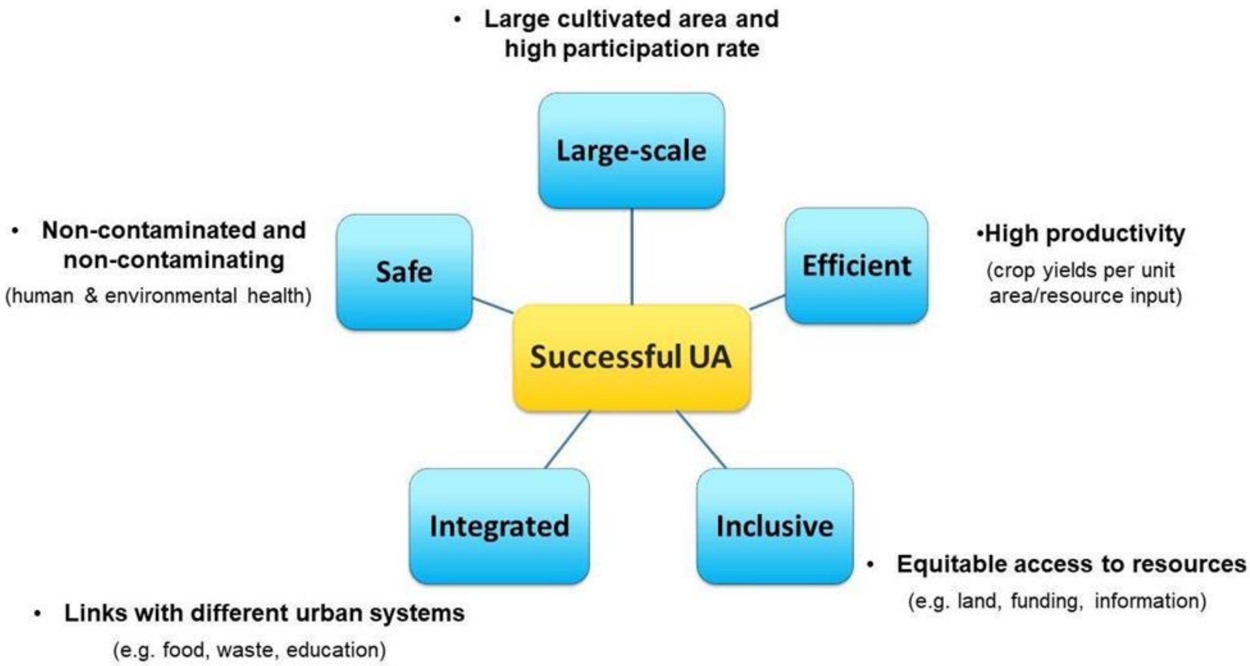

Figure 4. Key characteristics of successful urban agriculture (UA) in the context of promoting city resilience.

3.3. Current Challenges for UA

3.3.1. Scale

Perhaps the most obvious constraint on the scale of UA is the limited availability of space in cities, which is coupled with the fact that both urban and peri-urban land is under severe pressure from different contradicting uses, including housing, industry, infrastructure development, and recreation [38,50,64–67]. Moreover, vacant space in dense urban settings is often found in small patches among built-up areas, which can prevent the development of larger farms [68]. Another issue is that not all available space may be suitable for food production: urban soils can be contaminated [12,18,38], while concrete cover can make some open areas unsuitable for traditional cultivation methods [62,69]. Although suitable rooftops and vertical spaces could be used to expand UA area [12,30,48,50,59,64,69,70], it is estimated that the global availability of these is low compared to the amount of vacant urban land, and, therefore, their contribution may be limited [71], not to mention possible competition from other roof uses, notably photovoltaics [72].

Nevertheless, it can be argued that in many cases the biggest issue is not the lack of space per se, but rather its availability for potential growers—in fact, a recent case study has found that, although there are social and techno-scientific challenges to achieving this in practice, in theory there is enough suitable growing space in a typical UK city to fully meet the fruit and vegetable demands of its inhabitants [73]. Several reviewed studies point to a lack of supportive policies, ownership issues, and prohibitive legal frameworks as being the main constraints on the scale of UA. On the one hand, measures to safeguard agricultural land in urban areas are often absent, or only temporary, allowing the fragmentation and gradual disappearance of farms [13,50,62,74,75]. On the other, expensive land lease and zoning laws defining land use in different areas can limit opportunities to put more land to food production, and can sometimes cause the implementation of UA to outstrip policy and lead to farms being shut down on legal grounds [13,34,39,48,50,58,59,71,76].

Along with the availability of growing space, the level of participation by citizens is a key factor determining the scale of UA. It has been argued that certain forms of urban food production are dying out in some parts of the developed world [38]. For instance, many commercial peri-urban farms in Europe have been abandoned or become inhabited by people with little interest in agriculture, and studies suggest that the majority of active growers in some cities are among the elderly [13,18,38,62,72]. Expensive land lease, lack of security of growing space, potentially high costs of setting up and operating farms in urban areas (e.g., for building materials, water, fertiliser, and electricity for supplementary lighting, or circulating water in some nonconventional methods) and limited demand for urban-grown produce can also be discouraging or prohibitive for those wishing to start a UA business or social enterprise [30,38,39,48,50,56,71]. Nonetheless, other forms of UA are becoming increasingly popular. For example, own-growing is enjoying a recent resurgence of interest in the UK, where higher participation is hindered by dwindling allotment supply [44,77,78].

3.3.2. Efficiency

It has been argued that, in many cities of the global North, the knowledge of how to grow food is being lost [38,39,53,79]. A lack of skills among growers can mean that practices are inefficient [74], which, especially if the availability of growing space is limited, can limit food provision by UA [39,62]. While alternative practices like aquaponics or hydroponics can allow for high yields in restricted spaces, these are still in relatively early stages of development and, thus, not yet well known among the public. In addition, technologically advanced methods can be quite expensive and may require specialist knowledge, which can be an issue for own-growers and small businesses and community initiatives that cannot afford the hiring of professionals [30,48,56,79]. While urban waste water, organic materials, and energy streams could be exploited to decrease costs and improve the efficiency of production, the infrastructure and markets for such products are yet to be developed [30].

3.3.3. Integration

One main challenge in this area is linking urban producers with consumers. Due to high land prices in more central areas, commercial farms and market gardens are often established on the outskirts of cities, which can complicate the logistics of reaching customers [13,50]. Another potential issue for small-scale commercially-oriented projects is that many supermarket chains only accept fruit and vegetables of certain size and appearance, making it difficult for producers to secure contracts with them [74]. Restrictions related to food safety [13] and organic certification of produce (especially when grown using nonconventional methods) can present further obstacles [72]. Although alternative distribution systems and retail outlets (e.g., growers' markets) do exist for urban produce, these are not available everywhere, at least partly due to limited government support [13,80,81]. In addition, it is often difficult for urban-grown produce to compete with the low prices available through globalised markets, especially in lower-income neighbourhoods where people cannot afford the alternative [39]. As well as difficult access, cultural factors might also limit consumer demand for UA produce [72,81].

Another major issue is the widespread lack of comprehensive planning for resilient urban food systems and, in fact, for food in general: in some countries, there is no government department dedicated to food, and even in highly developed European countries like Sweden, Denmark, or Belgium, explicit strategies for urban food production are rare [13,65,71,80,82]. Another related issue is that grey and green areas tend to be treated as distinct systems in urban planning, and so potential synergies that could be achieved through their integrated management (e.g., water and organic waste could be recycled to provide a source of irrigation and nutrients, contributing to more resource- and cost-efficient closed-loop systems, green walls could increase the energy efficiency of buildings while improving air quality and local microclimate [30]) are seldom exploited [52,83].

3.3.4. Inclusiveness

Urban development patterns in many parts of the global North have led to uneven distribution of green space, often favouring more affluent areas, making equitable access to growing space a major issue, especially in urban centres and for low-income or racially segregated communities [13,38,39,62,65,66,75,77,79,81–86]. In addition, the success of UA projects is often dependent on networking, social work, and business skills in addition to horticultural knowledge [13,39,87]. As well as growing space, relevant skills and access to financial and material resources is also distributed unequally, and even where support systems exist many people may be isolated from these geographically or due to socio-economic factors [13,49,79,81,88]. For example, the low-income and the elderly may have limited access or ability to use digital tools that could facilitate knowledge and resource sharing [85], which will be crucial for realizing the potential of urban horticulture [73].

Another crucial factor that can limit the positive impacts of UA is unequal financial and physical access to urban-grown food [64,81]. Many areas lack walkability to urban farms and alternative food shops, and, for various reasons, local produce tends to have higher prices than that grown on larger, commercial farms. As a result, purchasing locally grown fruit and vegetables has become mostly widespread among people in higher-income groups, and producers in lower-income neighbourhoods often struggle to sell their produce, which may force them to raise prices, intensifying issues of unequal access to local food [39,80].

3.3.5. Safety

In some areas, urban soils and groundwater can contain high levels of heavy metals and other toxic chemicals due to industrial activities, current and past emission from vehicles or the use of amendment soil delivered from contaminated sites. This is coupled with a lack of detailed legislation regarding the safety of urban-grown food in some countries (and even where strict controls exist, domestic practices are not regulated), which has given rise to concerns over the health effects of consuming potentially contaminated produce [12,18,38,72,89,90]. Air pollution near main roads and in urban centres has also been suggested as a potential health risk to people gardening in these areas [38].

Another possible issue is related to potentially inappropriate domestic agrochemical use. It has been argued that, as a result of reduced ecological understanding or in an attempt to enhance yields, some urban growers might use excessive amounts of fertilizers or pesticides, which could cause harm to the environment or introduce agricultural pollutants into the city's water and food supplies—although, due to the lack of monitoring of such residues in waterways or produce, the reality of these concerns is largely unknown [39,74,91].

3.4. Underlying Factors

While there are a variety of potential issues that can limit the success of UA, there seem to be some common themes underlying them. These will be discussed in turn here.

3.4.1. Public Support

In modern societies, there is often a cultural bias towards manicured landscapes, which people might associate with safety and higher quality of life and, thus, may prefer over green areas with a less tidy appearance, like many UA sites [38,59,86]. Urban food gardens might even be seen as a sign of poverty or under-development by some, who might not want to see these near their home or workplace [40]. Part of the reason for this could be what has been described as an "environmental generational amnesia", meaning that many people today fail to reconnect with and understand their dependency on natural ecosystems [40], and as a result may have little interest in and underestimate the benefits that spending time in nature and growing their own food can offer. In addition, research suggests that the concept of urban agriculture—especially its more urban-specific forms, like aqua- and hydroponics—may be little known and understood among the public, and certain practices, such as highly engineered cultivation methods or animal farming, may have low acceptance [72].

Single-family residential gardens take up a significant proportion of open space in many cities and, thus, hold great potential for increasing UA area [53,62,68,91,92]. However, this will require public willingness. A key issue can be that even if they are generally supportive of UA, due to busy schedules characteristic of modern lifestyles, higher levels of engagement may be outside the comfort zone of most people [59,76]. The importance of this factor is shown in the huge increase in interest in 'grow-your-own' in many countries during the lockdowns that followed the outbreak of the Covid-19 pandemic (for example, evidenced by rises in waiting lists for allotment plots in the UK [44,78]), when many people suddenly had more free time. Voluntary contributions to community gardens also tend to be limited and unreliable, and few people are likely to be willing to help with product distribution or provide financial support for projects [72]. The lack of long-term security of growing space, fees for garden use, difficult access to sites, including perceived access (e.g., allotment sites are often fenced off from non-members), and potentially insecure environments (e.g., risk of vandalism or presence of homeless "tramps" near sites) can also discourage people from getting involved in some forms of UA, while insecure funding for projects can make those who want to make a living from horticulture reluctant to start [38–40,50,64,84]. Finally, conflicts amongst users of communal sites—especially if there is high cultural diversity in the group—have also been suggested as a potential issue limiting participation [15,64].

Another important social factor affecting the success of UA is the amount of demand for fresh local produce, which might be limited. Food shopping and consumption patterns in most parts of the developed world have become supermarketised, and many people may not give a high priority to sustainability in their product choices, or have a limited understanding of what constitutes a healthy diet [13,72,80,81]. In addition, reduced choice, difficult access, an absence of an enabling culinary culture, concerns over the safety of consuming urban-grown food, and beliefs that local produce—especially if organic—is always expensive can also make people reluctant to buy such products [48,81].

3.4.2. Institutional Support

Another key factor that can limit the success of UA is the amount of support for it from authorities [64,71,74]. Despite increasing recognition of its benefits and potential importance on various levels of governance [33,36], the fact that food production is rarely considered as an urban issue, and as a result UA tends to receive little attention in local council legislation and city planning, is frequently mentioned in the literature [13,40,50,52,62,65,72,74,80,82,93]. It has been argued that current and potential growing spaces in municipal ownership are often maintained as reserves for urban development, while zoning regulations put constraints on expanding UA area [38,52,74]. Many peri-urban farms might be threatened by urbanisation, and liberalised legislation can sometimes allow anyone to purchase agricultural land and pursue activities other than farming, which poses a further threat to how scarce fertile land is used [13,50,52,59]. Regulations related to producing food in urban areas are also sometimes absent, and in some cases a system of "organised irresponsibility" may be observed around complex issues like pesticide pollution, with multiple relevant agencies all assuming it to be another's responsibility [38,72,74,91]. Furthermore, it has been argued that governments might tend to subsidise export-oriented food production in order to promote broader national development, a strategy that is in contrast with building resilience through increasing local self-sufficiency [74,81]. Some international policies, such as the EU's Common Agriculture Policy (CAP), also promote the globalisation of markets and favour larger rural producers [13]. Although strategic declarations about creating more resilient urban food systems, acknowledging the role of UA in it, have now been made by many cities [33,94], specific targets and action plans are still relatively rare [93]—although not absent (see e.g., [95]).

As a result of a lack of effective measures to facilitate their access to resources, smaller UA businesses may often struggle to compete with larger producers [13,71,74,81,82,86]. While the development of multifunctional UA projects could provide additional income streams (e.g., through tourism or education), it requires additional investment and can still be complicated by banks' reluctance to fund "risky" urban horticulture projects [39] or contradictions in legislation relating to different activities involved [13,74]. City agencies have also been argued to take only a small part in efforts to ensure equitable access to healthy food for more disadvantaged communities—mostly leaving this task to community groups and NGOs—limiting some of the potential benefits of UA [65].

Lastly, limited governmental budgets and plans for green space development (for example, in 2016 only 1% of brownfields in England were proposed to be reused as green space [62]), and the fact that it usually focuses on parks, playgrounds, or urban forests, can also present a problem for UA, which tends to be given lower priority [13,52,64,79]. In addition, in larger-scale municipal-led greening initiatives sometimes the most disadvantaged areas get the least attention, and measures might overlook or even reinforce existing issues of spatial and social inequality [38,62,65,66,75,79,81,86]. Moreover, the ways in which green spaces are increasingly incorporated into private development schemes can lead to "green stealth", a process of spatial exclusion through privatisation of these areas [62]. Finally, while the concept of promoting resilience through ecosystem services and nature-based solutions (including UA) are increasingly well-known, the actual incorporation of these approaches into urban policy and planning is still weak in most parts of the global North [38,53,63,75,83,86], and may be sidelined in favour of hard engineering solutions that might provide more immediate results or direct economic returns [15,59,62,71,79,83,87].

3.4.3. Knowledge Base

A likely reason behind sometimes limited municipal attention and policy support for UA is that, until recently, the quantitative evidence base for its various benefits, including its current and potential contribution to city resilience, was lacking [52,71,83]. One issue is that land cover and use characterisation at high resolution can be difficult and very time consuming, and as a result, such information is often sparse or lacking in sufficient level of detail [68,71,76]. Estimating the area of rooftops and building façades suitable for alternative production methods is also problematic because many factors need to be taken into consideration (e.g., load-bearing, accessibility, availability of light) [12,71]. In addition, data from different sources is sometimes inconsistent or difficult to integrate, not to mention that some essential information might be proprietary [50,71]. As a result of these factors, data on how much land is, or could be, used for food production in urban areas is often unknown—although recent research suggests considerable potential [73,96].

Another challenge is that a large proportion of food production in cities takes place on private gardens, allotments, and small farms where yields do not normally get recorded [13,50]. Although estimates could be made based on conventional agriculture or mathematical models, these may not reflect ground level realities [76]. In the UK, the actual productivity of allotments and gardens has recently been estimated [73,96,97], but in other countries own-grown crop yields are yet to be quantified adequately to support arguments about possible levels of local self-sufficiency, and the role of different forms of UA in providing food security still requires further research [80,82,98]. The economic characterisation of urban-grown food can also be difficult, as its value is affected by quality, production methods, and supply–demand conditions [82]. In addition, the safety of consuming urban produce is often uncertain as the presence of toxic residues in private growing spaces is seldom monitored. Similarly, the potential risk of agrochemical pollution in cities is largely unknown, with insufficient toxicity data, debated historical accounts, and mathematical ecosystem models, and a lack of consensus on what tests and thresholds should be used complicating its regulation [71,74].

Another potential issue is that cultural services provided by UA are subjective and difficult—and arguably senseless—to translate into quantitative metrics, making it hard to provide evidence for these benefits [58,92]. Moreover, ecosystem service provision by urban food gardens is generally evaluated from the perspective of practitioners only. Very few studies so far have addressed public perceptions on UA, therefore, the extent to which an increase in its scale and its different forms would be supported by global society is not yet clear [72]. In addition, participatory research essential for studying social factors is time-consuming, and effective study designs can be difficult to create. As a result, participatory data sources are relatively rare and seldom have inter-annual continuity [50].

Finally, a fundamental problem is that, despite the growing popularity of the concept, it is still somewhat unclear what resilience actually means for urban planning and policy, let alone UA's role in it [17,79,85]. These uncertainties, combined with the fact that UA sites do not usually provide direct economic benefits to local authorities, can make them reluctant to increase the provision of growing space, and can limit the effectiveness of measures intended to promote UA practice [71,92].

3.4.4. Communication and Collaboration

Another key factor that can limit the success of UA is a lack of communication and collaboration among researchers, policy-makers, and communities. Multiple authors argue that weakened social bonds and a decreased sense of participation, characteristic of modern urbanised societies, have resulted in decreased informal learning and exchange of knowledge among individuals and groups—importantly between generations—making the social memory of UA vulnerable [13,39,75,85,98]. In addition, limited connection and collaboration between individual initiatives and agents working across larger scales can present a barrier to knowledge and resource sharing, and to building a critical mass on debate [13]. The potential reluctance of smaller UA initiatives to work with larger companies or institutions, or accept advice from external experts, can be a problem because a lack of support from stakeholders with better access to information and resources (for example, councils could act as "anchor institutions" to provide security for community-based urban horticulture businesses [73]) can limit the success of projects [13,38,50,52,79,86,99]. In particular, the spread of alternative UA practices can be hindered by a lack of willingness to collaborate, as well as by proprietary control of knowledge and tools for innovation [85,87]. For instance, most rooftop greenhouse projects currently operate in isolation, which likely limits their success and technological development [48].

A lack of communication between municipalities and communities, and views that scientific knowledge is superior to non-scientific, local knowledge can also mean that the latter is overlooked in making plans and policies related to UA practice and the provision of growing space. Although it could be argued that a synergistic interaction between governments and citizens is sometimes over-idealised [76], the issues of local practitioner groups often cannot be addressed through traditional institutional regulatory instruments [18] and measures devised without a sufficient understanding of the local context might not be well-received by the public, or even have unintended negative consequences, like increasing social or spatial inequalities [64,75,87,99]. For example, top-down approaches to mobilizing citizens can lead to the exclusion of less vocal communities [64,75], and there is evidence that government attempts to make people cultivate abandoned areas may not be effective if these people do not feel attachment to the gardens allocated to them [15,34].

Another issue is that the science and policy of climate change adaptation, environmental protection, agriculture, food systems, and public health tend to be disconnected across a range of institutions and government departments [49,62]. This puts UA in a difficult position, since, due to its multifunctional nature, it is not fully in the domain of any particular agency. Instead, its different aspects concern a number of sectors, in all of which it may be given relatively little attention. Complex issues like city resilience and urban agriculture's role in it can also have different understandings, which, combined with limited information sharing and coordination among different government departments, can result in contradicting policies. Current resilience plans often have multiple contrasting goals, overarching city-wide strategies are rare, and possible synergies between different plans (such as opportunities to link green space development with improving urban health and living conditions) are seldom exploited [49,52,62,74,79,80,85]. In addition, possible opposition grounded in political differences can make it more difficult to reach a consensus between parties and mean that legislation generally emerges slowly [38,76,79,98], whilst dominant policy discourses and entrenched urban planning practices can be inhospitable for new frameworks [52].

Finally, limited knowledge exchange can also be observed within research. For instance, while multi- and interdisciplinary approaches to evaluating ecosystem services are becoming increasingly popular, there is still a shortage of such projects. Multifunctionality is often poorly covered in assessments of urban green spaces (for example, combining green space mapping with related health and wellbeing data), with most studies dealing with only one service from the perspective of one type of stakeholder [71,76,92]. In addition, urban resilience and ecosystem service research rarely involves stakeholders [50], and might not focus on the most deprived areas where increased provision of green space, including UA sites, is most needed [52]. Another important problem is that, in many cases, research findings are not communicated sufficiently to relevant planners, policy-makers, and practitioners, or are not directly transferable to real life settings [53]. City resilience and ecosystem service frameworks might also lack specific guidelines or fail to take existing administrative and governance structures as a starting point, which can make them difficult to operationalise [52].

3.4.5. Contextual Diversity

The last underlying challenge identified is the fact that there can be considerable differences between, and even within, cities in key factors affecting urban agriculture and the types of resilience benefits it can provide [76]. These include geographic constraints on food production (e.g., climate, soil, and groundwater properties) [12,82], landscape features and land cover characteristics (e.g., amount of brown or green vs. grey area, urban built form) [12], land ownership [12,82], costs of key items (e.g., labour, land rent, materials) [71], pressures on land use [82], institutional designs and policies (e.g., tax treatments, subsidies, regulations) [71], cultural factors that affect practice, public perceptions of different forms of UA, and demand for urban produce [34,50,66,75,84,91]. Such wide contextual diversity can limit the transferability of research and policy approaches between different scales and locations, and makes it difficult to find solutions for promoting UA that are appropriate across space [13,99]. It also means that the cost and effort of implementing certain measures will likely vary between locations. In addition, the development of locally suitable actions may be hindered by the fact that municipal plans need to conform to larger regional, national, and international policies [76].

3.5. Pathways to Promoting UA

Based on the reviewed literature, it is proposed that the overall success of UA in increasing city resilience depends on the amount of institutional and public support for it, the presence of a sufficient knowledge base to guide policy and practice, communication and collaboration among different actors, and resourcefulness in finding locally appropriate solutions and alternative ways to use space and other resources efficiently. Figure 5 shows a conceptual diagram illustrating how these factors could promote key aspects of UA through a number of direct and indirect mechanisms.

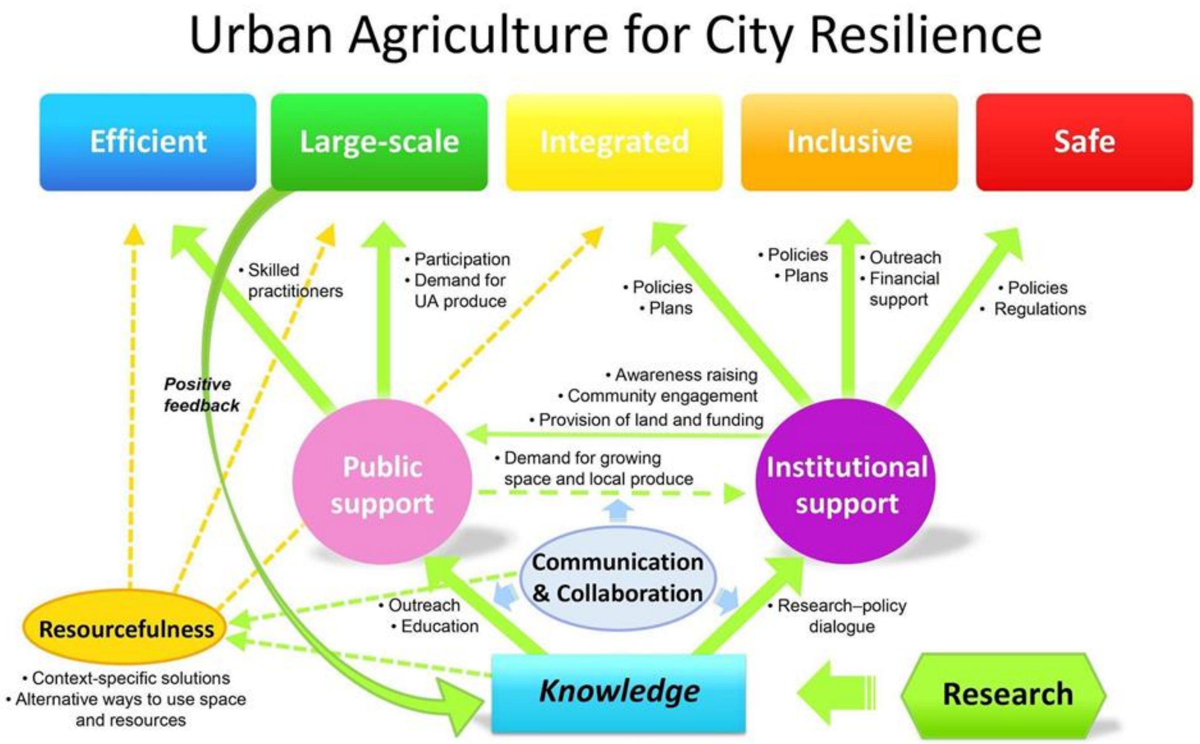

Figure 5. Pathways to promoting urban agriculture (UA) for increased city resilience: five key aspects of successful UA (top of figure), factors that determine UA's success in increasing city resilience (objects below), and main mechanisms through which these can contribute to different aspects of UA (arrows; all represent promoting effects).

People's ability and motivation to engage in UA and related activities is a crucial factor determining its success. In fact, since a significant portion of space in cities is owned or managed by private individuals and local user groups [92], it could be argued that the scale and impact of urban agriculture is ultimately a function of the level of participation from citizens. Nonetheless, the public's contribution is limited without the support of local governments, which have a crucial role in creating enabling policy frameworks and facilitating access to land, funding, and information. It should be noted that there is a bidirectional relationship between public and institutional support for UA. On the one hand, high public demand for growing space and locally grown food can trigger increased attention and support from governments in the form of different policies and urban development plans, which can promote the integration, inclusiveness, and safety of UA. On the other, awareness raising, community engagement, and provision of growing space can increase public interest and participation in UA-related activities, which in turn can increase the scale of the practice. To facilitate such a synergistic relationship, it is important that effective communication takes place between communities and local governments.

Through generating an evidence base to underlie the amount of both institutional and public support and the effectiveness of policy and practical measures, research plays a fundamental role in determining the success of UA, potentially having downstream positive effects on all of its five key aspects. In order to have a real impact, as well as the creation of knowledge, its communication to government administrators, practitioners, and the general public is also crucial. Researchers have a responsibility in increasing key actors' awareness of issues around urban agriculture and resilience, the importance of actions being taken, and how they can contribute. Thus, outreach, education, and good research–policy dialogue are essential. Last but not least, resourcefulness is important for finding effective and locally appropriate solutions, the success of which is greatly dependent on knowledge exchange and collaboration among practitioners and between researchers and communities [14,40,85]. Finally, there is a positive feedback relationship between the scale of UA and the amount of knowledge potentially available on it, completing a virtuous cycle of research, science communication, and collaborative action.

4. Discussion

The importance of increasing the resilience of our cities has become clearer than ever after the recent global Covid-19 outbreak. Achieving greater resilience is a complex challenge and, while related research and policy often focus on engineering solutions [15,62,87], it is arguably as much a social issue as it is a technological one. Despite growing evidence for its various benefits, urban agriculture's contribution to city resilience is a fairly new concept in academia, and our understanding of its role and potential is still limited. At the intersection of multiple dynamic urban systems, UA faces a number of socio-economic, environmental, and technical issues. Thus, increasing its success requires the support of a range of actors (including governments, nongovernmental organisations, researchers, industry, and the general public), as well as holistic, interdisciplinary, and inter-institutional approaches combining knowledge and insights from different areas [12–15,59,62,66,76,85,86].

4.1. Directions for Policy and Practice

In complex urban systems, planners and policy makers have to address a wide range of issues and prioritise different goals [12,18,30,38,49,52,62,63,65,66,82,85,86]. In order to be able to compete for cities' limited resources, UA must receive enough attention and support from governments. City authorities need to recognise agriculture as an important urban land use, devise appropriate policy frameworks, and incorporate UA into their different agendas (such as green space planning, food, wellbeing, and education), paying particular attention to spatial and socio-economic equality [13,30,59,66,76,86]. There is also a need for better integration among sectors and initiatives and more clarity around the responsibilities of different actors [30,62,66,74,80,88,99], and for strategic declarations to be complemented with action plans that include specific, measurable objectives [64,66,93].

Local governments should improve access to growing space, information, and funding for UA-related projects [13,62,64,80], as well as to local produce (e.g., through promotion of farmers' markets [18]). Since much potential growing space in urban areas is in the private domain, it is also vital that UA be promoted as a business, social enterprise, or recreational activity among various groups and individuals. Therefore, increased support for local stakeholder-led innovation [69], active citizenship and self-organisation [40,58,64,69,75,87], promotion of domestic food production and community farming [40], awareness raising and educational programmes (e.g., on healthy and sustainable diets, horticulture, and the environment) [14,18,62,69,72,80], public engagement (e.g., through hiring "community organisers") [15,62,64,85], and development of multistakeholder communication and collaboration platforms [64,66,76] will be important.

Finally, since the wide contextual diversity that exists between locations may preclude one-size-fits-all solutions, it is important that locally appropriate measures are designed based on a holistic consideration of the environmental, economic, and social setting [18,76,79,82,93]. Green Infrastructures and Nature-based Solutions could be appropriate tools to support integrated planning of urban green space [53,58,62,63,65,66,86], while Strengths, Weaknesses, Opportunities, and Threats (SWOT)-type assessment frameworks [83,100] supported by participatory approaches to planning and management [14,15,53,58,62,64,65,72,76,85,88,98,101] and geospatial information and communication technologies [12,76] could be useful in identifying the specific challenges and opportunities that exist in each city and points where interventions might be the most effective.

4.2. Directions for Research

Greater institutional support for UA and effective enhancement of its resilience benefits require a better understanding of and larger evidence base for its contribution. More research is needed on the current and potential area of UA in different cities, its ecosystem service provision capacity (including food, climate change mitigation and various social benefits) and how this varies with type of practice (e.g., traditional soil-based vs. technological cultivation methods), and environmental and socio-cultural factors (e.g., acceptance of different forms of UA, motivations to participate in UA-related activities, demand for urban-grown produce). In particular, research taking a whole-system perspective and innovative multidisciplinary approaches will be essential [62,76,93]. Examples of research methods suggested in the reviewed literature include GIS-based models (e.g., for land cover, use, ownership, and ecosystem service provision) [62,76,92,100]; life cycle analysis (e.g., of alternative food supply chains) [80]; field surveys (e.g., of soil quality, current cultivated areas, and crop types) [71,89]; computational modelling of different scenarios [39,76]; synthesis of interdisciplinary information [12,86]; place-based research [99]; surveys and interviews (with both practitioners and the general public) [50,66,71,92]; participatory research (including higher education–community partnerships, bottom-up data collection, and online crowd-sourcing, e.g., for mapping unused spaces in urban areas) [15,39,50,76,99]; and development of better indicators and tools for measuring both quantitative and qualitative aspects of resilience [15,92,93].

As well as filling knowledge gaps, it is equally important to create real-world solutions that can help increase the success of urban agriculture. Therefore, research should also focus on developing communication channels (e.g., digital platforms) and affordable and user-friendly tools to facilitate knowledge- and resource-sharing and different practical aspects of UA projects [87], designing alternative solutions for dealing with space and resource constraints (e.g., ponics technologies, green walls and roofs) [71,99], and understanding how institutional actors can best support various initiatives and engage people from different backgrounds in UA-related activities [15,62,85]. Finally, there needs to be a greater emphasis on effective science–policy dialogue and communicating research findings to different audiences [12,15,17,62,66,79,92,99].

4.3. Relevance and Limitations of the Study

The potential role of UA in increasing city resilience in the developing world has been reviewed by de Zeeuw et al. [61]. This study adds to existing knowledge by identifying the factors that determine UA's successful contribution to city resilience in the global North, using a systematic approach. Furthermore, the conceptual model we present highlights some key pathways to enhancing the resilience benefits of UA, and could serve as a basis for the development of (e.g., SWOT-type) assessment frameworks to assist policy-makers and urban planners in devising locally appropriate and effective strategies. The research and policy directions we identified could further contribute to the success of these efforts.

Nonetheless, some limitations of the study are recognised. First, a single literature database was used to identify relevant publications in English, which means that some potentially important work that was only available elsewhere, in other languages, or which did not include the search terms used here may not have been considered. Second, due to the qualitative nature of the study, some degree of subjectivity might be inevitably present in the interpretation and synthesis of findings.

5. Conclusions

Urban agriculture (UA) could increase city resilience in the global North against various environmental and socio-economic disturbances, which are expected to increase in frequency and severity in the near future. However, its current and potential contribution to this has been little understood. The aim of this study was to conceptualise the success of UA and identify the pathways through which its resilience benefits can be enhanced. It is proposed that the success of UA in increasing city resilience is determined by five factors: its scale, the extent to which it is integrated into the urban fabric, its inclusiveness, the efficiency of food production, and human and environmental safety of practices. These factors in turn depend on the amount of institutional and public support for UA, the presence of a sufficient knowledge base to guide policy and practice, communication and collaboration among different actors, and resourcefulness in finding alternative ways to use space and other resources efficiently. Increasing its contribution to city resilience requires more research on the current and potential area, ecosystem provision capacity and social factors affecting UA, joined-up thinking and collaboration among governments, researchers and communities, and creative, context-specific solutions based on a comprehensive assessment of local conditions. Despite a number of challenges, through innovative solutions, flexible and integrated approaches to urban planning, and taking collective and local ownership of issues, most apparent space and resource constraints could be overcome, and urban agriculture could form an integral part of the resilient cities of our future. By conceptualising this rather complex topic, identifying some key issues that exist, and providing directions for research, policy, and practical courses of action, it is hoped that this study will contribute to these efforts.

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