Should we reduce the use of plastic in agriculture?

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Declaration

I declare that the work in this thesis is my own and has not been submitted for another degree or qualification at any other institution. Any collaborators involved in this research are properly acknowledged.

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Statement of Authorship

This thesis is prepared in an alternative format as a collection of five papers. Two are published in peer-reviewed journals and another is currently in-review. The other two papers have been prepared for submission to journals and are presented here in an alternative format. All papers have multiple authors, some of which are co-authors outside of my supervisory team. The details of these papers are outlined below. My contributions to these papers are made using the CRediT taxonomy system and have been approved by my supervisory team. Chapters 1 and 7 form the introduction and discussion to the thesis, which are not intended for submission.

Chapter 2 *is published as:*

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Abstract

Plastic use in agriculture has transformed agricultural systems worldwide, facilitating the production of fresh produce in yield-limiting conditions, extend the growing season and improving the food security of many regions. As global food systems come under increasing pressure from the future impacts of climate change and other global crises, the need to provide a stable, readily available supply of healthy, nutritious produce is increasingly important. Whilst plasticulture is considered an effective measure to maintain food security and increase agricultural productivity, there is a global call to reduce plastic use in agriculture. The impact of plastics from 'cradle-to-grave' are overwhelmingly negative, thought to compromise long-term agricultural productivity, human and planetary health. Even though there is an urgent call to reduce plastic use in agriculture, we are not equipped with an adequate knowledge base to assess and reevaluate plasticulture. Our understanding of plasticulture and its importance in food systems has not yet been comprehensively assessed. In parallel, the implications of plastic use in agricultural systems are not fully understood, in particular the quantification of microplastics in agricultural soils and risks to future agroecosystem functioning. This thesis presents a review of the UK food system and a meta-analysis to explore the relative importance of plasticulture. The meta-analysis found that plasticulture is key to increasing the yield of globally-important crops in agricultural systems worldwide. This is followed by a nationwide survey, soil archive analysis and a mesocosm experiment that investigate microplastic concentrations, fate and impacts in agricultural soils. The nationwide survey suggests that plastic crop covers are a significant contributor of microplastics to agricultural soils. Analysis of the Rothamsted soil archive revealed that agricultural soils are receptors of microplastic pollution from different agricultural sources and non-agricultural sources which predate modern plasticulture. A mesocosm experiment was used to determine the effects of microplastics on soil and crop health, as well as the influence of soil and crop type on microplastic transport. The results from the mesocosm experiment indicate microplastics pollution affects agroecosystem functioning. This thesis is an essential contribution to producing a comprehensive assessment of plastic use in agriculture in future food systems. The findings from this thesis highlight an urgent need to reassess plastic use in agriculture. Sustainable plasticulture will be vital to build the resilience of a future food system that prioritises human and planetary health.

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1. Introduction

The use of plastics in agriculture developed from a need to reduce the costs of agricultural infrastructure and boost agricultural productivity. Since the practice began in the 1940's, the use of plastics has evolved to become an integral part of global agricultural systems (Le Moine and Ferry, 2019; FAO, 2021). Plastic use in agriculture, particularly crop production, is driven by the almost immediate benefits of the practise; better temperature and moisture regulation, protection against disease, weather and pests, weed suppressant and improvements in resource-use efficiency, which translate to an increase in early- and late-season production and crop quality and yield (FAO, 2021; Harrison and Hester, 2018). In fact, the use of plastics is so deeply embedded in global agricultural systems that 60 % of global vegetable and animal production may be compromised without plastics (Le Moine and Ferry, 2019).

However, the use of the same applications to boost crop production (crop covers, crop housing, irrigation and fertilisers), have unintended and largely unknown consequences for agroecosystem and human health (Steinmetz et al., 2016; Qi et al., 2020; FAO, 2021). From 'cradle-to-grave', plastic begins to degrade into smaller particles via chemical, mechanical and microbial pathways (Allen et al., 2022; MacLeod et al., 2021). Macro-, micro- and nanoplastic pollution is prevalent in the agricultural environment, partly due indirect sources of urban-industrial origin and the degradation of plastic applications in use, but also from agricultural plastic waste, of which 16 – 50 % is mismanaged (FAO, 2021). Microplastics, defined as particles between 1 μm – 5 mm, are a novel entity in the planetary boundaries model and are now beyond the safe operating space and pose a high-risk to the Earth system (Richardson et al., 2023; Persson et al., 2022). As proposed by Richardson et al., (2023), the only safe operating space for novel entities is one where the entity in question is truly inert.

Plastic pollution is ubiquitous and hazardous, which has led to bans on single-use materials and the prohibitive use of certain plastics in consumer products, yet current legislation does not capture the use of plastics in agriculture (Mitrano and Wohlleben, 2020). Whilst there is increasing pressure to reduce and even remove the use of plastics in agriculture from NGO's (FAO, 2021; WWF, 2019; UNEP, 2021; IPCC, 2021a), doing so may destabilise an already fragile food system (Hofmann et al., 2023).

Global food systems are complex, diverse and heavily reliant on plastic use, therefore removing plastic will have cascading impacts on a local to national scale that are somewhat unexplored (Hofmann et al., 2023; Le Moine and Ferry, 2019). As the UK is facing increasing pressure to meet the current and future dietary needs of the population (SHEFS, 2023a), whilst preparing to cope with increased climate variability and global crises (House of Commons, 2022; Benton et al., 2022), the role of plastics in crop production must be reassessed. Whilst some studies have assessed the impact of plasticulture on a nationwide scale, no modern assessments focus on the UK or at a global scale (Zhang et al., 2018; Gao et al., 2019).

Historical, current and future use of plastics in agriculture is of growing concern. Even though research into plastic pollution in terrestrial environments has received more focus, the sources, magnitude, fate and consequences of microplastics remain largely unquantified, particularly in agricultural soils (Qi et al., 2020; MacLeod et al., 2021). Agricultural soils are receptors of microplastics from a wide range of sources and are thought to contain some of the highest concentrations worldwide (Nizzeto et al., 2016; Tian et al., 2022). Despite this, baseline concentrations of microplastics in agricultural soils and the load from direct and indirect agricultural sources are not well established, particularly in the UK.

The legacy of microplastics in the terrestrial environment over time is unknown, particularly in agricultural soils. The pervasive use of plastics in modern society has led to the accumulation of microplastics in agroecosystems (MacLeod et al., 2021; de Souza Machado et al., 2018). It is unknown how the sources and scale of microplastics in agricultural soils have changed over time and whether microplastic pollution is the result of historical farming practices or societal plastic use. It has not been determined whether microplastic pollution predates modern plasticulture. Determining a temporal record of microplastics is crucial to retrospectively assess the occurrence, storage and risk of microplastics over time (Turner et al., 2019).

There is limited understanding of how microplastics affect soil and crop properties, and how these properties, in turn, influence microplastic distribution in soils. Additionally, the movement and distribution of microplastics in soil is an important factor to determine retention time, risk and establish thresholds, of which there is currently little evidence (Ren et al., 2021; Rillig et al., 2017a). Our current understanding is largely based on the use of unrealistic concentrations in short-term field trials (Lenz et al., 2016; Qi et al., 2020; Hofmann et al., 2023). Even though experimental studies have reported mixed effects in agroecosystems, long-term changes to agricultural productivity and compromised soil function are overwhelmingly negative, but remain unquantified (Zhang et al., 2022a; Allen et al., 2022; Tian et al., 2022; Gao et al., 2022). There is an urgent need to better understand the mechanistic behaviour and impact of microplastics in agricultural soil. Addressing these gaps is key to better understanding plastic use, management, fate and consequences in agricultural systems. Given the development of novel polymers, benign additives, management practices, regulatory frameworks and end-of-life treatments, it is essential to continue monitoring and reporting plastic pollution in agricultural systems to assess how successful actions are to develop sustainable plasticulture (Hofmann et al., 2023).

1.1 Thesis overview

1.1.1 Thesis aims and objectives

This thesis explores the use, usefulness and effects of plastic in UK agriculture. The importance of plasticulture in agricultural systems and the consequences of microplastic pollution on agroecosystem function and agricultural productivity are relatively unknown. The aim of the thesis is to provide an assessment of plasticulture from 'cradle-to-grave' and evaluate whether there is an opportunity for plasticulture to exist in future crop production systems and in what form.

The thesis addresses the following objectives:

1) To assess the relative importance of plastic crop covers in UK crop production and judge whether plasticulture is a tool to develop the resilience of the UK food system (Chapters 2 and 3).

2) To determine the concentrations of microplastics in agricultural soils across the UK and how plastic crop covers directly contribute to microplastic pollution in terrestrial environments (Chapter 4).

3) To examine whether agricultural soils are receptors and reservoirs of microplastic pollution over time and whether the presence of microplastics predates modern plasticulture (Chapter 5).

4) To evaluate how microplastics affect soil and crop properties in an agricultural system, and how soil and crop type may influence microplastic movement in the soil profile (Chapter 6).

In a rapidly growing area of research with many research gaps, this thesis aims to provide valuable information about the intended and unintended outcomes of plasticulture in agricultural systems, not restricted to the UK.

1.1.2 Thesis structure

This thesis consists of five chapters that have already been published or are intended for submission in peer-reviewed journals, followed by a discussion chapter to conclude. Supplementary material and references for each chapter have been ordered and presented after the end of the discussion chapter.

Chapter 2 provides a comprehensive review of the literature about the current challenges and growing pressures on the UK food system. It explores how plasticulture occupies an important role in the UK agricultural system and discusses the negative implications of the practise. To develop a more resilient food system, the proposition of a transformative change in plasticulture is also explored.

Chapter 3 investigates the relative importance of plastic crop covers on crop yield. Through a meta-analysis, it is highlighted how plastic crop covers are used in a range of production systems to increase yield of fruit and vegetable crops. The study considers how the success of plastic crop covers varies between crops and geographical location. Given the global call to reduce plastic use in agriculture, reasoning for the continued use of plasticulture is provided under the conditions the practice is reassessed to prioritise planetary and human health.

Chapter 4 is an experimental chapter which examines how the use of plastic crop covers in potato and carrot production contributes to microplastic concentrations in agricultural soils. By conducting a comparative nationwide survey of agricultural soils where plastic crop covers were and were not used for crop production, background levels of microplastic contamination were established, as well as the relative microplastic load from plastic crop covers. Microplastics were separated from the soil, then identified and quantified in the laboratory to measure concentrations of microplastic pollution in agricultural soils.

Chapter 5 uses a preserved soil archive from Rothamsted Research (UK) to establish a temporal record of microplastics in agricultural soils. It investigates how microplastic concentrations in agricultural soils have changed over time and how the use of soil amendments has contributed to these loads. The study also aims to determine whether microplastic pollution is largely of agricultural or non-agricultural origin and whether the microplastic load from these sources changes over time.

Chapter 6 uses the environmentally representative microplastics concentration determined in Chapter 3 to evaluate the impacts of microplastics in agroecosystems. By conducting a mesocosm experiment, how microplastics affect the soil physiochemical environment, microbial community and crop health is explored. Similarly, it investigates how soil and crop properties may affect microplastic movement in the soil profile and redistribution to other environmental media.

Chapter 7 provides a summary of the findings from the research, discusses the role of plasticulture in agricultural systems and the implications of microplastic pollution for long-term agroecosystem functioning and agricultural productivity. This chapter concludes with suggestions for future research.

2. Sustainable production of healthy, affordable food in the UK: The pros and cons of plasticulture

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Abstract

An evolving green agenda as the UK seeks to achieve 'net zero' in greenhouse gas emissions by 2050, coupled with our new trading relationship with the European Union, is resulting in new government policies, which will be disruptive to Britain's traditional food and farming practices. These policies encourage sustainable farming and land-sparing to restore natural habitats and will provide an opportunity to address issues such as high emissions of GHGs and dwindling biodiversity resulting from many intensive agricultural practices. To address these and other food challenges such as global conflicts and health issues, Britain will need a revolution in its food system. The aim of this paper is to make the case for such a food revolution where additional healthy food for the UK population is produced in-country in specialised production units for fruits and vegetables developed on sites previously considered unsuitable for crop production. High crop productivity can be achieved in low-cost controlled environments, making extensive use of novel crop science and modern controlled-environment technology. Such systems must be operated with very limited environmental impact. In recent years, growth in the application of plasticulture in UK horticulture has driven some increases in crop yield, quality and value. However, the environmental cost of plastic production and plastic pollution is regarded as a generational challenge that faces the earth system complex. The distribution of plastic waste is ubiquitous, with a significant pollution load arising from a

range of agricultural practices. The primary receptor of agriplastic pollution is agricultural soil. Impacts of microplastics on crop productivity and quality and also on human health are only now being investigated. This paper explores the possibility that we can mitigate the adverse environmental effects of agriplastics and thereby exploit the potential of plasticulture to enhance the productivity and positive health impact of UK horticulture.

2.1 Introduction: Current challenges for the UK food system

Global food security can be defined as a situation where all people at all times have physical, social and economic access to sufficient safe, nutritious and sustainably-produced food that meets their dietary needs and preferences (Global Food Security, 2021). There is now increasing confidence that within the next 25 years our society will have the capability, the resources, the knowledge and the technology to feed an expanded global population while delivering improved human-and planetary health (Global Food Security, 2021; Horton et al., 2021).

Despite this confidence, we are still faced with a necessity to address a range of significant food-related challenges. Perhaps foremost among these is the development and the impact of the climate emergency. A recent report from the Intergovernmental Panel on Climate Change (IPCC, 2021b) highlights with high confidence the observation that elevated temperatures and increased drought are already significantly negatively impacting agriculture, food availability, food access, food utilisation and food stability on most continents of the world. At the same time, our global food system currently contributes a third of global greenhouse gas (GHG) emissions, thereby driving further climate change (Crippa et al., 2021) and this issue must be addressed with some urgency. GHG emissions from grazing ruminants and accompanying feed production, from soil tillage and from the significant production of the rice crop in several parts of the world are identified as significant targets for those seeking to increase the sustainability of food and farming. Overuse of input resources such as water, nutrients and other agrochemicals coupled with the use of some inappropriate farming practices are also environmentally damaging (e.g. Willett et al., 2019). In the UK there is some regulation of water use, yet there is still scope to improve the water productivity of many crops (e.g. Morison et al., 2008).

Deteriorating public health is a growing challenge in many regions of the world and malnutrition is now a leading cause of early deaths globally (Global Food Security, 2021). More than half of the global population is now underweight, overweight or obese (FAO, 2021). By 2035, the UK National Health Service is predicted to be spending more on complications of type 2 diabetes (often a consequence of a poor diet) than its entire spend on cancer treatment (Royal Society of Biology, 2021) and two-thirds of the UK population may be malnourished. The UK's childhood obesity problem is particularly acute (Gov UK, 2020; World Health Organisation, 2020). While addressing these problems requires us to take account of many socio-economic challenges and modify much consumer behaviour, we must also work to improve people's access to healthy and sustainable foods (Willett et al., 2019).

Making more healthy food available to people in the UK is a significant challenge as the UK cost of living rises and could require an increased focus on food produced in the UK by organisations ranging in scale from multi-national suppliers to local producers. Our focus must also be on more reliable international trade, as shown by a recent report supported by the UK food retailer Morrisons (Benton et al., 2017). This report shows that while the UK produces 52 % of the food that we eat in the UK, only 23 % of the fruit and vegetables consumed are produced here, (percentages based on the farm gate value of the crops). The EAT Lancet commission and others (Benton, 2019; Willett et al., 2019) emphasise the importance of increasing the proportion of fruit and vegetables in diets, particularly those of young people.

There is general recognition that reduced consumption of meat in most diets in the developed world would have both dietary and environmental benefits.

As well as generating environmental problems from our own agricultural activities (e.g. GHG emissions and other environmental issues such as overuse of water and fertiliser), we import food from nearly 200 countries across the globe (Benton et al., 2017), thereby generating emissions and other pollution and resource use issues offshore as a result of both production and transport of food. Any changes in our food system driven by dietary requirements must take into account the impact of such changes on planetary health. The UK has committed to achieving 'Net Zero' by 2050 (Gov UK, 2021), and this will likely require significant changes to environmental accounting both at home and abroad. Despite our requirements for more overseas trading partners, it will be hard to sign new trade deals with countries with lower food production emissions and health standards than our own. This challenge has been compounded by procedural and political changes post-Brexit. Recently published proposals for a National UK Food Strategy (UK National Food Strategy, 2021) highlights many of these issues in some detail. The strategy aims to deliver healthy, affordable and safe food for all in the UK. Emphasis is placed on increasing the resilience and sustainability of food production and supply but also on restoring and enhancing our natural environment.

In the UK, in recent years some discussion has focussed on rewarding farmers for good environmental stewardship, rather than for productivity. The Government's new Environmental Land Management (ELM) strategy is now being set out (January 2022). This is expected to lead to significant changes in land management, benefiting the natural environment and addressing the challenges of the climate emergency. ELM will pay farmers for undertaking actions to improve the environment. It has three components, each of which will be launched in full in 2024 (NAO, 2021):

- *The Sustainable Farming Incentive (SFI) will be open to all farmers and will pay them for actions to manage their land in an environmentally sustainable way.*

- *Local Nature Recovery will pay for more complex actions that deliver benefits at a local level and aims to encourage collaboration between farmers.*

- *Landscape Recovery will support large-scale projects to deliver landscape and ecosystem recovery through long-term land-use change projects such as large-scale tree planting and peatland restoration.*

Although there is much concern across the farming community about the withdrawal of much financial support currently available to reward farmers for food production there is general recognition that the UK must give increased attention to maintaining and even enhancing biodiversity, as well-functioning ecosystems are critical for human existence, economic prosperity and a good quality of life. A healthy, diverse biosphere aids in the provision of food, energy, shelter and medicines. It will also sustain water and soil quality and help regulate the Earth's climate. Early ELM proposals released in January 2022 have caused some alarm among the UK farming community. There are reservations about the rewards that will be available to small farmers (compared with the current support arrangements) and worries that current proposals cannot reward tenant farmers who currently make up almost half of UK farmers (13 % of farm holdings are wholly tenanted and 34 % are ‘mixed tenure’, DEFRA, 2019). Small scale farmers may circumvent these barriers by forming a collective group to pass the land area threshold but are then met with other challenges that come with collaboration (DEFRA, 2020).

The recent National Biodiversity Network (NBN) report on biodiversity in the UK (NBN, 2021) shows that we retain only half of our natural biodiversity, a disturbing figure, especially when compared to other G7 countries. The UK is at the very bottom of the G7 table in terms of how much biodiversity still survives and is in the bottom 10 % of all countries globally. Loss of soil biodiversity may be particularly critical as changes in soil communities and the loss of biodiversity threaten ecosystem multifunctionality and sustainability (Wagg et al., 2014). There are around 11 million species of soil organisms, but fewer than 2 % have been named and classified and a 2019 Environment Agency report indicated that the UK soil invertebrate community has not been fully surveyed since 2007. This highlights the evidence gap for one of the major indicators of soil health. Results from this survey indicate significantly fewer invertebrates in arable habitats than in other habitats (Emmett et al., 2010). There are considerable data showing worldwide decline in soil health and soil biodiversity (e.g. FAO et al., 2020).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has reported that land-use changes have had the greatest overall negative impact on nature since 1970 (IPBES, 2019). Unsustainable agriculture, logging, transport infrastructure, residential and commercial development, energy production and mining are all common problems in this context. Where and how food is produced has been one of the biggest drivers of land-use change (World Wildlife Fund, 2020). This issue is acute in the UK where 70 % of our land area is devoted to agriculture, this is around 17 million hectares, of which 6 million hectares are under cultivation for cereals, oilseeds, potatoes, salads, fruit and vegetables, with the remaining land used for grazing and raising livestock (Benton et al., 2017). A dietary change involving reduced meat consumption to address health and environmental issues potentially frees up land previously used for grazing and production of animal feed and opens the possibility for the development of new agricultural systems to allow for enhanced fruit and vegetable production. Such a dietary change also brings benefits in terms of reduced CO2 emissions and nutrient losses (Foly, 2022).

Consideration of this welter of new policies on food and farming does suggest a possible conflict between policies designed to encourage the production of more food in the UK and large-scale projects to deliver landscape and ecosystem recovery through changes in long-term land-use (such as large-scale tree planting and peatland restoration for carbon capture and storage). More ‘extensive’ agriculture will almost by definition reduce the production of some foods. If enough land is to be spared to store enough carbon to offset emissions from UK farming, then a proportion of what remains dedicated to food production will have to focus on intensive production (Balmford, 2021). Such intensification is potentially problematic for the welfare of animals, but advances in modern plant biology and the exploitation of novel engineering solutions may provide exciting opportunities for agronomy and horticulture in the UK (UKPSF, 2019).

2.2 Scenario planning: How do we adapt our food system for the future in order to cope with growing pressures on UK society?

The UK Global Food Security (GFS) programme (Global Food Security, 2021) has addressed this and related questions implicit in our efforts to define and develop a global food system that is better at feeding us while it is also better at looking after the planet. They have done this by scenario planning, which considers different UK responses to two much-lauded, landmark global agreements: the Paris Agreement on climate change and the UN's Sustainable Development Goals (SDGs). Importantly, ‘*the scenarios in this report do not aim to predict what will happen in the future, nor do they suggest what the preferred future might be. They are designed to stimulate thought, identify opportunities and threats that the UK food system may face in the future, and aid long-term decision-making’*. (Global Food Security, 2021).

In the GFS exercise, scenarios were developed based on two critical uncertainties that are expected to drive changes to the UK food system in the coming years. One uncertainty was whether by 2050 the UK food system would rely more on local production and supply or upon greater globalisation to make food available to the UK population? The second uncertainty was a consideration, over the same time period, of what would be the impact on the UK food system if it were transformed to deliver either some climate mitigation (as suggested in the Paris Agreements) or to deliver on a broader range of sustainability metrics (i.e. the issues implicit in nearly all of the Sustainable Development Goals (SDGs)).

In all four scenarios (localised system focussed on general sustainability targets, localised /climate mitigation targets and two globalised scenarios with climate or general sustainability foci) developed by the GFS exercise, the proposal is that climate change will contribute directly or indirectly to higher costs in the food system. Another major conclusion is that, as suggested in other recent papers (e.g. Willett et al., 2019), the elimination of food waste in both the food supply chain and in the household combined with a shift towards diets with reduced animal protein is highly likely to be of major importance in the delivery on the respective global agreements. A recent report by the Copernicus Climate Change Service (Copernicus, 2022), highlights the potential rate of future climate change and they note that the last seven years have been the hottest on record for the planet. GFS scenario planning and our own historical experience of the development of the global food system suggest that a focus only on reducing the effects of climate change on the operation of the food system in the UK could undermine key issues for society, such as biodiversity, human health and the economic well-being of many people. Nevertheless, the GFS exercise also suggested that both greater self-sufficiency in food and multilateral cooperation could to some degree protect the UK food system against future climate disruption of food supply. Because of the current opportunities offered to the UK by political changes affecting food and farming policy we now consider how a more-localised, communal UK food system might be developed and how it might help deliver benefits to both human and planetary health (see Figure 2.1).

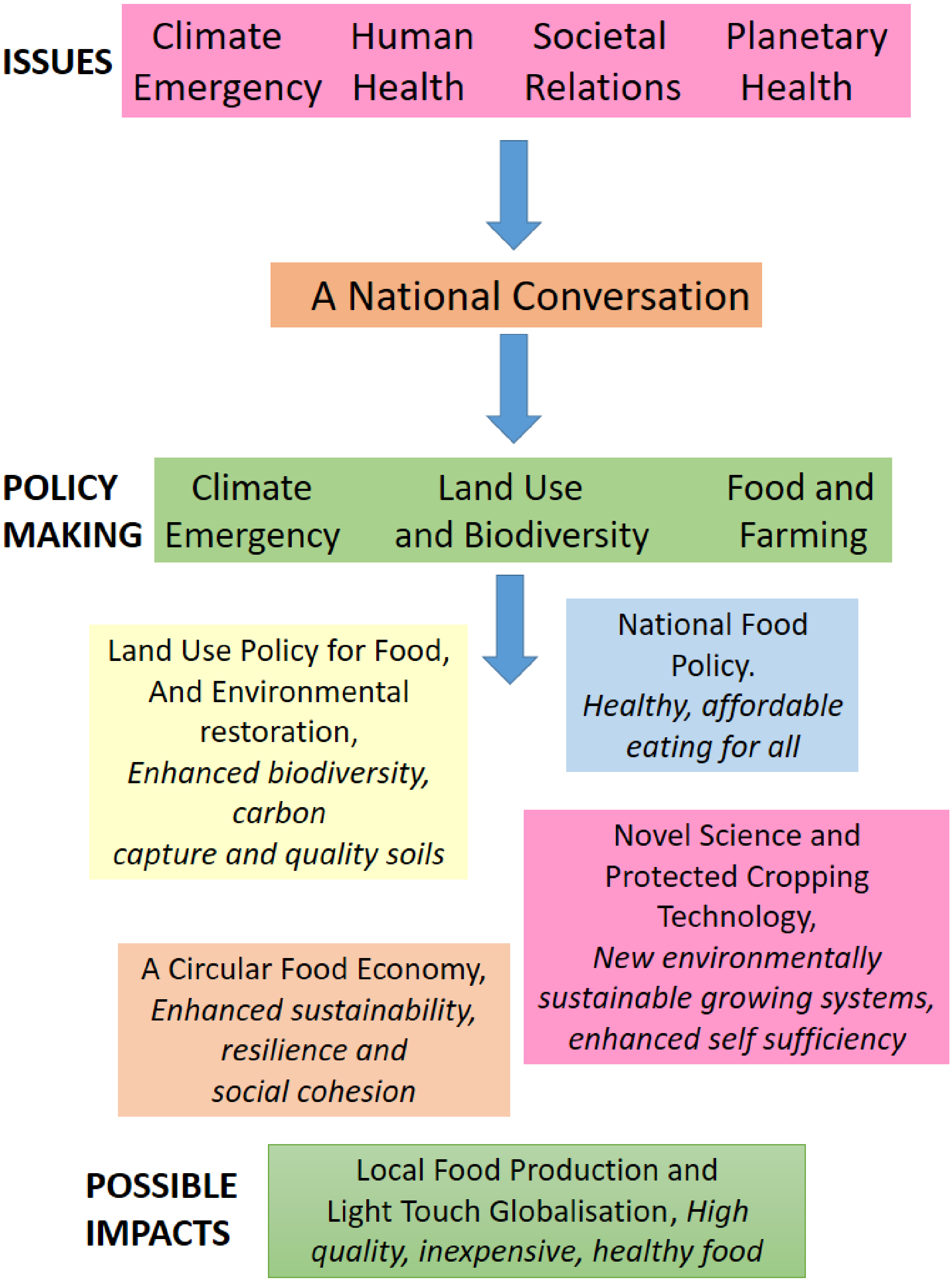


Figure 2.1 A localised communal food system developed in the UK in response to current environmental and social issues. Impacts are developed within a framework of possibilities suggested by UK Plant Sciences Federation (2019) and Global Food Security (2021).

Among several scenarios from the GFS, exercise is the possibility that the national food system could be characterised by 'a local-production for-local-consumption ethos'. Local crop production facilities might allow high yields of reasonably priced, healthy food in more months of the year. Such changes, stemming from novel protected cropping might allow some increase in UK food self-sufficiency. Novel production facilities might be located in urban and peri-urban locations, potentially reducing the demand for agricultural development in rural locations (Walsh et al., 2022). This demand might be further reduced by changes in diet and reduced demand for animal protein thereby allowing land sparing for environmental restoration, carbon capture from reforestation and some green energy production. In making changes to land use of this kind, care should be taken to ensure that habitats of high conservation value are not lost in a change to more productive habitat types.

The GFS Food Scenarios project further foresees that UK agricultural policy, currently under development, supports the production of climate-friendly nutritious foods. Future health policy might use financial incentives to encourage citizens to adopt healthy, environmentally sustainable diets, although the 2022 food price challenges have delayed proposed policy changes in this area. The hope is that the typical UK diet will include more fruit and vegetables, and less sugar, starch and fat. One particularly significant GFS suggestion is that as a result of likely agricultural diversification, UK food production could be made more resilient to changing weather patterns resulting from predicted climate change. We now consider the possible evolution of the UK food system in more detail.

2.3 An evolving UK food system

In this section, we consider the question of whether it is possible for the UK to increase the quantity and diversity of fruit and vegetables grown in the UK. This requires a brief look at some recent historical development of our food production systems.

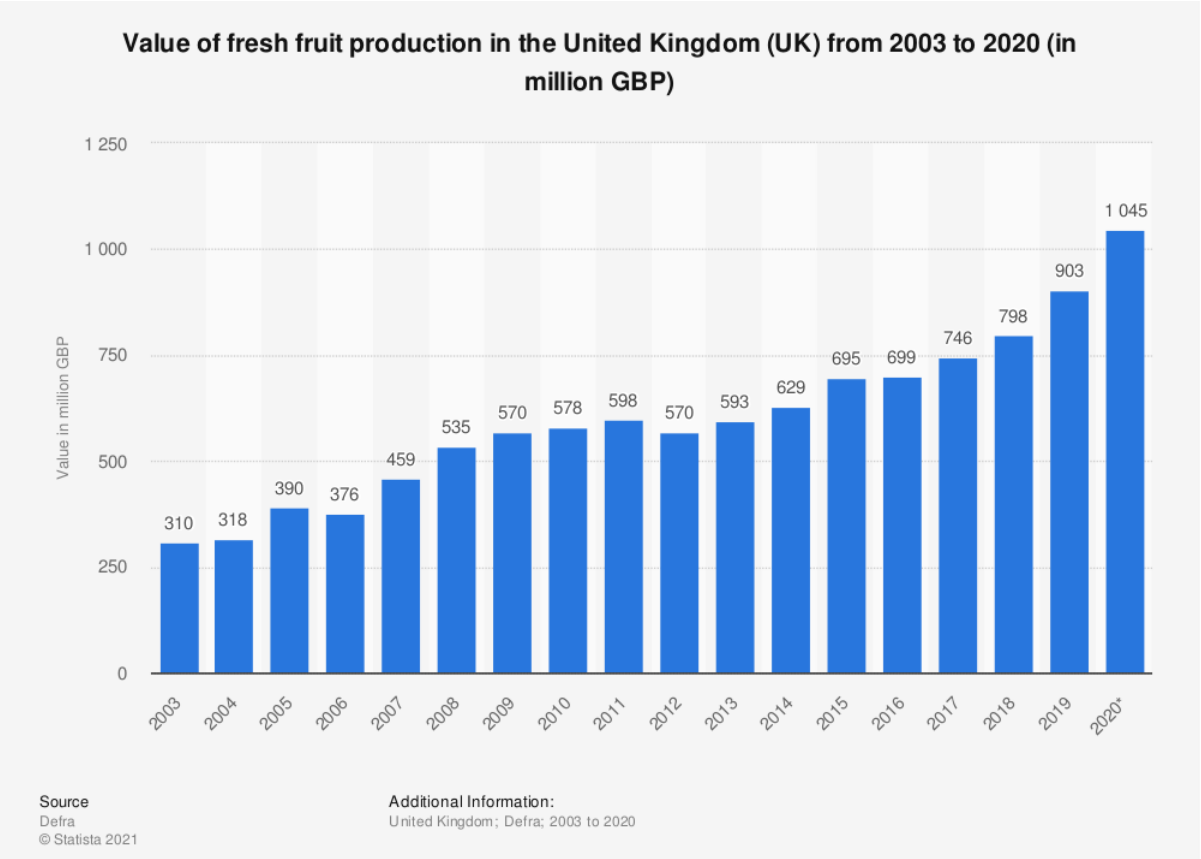
The 18th and 19th centuries saw the development of glasshouses for food production in the UK. Food storage technologies also improved during this period and increased use of pest and disease control measures for both crops in the field and in storage also increased food availability. The development of plant and animal genetics has further increased yields with agronomical advances contributing to reduced yield gaps (the difference between potential and actual crop yield). Over the years the practice of highly-productive intensive agriculture with high input resources has evolved. In combination with a highly efficient import/export trade, this has resulted in the development of a sophisticated supply chain for food for the British public. Diets of many are largely determined by costs of food, but for the more affluent, the policies of retailers have been devoted to supplying whatever customers demand whenever they want it, whatever the monetary and environmental cost. This situation is likely to change as the Government legislates to make more healthy food, produced in an environmentally-friendly fashion, available to more people. However, while Britain's food and farming policy has resulted in an enviable productivity and an efficient supply chain, intensive farming practices are now commonly blamed for Britain's biodiversity crisis and a significant portion of the UK's GHG emissions. Activists and policymakers are beginning to imagine new types of food production for the UK, which are more planetary friendly.

Britain's colonial history has made available a broad range of exotic crops from different parts of the world as food sources for the British population. Lang (2020) has noted that the historical strength of the British Navy has ensured the security of these supply lines. However, global conflict and a general reduction in Britain's global influence have increased the potential fragility of the UK's supply chains (Lang, 2020). Supply chain instability may require more domestic production to ensure greater food security for the UK population (and a reduction in the environmental footprint of the food items). It is important therefore to consider the degree to which this policy conflicts with the UK Government's land-use policies where farmers are rewarded primarily for the delivery of public goods with seemingly little encouragement to produce more, good quality food.

Many of the fruits (and some of the vegetables) that are consumed in the UK are intolerant of freezing- or even chilling temperatures. Some countries with climates colder than the UK do grow commercial quantities of exotic fruits and vegetables under protected cropping (e.g. bananas in Iceland), but the likelihood of being able to grow significant quantities of such ‘exotics’ for mass consumption in the UK would be prohibitively expensive, both financially and environmentally.

Suppliers of fruit and vegetables to the UK market have demonstrated best practices in growing staple crops for the UK in overseas environments where radiation levels and temperatures are high enough for very high productivity (e.g. G's Fresh (2022) and Barfoots (2022)). The sustainability of such operations has in the past been questioned because of the ‘food miles’ involved, but these farming operations in many countries where the climate delivers high productivity can supply the UK market with a product with a lower total global warming potential (GWP) than is the case for UK production (e.g. Webb et al., 2013). This will only be the case if refrigeration and transport costs are low (as is the case in the shipping of vegetables from West Africa by sea. In this case, transportation to the UK takes only 4 – 5 days and so this highly-productive year-round production system has to this point in time (2021) fitted well with the ‘just-in-time’ supply chains used by most UK retailers. Whether this will continue to be the case as the consequences of Brexit unwind, remains to be seen. A future UK food policy that is climate-friendly and supports the production of nutritious foods is likely to involve imported food grown and transported appropriately to the UK market. Nevertheless, as suggested by Global Food Security (2021), the possibility that the national food system could be characterised by 'a local-production for-local-consumption ethos' deserves serious consideration. We must therefore ask how this can be achieved. The urgency of providing answers to this question is emphasised by the current (May 2022) conflict in Ukraine. This has involved two countries that contribute significant amounts of food to the global food system and we are already experiencing changes in both the availability and the cost of food. A recent report from Chatham House (Benton et al., 2022) proposes that governments must invest now to build the long-term resilience of societies and economies against global shocks such as Russia's war in Ukraine and the COVID-19 pandemic. The Chatham House report emphasises that effects of serious market disruption and geopolitical upheaval should be buffered by what the authors' term 'no-regrets' measures. As we have already emphasised, a national food system with extended food supply chains is highly vulnerable to disruption. Enhanced UK food production will help to buffer the effects of external shocks to our food system and might be thought of as such a 'no-regrets' measure. Introduction of measures of this kind will require a national debate with, among others, the general public. These considerations are further discussed later in the paper.

In recent years, horticultural production has been a success story for the UK (DEFRA, 2021). The value of home-produced vegetables increased by 10 % to just under £1.7 billion in 2020, and the volume of home vegetable production also increased in the year 2020 by 3 %, compared with the year 2019. Home-produced fruit has grown in value to £1.0 billion, an increase in 16 % compared with 2019 (see Figure 2.2), with production volumes falling 4.5 % (DEFRA, 2021). We now examine the basis of these changes and ask whether further gains are possible using technology and genetic material accessible to the industry.



Value of fresh fruit production in the United Kingdom (UK) from 2003 to 2020 (in million GBP)

Source
Defra
© Statista 2021

Additional Information:
United Kingdom; Defra; 2003 to 2020

Figure 2.2. Data from GOV.UK and DEFRA (2021) illustrate a general increase in the value of fresh fruit produced within the UK from 2003 to 2020 (in million GBP).

There are many reasons for increases in crop productivity and value shown over the last several years, but prominent among these is the availability of new varieties generated by breeding programmes for many crops, which have been successful in generating enhanced fruit and vegetable quality and yield, and some degrees of stress tolerance (e.g. https://www.harper-adams.ac.uk/research/project/148/vegetable-genetic-improvement-network-vegin). A recent announcement made by the UK government (Gov UK and DEFRA, 2022) on crop improvement, which is of great importance for the sustainability of UK agriculture, makes it clear that the crops improved by the novel technique of gene editing are soon likely to become an important part of UK Agriculture. As part of a gradual approach towards allowing gene editing as a means of improving yields, stress resistance and resistance to pests and diseases of

UK food crops, research into the gene editing of plants in the UK will become much easier. New rules brought forward by the Government in 2022 encourage field trials and other research efforts and a bill introduced in Parliament in May 2022 allows commercial growing of gene-edited crops in England. Tomatoes that boost the body's vitamin D could be among the first gene-edited crops allowed on sale in England. One in six people in the UK are deficient in vitamin D, which is vital to strong bones and muscles and helps reduce the risk of cancer. Although the introduction of this new technology, which can also result in increased drought and pest and disease resistance of crops, will be controversial for some and will require an open conversation with the British public to aid public acceptance, it does offer the opportunity of increasing the sustainability, resilience and profitability of UK agriculture.

Conventional plant breeding coupled with the observation that the changing climate in the UK has already had the effect of increasing the UK growing season by up to a month (Carbon Brief, 2016). This means that the period of the year during which many crops can be supplied to the market has been lengthened. Many mature crops can be stored at the end of the growing season, using low-tech, low-cost systems before being brought to the market. A growing understanding of postharvest biology now leads growers to use often-simple techniques to take the heat out of certain crops soon after harvest, thereby prolonging storage opportunities. Advanced packaging and storing methodologies will also extend storage periods by reducing the loss of water from many crops. Such extended storage techniques allow growers the opportunity to benefit from higher prices for products in the ‘off-season’. In addition to this, many/most higher value crops such as soft fruit, tomatoes, peppers and cucumbers are grown in the UK under more sophisticated protected cropping systems involving glasshouses or polythene tunnels and crop mulches, examples of a system commonly referred to as ‘plasticulture’.

Exploiting modern genetics in combination with modern agroecological crop management techniques to increase productivity and sustainability of UK farms will potentially require more land devoted to crop production. Arable production comprises a relatively small part of the total land area currently required for UK food production (6 million of 17 million hectares devoted to agriculture, Benton et al., 2017). Therefore an expansion of this segment of the market should not be an insurmountable problem, particularly as in the future we may reduce the requirement of land for meat and dairy production (Benton et al., 2019). It is often noted that much grazing land in the UK is not of high enough quality for arable farming, but much high-quality fruit and vegetable production now involve specialist high-production systems where many crops are no longer grown in soil. Rather, to minimise problems with soil-borne pests and diseases, artificial growing media are employed which themselves may serve as a support medium for a crop relying on a flowing solution culture for water and nutrient supply. These systems can reduce pollution issues arising from diffuse use of fertilisers and indiscriminate use of pesticides and can also deliver enhanced efficiency of water use (FAO and IWMI, 2017), thereby constituting an important part of the response of the UK farming community to new environmental legislation. Highly-productive protected cropping systems also do not always require large areas of land, but there are still environmental challenges for these systems as many people already resent the visual impact of such developments in areas of outstanding natural beauty (Rogge et al., 2008). The most sophisticated of these developments, taking profit from modern environmentally-efficient glasshouse technology, lighting developments, farming systems, etc., may be too expensive for extensive deployment in some parts of the UK market. Nevertheless, novel developments in science and technology still provide lots of opportunities for the industry that will impact positively on UK food and farming and increase the broader social and financial benefits from such sustainable and localised developments. The UK Plant Science Federation (UKPSF, 2019) in its seminal report

'Growing the Future' has recognised as a priority 'Promotion of public-private partnerships and collaborations with consistent, long-term R&D policies, and support to bridge the gap between discovery science and commercial application' and has suggested that future funding should 'support innovative strategies to develop nontraditional agricultural and horticultural systems'. We propose that intensive production systems of the kind that are currently in use across segments of the UK horticulture industry can be further developed to become more environmentally sustainable and to provide the UK with increased quantities of healthy food to provide increased resilience against environmental and societal changes.

2.4 Plasticulture: A key component in achieving increased food security and healthy diets

Given the success of much-protected cropping under plastic in the UK, we consider here the arguments for and against the increased use of plastic in the UK for food production. The use of plastics in crop production systems is a worldwide practice originally introduced in the late 1940s to reduce the cost of agricultural infrastructure (Le Moine and Ferry, 2019). Plastic use in our food system extends beyond crop production, as plastic films are commonly used for the transportation, protection and storage of fresh produce once harvested. Reducing food spoilage/waste is a key part of the food security challenge, and to that end, the industry is working hard to introduce less-environmentally damaging packaging alternatives.

Plasticulture is proven to boost agricultural productivity in yield-limiting conditions (Espi et al., 2006; Harrison & Hester, 2018) and is generally considered an inexpensive means to enable the food supply chain to meet food demand and consumer expectations on food quality. Uptake of plasticulture by producers and suppliers in the UK, much like other European countries, is driven by what can be almost immediate benefits of the practice. Current use in the UK is driven by the competitive advantage of producing early-season marketable yields (DEFRA, 2011). Plasticulture in the UK is also used to increase yields at other times in the season, reduce agrochemical loads and provide protection from birds, pests, frost and other adverse weather conditions. Following crop diversification programmes in Europe during the 1970s, plasticulture evolved to incorporate a range of polymers (Orzolek, 2017). Development of new polymers has facilitated new growing techniques such as soil-less cultures; hydroponics, aeroponics, vertical farming and controlled-environment agriculture more generally (Rubio-Asensio et al., 2020). Within the UK, 52 % of all soft fruit is grown under protection; 6222 hectares of 11,966 hectares are destined for crop production (Ridley et al., 2020). However, this is a generalisation of the sector and does not accurately represent the ratio of protected to unprotected cropping on a crop-by-crop basis. 92 % of UK strawberries, for example, are now grown under polytunnels, often on raised platforms in plastic bags, pots or troughs to maximise yield, quality and ease of harvest (Ridley et al., 2020). Recently-developed polymers that alter the spectral quality of solar radiation may be used to manipulate plant morphogenesis, improving the quality, aesthetics and taste of the produce (Orzolek, 2017). Crop protection from pests and diseases is often aided by the introduction of plasticulture. Considering the increase in domestic policies focussing on landscape recovery, competition for land use between food production, restoration and climate mitigation projects will intensify. New growing techniques such as those outlined above may help minimise the area devoted to crop production in the UK without compromising the productivity, thereby boosting domestic production of accessible, affordable, high-quality fruit and vegetables whilst freeing up land for landscape recovery.

The effectiveness of plastic applications is dependent upon the environmental conditions, crop type, location, season and quality and spectral properties of the film (Gao et al., 2019; Orzolek, 2017; Steinmetz et al., 2016). Because of variation in the type and magnitude of environmental stresses that affect crop yield and water-use efficiency on a local to the international scale, using plastic applications to boost crop production does not always equate to a more profitable production system because of the upfront costs and the effectiveness of the plastic application itself. For example, plastic mulch applied to wheat fields in China during the crop establishment phase was only cost-effective where water availability was low. When the soil water content exceeded 60 %, non-mulched plots showed better cost–benefit ratios and bigger net annual incomes (Xie et al., 2005).

A ‘best estimate’ of the extent of plasticulture in the UK, provided by Scarascia-Mugnozza et al., 2011, indicates that at that time, the UK grew around 12,000 hectares of crops under cover, 10,000 hectares of which were mulch films. There were estimated to be 2500 hectares of greenhouses and polytunnels and 1400 hectares of low tunnels. Data compiled by DEFRA suggest that an area of 7986 hectares was covered by plastic in 2017. Due to the inconsistencies in estimates, determining the trends of plastic-protected cropping over recent years proves difficult. Estimates suggest that the use and area covered by plastic applications in the UK have generally increased and continue to do so, subject to annual fluctuations (DEFRA, 2011; Steinmetz et al., 2016). Ridley et al., (2021) have suggested that between 2011 and 2017 the area of edible protected crops in the UK increased by 13.5 %. Between 2017 and 2019 the area of edible protected crops decreased by 30 %, but the crop value increased by 9.6 % over the same period (DEFRA, 2021; Ridley et al., 2021). Some of the increase in crop value is due to a general increase in crop quality arising from both agronomical and genetic developments. More value is added by the development of sophisticated glasshouse systems extending the cropping season at both ends of the year, from the period when cropping is possible under plasticulture. This development and the use of protected cropping generally may be driven by consumer expectations of the ready availability of seasonal crops in all months of the year and under potentially more challenging growing conditions as our climate changes (Else & Atkinson, 2010). In the UK, the economic advantage of growing under polytunnels has been most effective for soft fruit growers, particularly strawberry growers (Lewers et al., 2017; Warner et al., 2010). An increase or decrease in the area covered by plastic is not necessarily reflective of a proportional change in the volume of plastic used. Modern cropping techniques may use multiple plastic applications such as fleece wrapping of young strawberry plants inside a polytunnel late in the winter and early in the spring.

Across the world, an increase in water-use efficiency is one of the main incentives for farmers to use more plastic and as the climate emergency grows, this is very likely to increase in importance as a major driver of innovation in the UK. Plastic mulch films and fleeces, commonly made of low-density polyethylene (LDPE) or polypropylene (PP), are durable, flexible and cost-effective. Both applications conserve soil moisture by reducing surface evaporation. Higher soil water contents will aid seed germination of crops sown under a mulch film or fleece. It is anticipated that expenditure on irrigation and water management will be reduced once the plastic applications are integrated into the crop production system (Chang et al., 2013; Ruíz-Machuca et al., 2015; Steinmetz et al., 2016; Wang et al., 2016). The economic effect of using plastic mulch films may translate to an approximate 25 % saving in water costs (Steinmetz et al., 2016), particularly when the existing crop production system operates in arid regions with low-water availability (Biswas et al., 2015). In China, plastic film mulch decreased evapotranspiration from a maize crop (Fan et al., 2017). Importantly, because of changes in crop energy balance, the plastic film mulch accelerated plant growth and advanced maize maturity, and thus improved biomass production, grain yield and water-use efficiency. Water availability for irrigation is a growing issue around the world and this is increasingly the case, particularly in the south of the UK (Rio et al., 2018). Water savings combined with increases in yield can be of great importance to farmers as the climate changes.

Plastic mulch films, fleece, polytunnels and greenhouses induce localised soil warming. These plastic applications trigger a greenhouse effect as condensed water trapped beneath the film absorbs the IR radiation reflected by the soil. Variations in the colour of the film translate to a different soil warming effect as different films allow different parts of the incident solar spectrum to penetrate the film. Transparent films generally provide the largest soil warming effect by transmitting between 85 and 95 % of the solar spectrum and trapping long-wave infrared radiation (LWIR) (Snyder et al., 2015; Steinmetz et al., 2016), increasing soil temperatures, in some cases by more than 7°C (Wang et al., 2016).

The potential benefits of early-season soil warming are shown by the work of Gregory and Marshall (2012), where the analysis of historic climate warming in Scotland shows very significant yield benefits as a result of early chitting of seed potatoes in response to soil warming of only around one-degree centigrade. An increase in soil temperature resulting from the use of plastic films covering the soil induces early tuber growth and seed germination of other crops, which extends the growing season of many crops and increases the choices of crops that may be grown in particular regions (Chang et al., 2013; Gosling et al., 2014). Within the UK, plastic mulch films, fleece, polytunnels and greenhouses provide protection against frost to produce an early-season yield, when the price and demand of domestic production are high. Many economically valuable crops, particularly soft fruits, require warmer temperatures than those occurring in the UK in all but the mid-summer months and so the use of plastic will invariably increase productivity in spring and autumn (Lewers et al., 2017).

Plastic mulch films and fleeces can prevent the spread of viral diseases by repelling insects (Olle & Bender, 2010; Victor & Julius, 2018). Additionally, both applications may attract beneficial predators such as beetles and spiders, which limit aphid-borne diseases. Plastic mulch films are also effective in reducing weeds, bacteria, fungi and viruses through soil solarisation and can be used in conjunction with other soil sterilisation techniques. However, the new microclimatic conditions under these plastic applications may exacerbate the incidence of diseases such as powdery mildew, caused by the fungi *Podospaera xanthii* (British Summer Fruits, 2017). Generally, using plastic reduces the reliance on pesticides and herbicides and allows the use of integrated pest management (IPM), reducing the cost of pest and disease control per unit of crop production (Chang et al., 2013; Qi et al., 2020). Although the use of plastic mulch films and fleeces may reduce the reliance on fungicides compared with organic mulches, plastic mulch films and fleeces may create a favourable environment for fungal development (*Botrytis cinerea)* compared with uncovered cropping systems (DEFRA, 2011; Meyer et al., 2021).

Plastic structures, particularly greenhouses, polytunnels and nets provide protection from adverse weather conditions such as heavy rainfall or hail, high winds, extreme heat and exposure to intense sunlight—all of which may damage a crop (Orzolek, 2017). Cost/benefit ratios will determine the choice of protective covering (Ahamed et al., 2019). In Northern Europe, both glass greenhouses and polytunnels are used for extended production of a range of higher value crops throughout the year. The increased availability of these high-value, high-quality crops may give consumers an incentive to consume more healthy food. Greenhouses in Mediterranean countries are mainly plastic-covered (Chang et al., 2013; Orzolek, 2017). Even in northern Europe, plasticulture continues to be popular and between 1980 and 2015, the consumption of agriplastics in Germany rose from 136,000 tonnes to 635,000 tonnes (Brandes et al., 2021). Each covering material has pros and cons related to the cost and longevity of the structure, whether the material is compatible with particular growing and climate-control systems, the effect of the material upon the plant microclimate, the external climate and any maintenance costs. Direct natural light may scorch the uppermost leaves of the crop and cast a shadow on adjacent crops within a glass greenhouse and some expenditure on shading is therefore required. Due to the radiative properties of plastic films, incoming light is scattered to reduce the risk of scorching and increase the proportion of the canopy receiving light, due to better light distribution (Espi et al., 2006). Additives such as Lumisol may be used to positively manipulate the radiative properties of the plastic film. Lumisol minimises the condensation of water on the plastic film, which maximises light transmission and reduces the risk of fungal diseases such as *Botrytis cinerea*. The low cost of plastic has resulted in plastic greenhouses becoming a cost-effective but highly-productive method of growing in many parts of the world (Orzolek, 2017).

The recoverability, reusability and recyclability of plastics within greenhouses are better than open-field systems that use mulches, fleece and nets, as degradation rates are lower, reducing plastic pollution and the loading of microplastics into agricultural soils (Hablot et al., 2014). Degradation rates in open-field systems are higher due to greater exposure to sunlight, extreme weather and physical fragmentation from fauna. Glass greenhouses support many sophisticated growing techniques such as vertical farming, but variations of this development are also used in polytunnels often employing soil-less substrates as a rooting medium. Soil-less growing presents little threat to soil degradation and a reduction in soil quality via plastic pollution, loss of organic carbon, compaction or erosion (Manos & Xydis, 2019; Sambo et al., 2019), issues that already cost £1.2 billion a year in England and Wales (Environment Agency, 2019). However, whether glass or plastic is used to create the greenhouse, both growing methods are plastic-intensive so should be considered as a form of plasticulture.

2.5 The positive impacts of the increasing use of plasticulture in UK horticultural production

While the success of UK agriculture and horticulture in recent years is not entirely due to research, development and deployment of agriplastics, some crop production systems have been revolutionised by different applications of plastic. In the UK, the average yield of raspberries increased between 1996 and 2015 from 5 t ha^{-1} to 9.6 t ha^{-1} (see Figure 2.3), coinciding with an increase in the area of raspberries grown under polytunnels from 25 hectares to 1304 hectares (British Summer Fruits, 2017; Garthwaite et al., 2017). Hanson et al., (2011) have reported that raspberries grown under polytunnels are 12 % less likely to develop a fungal disease (*Botrytis cinerea*) than crops grown in the open field. Typical diseases such as spur light (*Didymella applanate*) and cane anthracnose (*Elsinoe veneta*), were significantly reduced under polytunnels (Demchak, 2009). Plasticulture provides near-year-round supply and better-quality of raspberries, whilst reducing wastage due to a decrease in spoilage and low-grade fruit. This is evident as UK-produced raspberries marketed for the year increased by 9900 tonnes between 2002 and 2015 (British Summer Fruits, 2017).

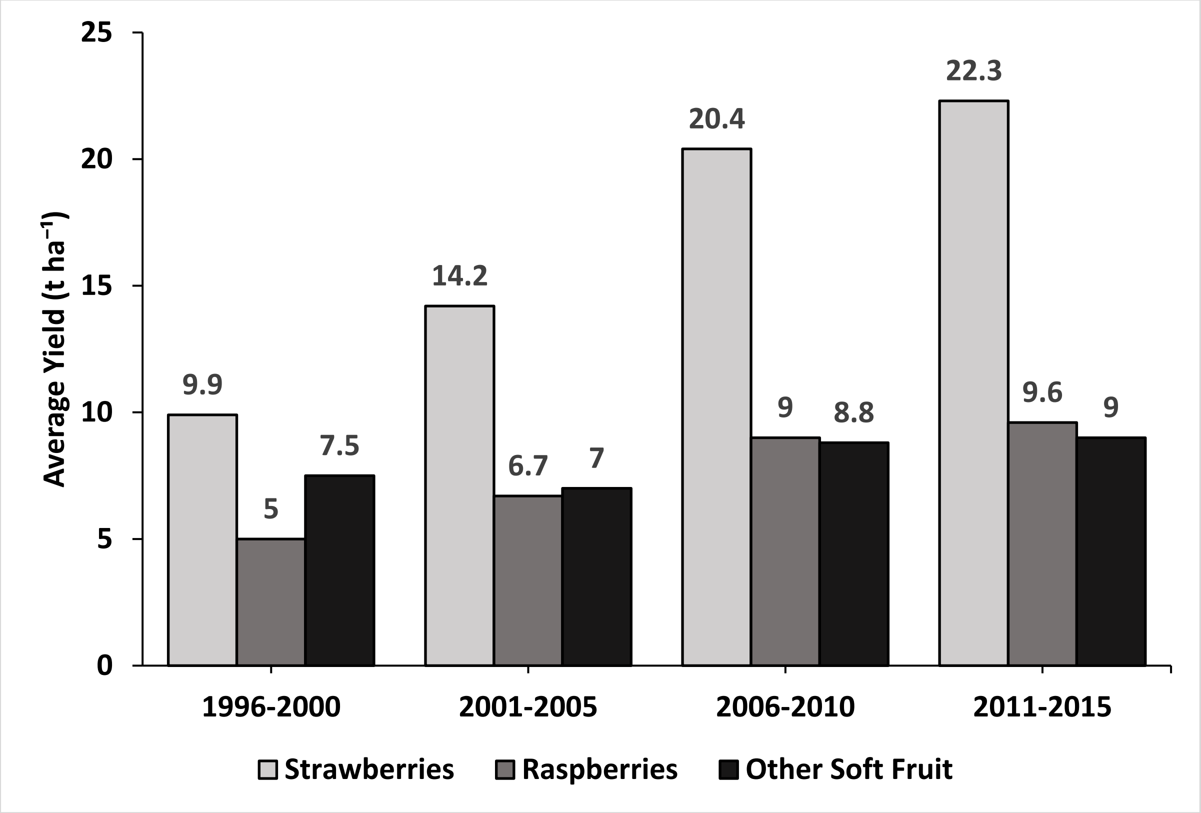


Figure 2.3. A graph illustrating the average yield (t ha^{-1}) of strawberries, raspberries and other soft fruit in the UK between 1996-2015, in 5-year periods. Data collected from British Summer Fruits (2017).

The strawberry is one of the most economically important fruit crops worldwide (García-Tejero et al., 2018; Lewers et al., 2017). Approximately 3900 hectares of strawberries in the UK are either grown under polytunnels, mulches or fleece, which resulted in an increase in the average yield of 9.9 t ha^{-1} to 22.3 t ha^{-1} from 1996 to 2015 (British Summer Fruits, 2017; DEFRA, 2011). Plastic coverings in the soft fruit industry are rarely used in isolation, more often in conjunction with other plastic applications. For example, strawberries may be grown in a soil-less substrate on a raised platform (allowing easier harvesting) under a polytunnel with a fleece wrapping during the coldest months. These new growing techniques have provided effective protection against fungal diseases, particularly *Botrytis cinerea* (Evans, 2013; Lewers et al., 2017). This once-prevalent disease limited the yield of strawberries and other soft fruits to around 50 % Class 1 yield, due to a significant reduction in shelf life and the presence of rot, which has since increased to 90 % following the use of plastic applications (British Summer Fruits, 2017; Evans, 2013). As more produce meets the criteria of supermarkets and groceries, food waste on the farm is greatly reduced. The benefits provided by plastic covers have resulted in the strawberry crop becoming one of the most economically important crops within the UK. Domestic production of strawberries was valued at £429 million in 2020, an increase in 165 % since 2016 (DEFRA, 2021). Although berries do not currently represent a significant portion of the typical UK diet, the increased production of these crops may positively impact consumer health, food availability and wider food security issues. Increasing the production of off-season produce could fill an otherwise seasonal void in the consumption of specific crops and may reduce the price of off-season produce. An increased availability and accessibility of healthy, high-quality products allow consumers to form consumption habits and adopt healthier diets (Kuchler & Arnade, 2016).

In another example, the use of plastic in blackcurrant cultivation is limited, but important nonetheless. The soil beneath blackcurrant bushes can be covered in polyethylene mulch, with the primary aim of suppressing weeds. Mulch film intercepts a proportion of rainfall, reducing the amount of water made available to the crop, which necessitates the use of an irrigation system. Cherries are often grown under multiple plastic structures, consisting of nets and polytunnels. These covers are used on approximately 80 % of the cherry crop in the UK (DEFRA, 2011), which is a relatively recent innovation that, along with low-cost storage techniques, has transformed the industry. These applications provide protection from intense precipitation events and prolonged periods of solar irradiation, which may cause fruit splitting, which has historically been a major problem for the UK industry (Mika et al., 2019).

Plastic mulches, fleeces and nets are also used in the UK for the cultivation of vegetable brassicas, leafy vegetables, fruiting vegetables and root crops. There is a lack of available data about the measurable effect of plastic mulches, fleeces and nets on crop yield and other parameters in the UK. One study in 1988 noted a 14.7 % difference in carrot yield under plastic mulches compared with uncovered crops (Peacock, 1991). The potential advantages of using plastic applications in UK horticulture are, however, widely recognised. Plastic mesh and nets are extensively used for swede and turnip cultivation. These applications are laid in the early spring, pre- or post-sowing or planting to increase the soil temperature and provide protection against frost. This is temporarily removed and re-laid periodically to monitor the crop and apply field amendments. Once the crop is established, the films are removed. Due to a ban on some pesticides that control cabbage fruit fly (*Delia radicum*), the use of nets on brassica and root crops has increased to prevent fly damage. Approximately 95 % of turnips and swedes grown in the UK are covered by nets for pest protection (DEFRA, 2011). Although plastic nets generally reduce disease, poor air circulation under the nets increases the risk of *Alternaria* (Saharan et al., 2019). Within the UK, plastic covers in potato production are primarily used to induce soil warming with the aim of producing earlier and higher yields. Plastic use in UK potato production has reduced due to developments in storage facilities and pressure from cheaper international imports, but plastics may be used more in the future to conserve soil moisture to control potato scab (*Streptomyces scabies*) and improve water-use efficiency following stricter water-use regulations and developing climate change (Biesbroek et al., 2010; Daccache et al., 2015).

2.6 Problems with plasticulture

While the UK horticultural industry has been extremely successful in recent years, the environmental cost of plastic production and plastic pollution is regarded as a generational challenge that faces the earth system complex and any evolving crop production system should not further complicate this problem. The effects of plastic pollution are global and the distribution of plastic waste is ubiquitous (Guo et al., 2020; Scheurer & Bigalke, 2018; Yates et al., 2021). Plastic pollution is a complex issue occurring on a scale of nanometres to metres. Most plastic is persistent and durable. Environmental effects range from physical blockages in rivers to cytotoxicological effects like inhibited spermatogenesis in earthworms (Kwak & An, 2021). In an important recent paper, Persson et al., (2022) reviewed the scientific literature relevant to quantifying the planetary boundary for novel entities and they highlight plastic pollution as a particular aspect of high concern. An impact pathway from the production of novel entities to impacts on Earth system processes is presented. This can be a key development in the assessment of plastic pollution loads and effects. The planetary boundaries approach has been used to great effect as we have sought to quantify the global impacts of the way that we lead our lives (Rockström et al., 2009).

Most plastics are derived from fossil-fuel feedstocks and therefore synthesis, use and disposal can have a big effect on global GHG emissions. Assuming that agricultural plastics comprise 2 – 3.5 % of annual global plastic production, the ‘cradle-to-resin’ emissions of production total 17 – 30 million tonnes of carbon dioxide equivalent (Mt CO_2 eq), predicted to increase to 27 – 47 Mt CO_2 eq by the end of 2030 (FAO et al., FAO, 2021; Hamilton et al., 2019). Emissions from European agriplastic production total 1.5 – 2.1 Mt CO_2 eq based on current estimates. ‘Cradle-to-resin’ estimates omit GHG emissions from the conversion stage; processing polymers into final products, and the end-of-life stage; the treatment and disposal of plastic waste, which is thought to contribute an additional 14 – 24 Mt CO_2 eq to current estimates

(Zheng & Suh, 2019). In comparison to the 8.26 Gt CO_2 eq emitted from global transportation, 'cradle-to-grave' GHG emissions from plastic production are minor (WRI, CAIT, 2021). Nevertheless, all of this undermines the efforts by the food industry to address the Climate Emergency declared in the UK, the Paris agreement and subsequent Conference of the Parties (COP), which aims to limit global warming to 1.5 °C (United Nations/Framework Convention on Climate Change, 2015). Although research is in its infancy, the degradation of plastics in the environment may increase GHG emissions (Shen et al., 2020), with the scope to affect biogeochemical cycles in the soils, and consequently the GHG flux and global warming potential (GWP) (Ren et al., 2020). Once agriplastics reach their end of life, they are often left on the ground, ploughed into the soil, burned or disposed of in landfill. Between 16 and 50 % of agricultural plastic waste (APW) is not managed (FAO, 2021). The estimate is region-specific, difficult to quantify and is considered an underestimate as many farmers store unknown quantities of APW on the farm (Blanco et al., 2018). The impact of mismanaged APW on climate change is relatively unknown.

The management of much APW continues to be inappropriate (Briassoulis et al., 2013). Recycling polytunnel and greenhouse films is more achievable due to low levels of contamination. Plastic mulch films, fleeces and nets removed from fields are often contaminated with soil, pesticides and fertiliser throughout their application, so are often rejected by recycling facilities (Aznar-Sánchez et al., 2020). If recycling facilities accept the contaminated film, growers are charged per unit of weight, which is costly and inefficient (APE, 2019). Following the implementation of the 'National Sword' policy, APW exports from the EU were banned from entering China for recycling, resulting in a larger proportion of APW being diverted to landfill (APE, 2019). Due to the high cost of sending APW to landfill, the traditional method of disposal has been to burn films on the farm (Sintim & Flury, 2017). Each of these approaches raises environmental concerns. Burning APW poses a threat to air quality and consequently public health, whilst APW disposed of in landfill can result in the leaching of a range of chemicals into the broader terrestrial environment and also contaminate the marine environment (Brodhagen et al., 2017).

In the absence of a regulated APW management system, farmers are left with limited choices for disposal. As a result, many growers store APW in temporary farming areas, with little knowledge of what to do with the material (Blanco et al., 2018). However, the growth of national collection schemes (NCS) and commercial operations dedicated to extending producer-responsibility of agriplastics in Europe is promising. APE UK, a NCS founded in 2020, expects to collect 22,500 tonnes of APW by 2022, a significant improvement from 2800 tonnes in 2021. Although there are challenges with recycling infrastructure and the low value of recycled plastic, the future of APW management appears promising.

Although recycling and reuse of agriplastics are practiced, it is difficult to recover plastic from applications where it begins to degrade shortly after use, this is particularly the case for plastic mulch films net and fleeces. The thickness of mulch films influences the recovery rate. Thicker films inherently use more plastic per unit area but have high rates of recovery. Thinner films are more likely to have low rates of retrievability due to lower structural integrity (Liu et al., 2014). Combined with the accelerated disintegration from extreme weather events and physical damage from fauna, some films are extremely difficult to recover (Hablot et al., 2014). Therefore, many plastic films are often left in the field to disintegrate further, regardless of whether this act of disposal is intentional or unintentional (Moreno et al., 2014).

The primary receptor of agriplastic pollution is agricultural soil. The effect of agriplastic pollution here is compounded by other agricultural inputs such as slurry, biosolids, municipal waste, plastic-coated fertiliser, agricultural machinery, atmospheric and fluvial deposition. It is unsurprising therefore that agricultural soils are likely to contain among the highest concentrations of microplastics worldwide (Nizzetto et al., 2016). These soils are also the most understudied. In addition, there is no unified procedure for the processes of extraction, impurity removal and identification of microplastics or nanoplastics, which makes quantifying and identifying point sources of plastic pollution in agricultural soils difficult (Qi et al., 2020).

Studies of plastic pollution in agricultural soils across the world vary with most focussing on microplastic contamination. In extreme cases where mulch film was buried or ground into the soil for over ten years, residual levels have varied between 50 and 260 kg ha^{-1} and have exceeded 380 kg ha^{-1} in other studies (Changrong et al., 2014; Liu et al., 2014; Qi et al., 2020). 63,000–430,000 tonnes of microplastics a year are thought to be applied to European farmlands through biosolids and fertiliser application (Nizzetto et al., 2016). Microplastic contamination in biosolids is thought to range between 10^3 and 10^4 particles kg^{-1} (Kumar et al., 2020; Qi et al., 2020). Due to low rates of plastic degradation in soil, the consistent application of plastic agricultural films and field amendments are thought to compound the concentration of microplastics in agricultural soils. Currently, there is no published systematic research that identifies the microplastic concentrations of agricultural soils in the UK. The effects of plastic pollution on the terrestrial environment, particularly agricultural soils are also understudied (see Table 2.1) (Qi et al., 2020; Zhang et al., 2020).

Table 2.1. A review of the existing global studies that have determined microplastic concentrations in agricultural soils across the world. Data collected from Büks and Kaupenjohann (2020).

Region	Number of studies	Median microplastic concentration (particles kg^{-1})	Range of microplastic concentration (particles kg^{-1})
East Asia	9	1112.5	0 - 690000
Europe	3	2830	0 - 528000
Middle East	1	333.5	0 - 10200
The Americas	4	1200	0 - 10200

During the production of plastics, various additives and plasticizers are included to tailor the polymer to a specific application. Phthalates, for example, are plasticizers that are used to increase the plasticity of polymers used in agriculture. Shortly after exposure, these chemicals may be released into the environment as they are loosely incorporated into the polymer (Steinmetz et al., 2016). Examples include diethylhexyl phthalate (DEHP), polychlorinated biphenyl (PCB) and decabromodiphenyl ether (DBDE), most of which are endocrine disruptors and may impair human health in high concentrations (Harrison & Hester, 2018; de Souza Machado et al., 2018). Once plastics decay into the smaller microplastic and nanoplastic particles, the broken carbon backbone of the polymer may be introduced to new chemical groups (Gewert et al., 2015). Toxicants may readily sorb to these particles, resulting in a host of toxicological effects (Velzeboer et al., 2014).

It is very difficult to quantify the impact of microplastics, nanoplastics and phthalates from agriplastics on human health, due to the difficulty in point-source tracing and numerous background pathways of contamination. Humans are exposed to plastic pollution through common pathways of ingestion, inhalation and cutaneous contact. Food, amongst other things we ingest, may be a source of contamination. In Catania, counts of plastic particles <10 um found in fresh fruit and vegetables ranged from 87,600–124,900 g^{-1} of produce (Conti et al., 2020). It is thought that humans may ingest over 100,000 plastic particles a day, consuming the weight of a credit card in plastic a year (Koelmans et al., 2020).

Due to the size of microplastics and nanoplastics, they are highly mobile, able to pass through cell membranes within the body and accumulate in human tissue (Prata et al., 2020) and plastic particles have been found in the human placenta, gut tissue and faeces (Ragusa et al., 2021; Schwabl et al., 2019). The proposed health effects of these particles and chemicals are overwhelmingly negative: inhibition of metabolic function and homeostasis (Deng et al., 2017; Prata et al., 2020), inflammation triggering an immune response or oxidative stress (Deng et al., 2017), respiratory conditions e.g. 'flock worker's lung' (SAPEA, Science Advice for Policy by European Academies, 2019), increased severity of autoinflammatory and autoimmune conditions (Yan et al., 2021), and cytotoxicity and intracellular damage (Danopoulos et al., 2021; Prata, 2018).

In highly contaminated agricultural soils, macroplastics will inhibit nutrient and water transport within the soil (Liu et al., 2014). The presence of macroplastics changes the physical structure of the soil, limiting plant uptake of moisture and nutrients, the development of an established root network and seed germination. Broad decreases in these variables can result in a reduction in crop yield. In Xinjiang, where soil mulches are commonly used to reduce soil water loss, when macroplastic pollution exceeded 200 kg ha^{-1}, a 15 % decrease in cotton production was observed (Liu et al., 2014; Zhang et al., 2020). Most studies show a negative effect of soil microplastics on plant physiology (Boots et al., 2019; Bosker et al., 2019), but the presence of polyester fibres in soil has been shown to increase root biomass (de Souza Machado et al., 2018). This suggests that polymers may induce different responses according to shape and type (Boots et al., 2019). The mechanisms behind these effects are currently unknown. It is thought that nanoplastics may accumulate in plant tissue through sub-micrometre openings in roots and may then be translocated through vascular networks (Lin et al., 2020). Research on plastic pollution and crop health is in its infancy. Current studies often test the effects of plastic pollution at unrepresentative environmental concentrations and lack data on how the presence of microplastics affects long-term crop health, particularly nutritional characteristics.

The structure, microbiology and the physical and chemical properties of soil are thought to change under varying levels of plastic pollution. Changes in soil structure are more likely to become prevalent in the presence of macroplastics (Qi et al., 2020). Macroplastics form an impermeable physical barrier, reducing aeration that may trigger soil anoxia, which is a serious issue for all crop plants (Steinmetz et al., 2016). Significant changes in soil pH have been noted in the presence of microplastics. It is thought that microplastics may impact the cation exchange in the soil and result in both positive and negative changes in soil pH (Boots et al., 2019; Zhao et al., 2021). Changes in soil chemistry have a direct effect on soil microbiology. The activity of soil micro-organisms directly impacts soil nutrient cycling, which is important for plant growth. Microplastics may directly affect the activity of soil micro-organisms, which can influence the decomposition of soil organic matter and carbon sequestration, both positively and negatively (Xiao et al., 2021). The effects on soil micro-organisms are exclusive to the shape, type, concentration and exposure time of the microplastic and are magnified higher up the soil food web (Lin et al., 2020; Zhao et al., 2021).

Profound effects of microplastics have been observed on earthworm populations. Earthworms influence soil formation, maintenance, structure and fertility (Edwards, 2004). Earthworms and other soil biota may misidentify plastic particles as a food source. As these particles have no nutritional value or serve any function, energy allocation for growth and other metabolic processes decreases (SAPEA, Science Advice for Policy by European Academies, 2019). Depending on the severity of pollution, the ingestion of microplastics may increase the mortality rate of earthworms as a result of significantly reduced feeding (Huerta Lwanga et al., 2016). A decrease in feeding activity not only affects the earthworm itself but reduces the mixing of soil by living organisms, a key process to maintain healthy soils through effects on soil water balance and nutrient cycling (Blouin et al., 2013). Bioturbation may also exacerbate plastic pollution. Earthworms are capable of transporting microplastics through the soil profile, exposing other soil biota and increasing the residence times of these particles (Rillig et al., 2017b). Plastic particles do not readily degrade within the soil and may remain within the soil profile for decades.

The societal impact of the operation of our food system is often overlooked (Yates et al., 2021) and this is particularly the case with the use of plastics in rural locations. Conflicts have developed between nonfarming residents in rural communities and farmers. Plastic structures can be displeasing to some and visible in valued landscapes. Due to the large scale of some of these operations, the extension of the picking season can be very disturbing to those living nearby. Many have voiced complaints about the noise, traffic and dust from greenhouses and polytunnels (Evans, 2013). These negative effects should be contextualised and balanced with counter-benefits such as increased employment opportunities, the provision of foods that are important for a healthy diet (Lillywhite, 2014) and a significant limitation of chemical pollution and GHG emissions from tilling of soil, etc. Particularly intensive operations can be located on brownfield, formally industrial sites in peri-urban locations.

2.7 The way ahead

Following Brexit, many UK trade policies are changing with restrictions on some imports and relaxation of standards and tariffs on other products. Restructuring of Britain's farming and land-use policies will provide an opportunity to address some of the practices leading to high emissions of greenhouse gases from the import of food and from farming practices that have become integral to the intensive agriculture practiced in much of the British Isles (Godfray et al., 2010). All of this and the development of the global Covid pandemic and the conflict in

Ukraine have led to a renewed discussion with the public about the nature of the UK food system including a possibility for more self-sufficiency and resilience in food production for the UK market.

The EAT Lancet Commission (Willett et al., 2019) and others (Global Food Security, 2021) have emphasised the need for the adoption of a diet for both the health of the individual and the health of the planet. For many in the UK, this can involve, for example, eating reduced amounts of red meat and such a dietary shift could free up a considerable amount of grazing land in the UK for the aforementioned land-sparing strategy (with its predicted positive impact on biodiversity). A healthier diet for most people means the consumption of considerably more fruit and vegetables. These foods should be made more affordable to many. Much of the considerable area of land currently used for grazing in the UK (Benton et al., 2017) commonly have soil, which is of a quality that is unsuitable for much agronomical production. If we assume that much of existing agronomy can be sustained on what is a comparatively small proportion of the UK's agricultural estate then much additional food needs to be produced in specialised units developed on sites previously considered unsuitable for crop production (Walsh et al., 2022). It is partly for this reason that we propose here that protected cropping production systems for high-quality fruit and vegetables could allow intensive production on comparatively small areas of land. High productivity can be achieved in controlled environments, potentially involving some vertical farming with artificial rooting substrates or solution culture. Such systems can be operated with a very limited environmental impact. Our expectation is that these facilities can be used to grow increased quantities and an increased range of crops in the UK, both by extending the production season of many crops and by enhancing the productivity of a range of crops during the main UK growing season, thereby future-proofing the availability of healthy affordable food in the UK. This system can be used to encourage new local business development, the development of circular agriculture and greater economic resilience (see Figure 3.1).

While there are many benefits from protected cropping, there are many issues with the widespread use of plastics. In particular, there needs to be multi-disciplinary action to remediate the issues of agriplastic pollution and waste, both in novel and existing operations. Interventions must be holistic and take a ‘cradle to grave’ approach (Zheng & Suh, 2019). The environmental effects of agriplastics can be mitigated by following the principles of source-pathway-receptor-consequence (SPRC) and 6-R's; refuse, redesign, reduce, reuse, recycle and recover (FAO, 2021).

Our consideration of the pros and cons of plasticulture is not a consideration of whether or not to decrease plastic use. Rather we believe that plastic use currently plays many essential roles in UK food and farming. We must consider how to develop the agriplastics industry into a sustainable, circular economy (Ellen Macarthur Foundation, 2021). Strategies to reduce the global carbon footprint of plastics include increased use of bio-based feedstocks and decarbonising the plastic supply chain by using renewable energy for the production and processing of plastic waste (Zheng & Suh, 2019). APE Europe has published criteria for farmers to enable them to practice ‘plastic-neutral farming’. For plastics on the farm to have a greatly reduced effect on the environment, farmers are encouraged to work to criteria that ensure that plastic for a range of applications: is recyclable and eligible for collection, has minimal visual environmental impact and causes minimal soil contamination because of improved recoverability (to optimise waste collection). Farmers are also urged to collaborate with collection schemes (APE, 2019). Facilities of the kind proposed here can be located in less highly valued locations in peri-urban and even in urban environments close to markets, thereby reducing the impacts of transport for just-in-time delivery.

While scenario planning has highlighted some advantages of a localised food system it is clear that because we are a small, highly-populated country we cannot become completely self-sufficient in food. A change in our everyday diet may help in terms of increasing self-sufficiency, but there are many fruits and vegetables, which should be part of a healthy diet but that cannot be grown year-round in the UK, even with protected cropping. A large proportion of fresh fruit and vegetables imported into the UK is sourced from growers in southern Spain, a comparatively short supply chain (Garnett et al., 2020), but year-round fruit supply to the UK requires access to production in most parts of the world. A less diverse supply chain is not necessarily a more resilient supply chain, a vulnerability that has been recently exposed by Brexit, COVID-19 and the Ukraine conflict. If particular regions of the world experience political instability, social disorder or a natural disaster that destabilises their own national food security, protectionism may divert produce away from the UK to local populations for a prolonged length of time. Considering that the UK food system functions on a just-in-time basis, the availability of fresh produce to the consumer could diminish in only a few days in response to a quite localised event many hundreds or thousands of miles from the UK. A good example of this was the eruption of an Icelandic volcano in 2010, which limited the supply of Kenyan fruit to the UK for several weeks (Justus, 2015).

While we argue here more UK production of healthy food will enhance the resilience of our food system, diversity in sources of food for the UK will inevitably be needed in the future.

Relatively energy-efficient overseas supply chains are required for us to decrease the environmental impact of our diet. We have given examples of production in parts of the world where such supply chains exist and where high radiation levels can mean the high productivity of many crops. Trading relationships of this kind and what will be a re-invigoration of our trading relations with the EU will be key to the sustainability of our food system. Enhanced, domestic production and enhanced local production combined with smart trading relations will also combine to reduce food waste in the food chain. An increased emphasis on local food production should be used to educate consumers about healthy food and how they can act to reduce domestic food waste.

In order to develop a more secure, food system that increases the accessibility of foods and ensures the accessibility of healthy diets for increased numbers of people, some increase in domestic production seems desirable. In line with the NFU's slogan to ‘Back British Farming’ (NFU, 2015), expanding the area of protected cropping in the UK through plastic use could provide cost-effective benefits for the nation through an increase in agricultural productivity. Further health-driven dietary changes for our population could, at the same time, provide substantial amounts of land for environmental restoration. Such developments where many new production systems could be in peri-urban/urban locations, coupled with a land-use strategy to encourage biodiversity, will help our population develop a more general appreciation of land management strategies and farming and food production and an understanding of the health benefits of particular diets whilst delivering a healthier environment for all of us. A reduced requirement for transport will enhance food system sustainability. Much of the science for these proposed developments are already available to us. New controlled-environment technology coupled with the UK Government's apparent backing for the adoption of gene editing in the development of UK crops is substantial opportunities, which will allow us to address one of the UK's key challenges for the future — how to feed its population more adequately and reliably while also improving environmental and social sustainability.

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3. Can plasticulture address the UK's need to develop a more resilient food system?

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Abstract

Plasticulture is used extensively in the UK, driven by the need to produce more home-grown, fresh and nutritious food. The impacts of this practice on environmental, ecological and human health are of growing concern, leading to pressure to reduce plastic use in agriculture. To assess the positive and negative effects of plasticulture we explored the impacts of plastic use on the yield of ten globally important fresh fruit and vegetable crops which are of significance to UK agriculture by conducting a meta-analysis, comparing crop production with and without plastic crop covers. Overall, we found that the use of plastic crop covers corresponded to a 30.3% increase in crop yield, with variation between crops and geographic location. Our results show that plasticulture can contribute to the enhancement of agricultural productivity offering the potential to address existing issues with the UK food system. To produce enough available and accessible food, maintain food security and minimize the environmental impact of crop production systems however, the reliance on plasticulture must be assessed alongside other key agricultural developments and an urgent transformation in the life-cycle of agriplastics undertaken to prioritise planetary and human health.

3.1 Introduction

The vulnerabilities of the UK food system to global crises and political instability have become increasingly apparent with the effects of the COVID-19 pandemic, Brexit, the conflict in Ukraine and increased climate variability (Garnett et al., 2020). The resultant volatility in global resource markets, causing shortages in fertilizers, machinery and packaging (Garnett et al., 2020; Benton et al., 2022), combined with labour shortages, a decrease in international imports and the disruption of domestic food production has led to a rapid increase in prices for fresh produce. This is reflected in 1 in 10 adults in the UK either skipping meals or going a day without eating in January 2022 (Benton et al., 2022). It is expected that by 2035 the UK's National Health Service spending on type 2 diabetes and associated complications will surpass the entire expenditure on cancer treatment (Royal Society of Biology, 2021). Together with a decline in global public health and an increase of early deaths caused by malnutrition, this emphasises the importance of increasing the proportion of fruit and vegetables in diets globally (Benton, 2019; Global Food Security, 2021).

In the UK, to meet dietary recommendations, the population needs to consume 86 % more fruit and vegetables, which could prevent 31,000 premature deaths (SHEFS, 2023a). The additional production of fruit and vegetables this will require is juxtaposed with an urgent need to reduce the impact of the UK agricultural and food system on GHG emissions, biodiversity loss, diminishing natural capital and recreational devaluation (The Royal Society, 2023). This extends to the offshore impact of the UK food system in which a heavy reliance on imports from nearly 200 countries also has an impact on GHG emissions, resource use and pollution (Benton et al., 2017). Importantly, to meet the UK's targets for net zero and biodiversity, up to 1.4 million hectares of additional land could be needed by 2030 if agricultural production and current land use remains static (The Royal Society, 2023). This contrasts with the need for 7 – 16 % of agricultural land in the UK to be used for emissions reductions and carbon storage (Thomson et al., 2020).

Enhancing domestic production using less land and low-cost protective systems will help to buffer the effects of these externalities and has the potential to align with the dietary requirements of the UK whilst prioritising planetary health (Cusworth et al 2022). 'Plasticulture' is the term used to describe plastic use in agriculture. Plastics are typically used in, but not confined to, crop production applications such as greenhouses, polytunnels, mulch films, netting, silage films and irrigation. The use of plastics has revolutionised agriculture; productivity of production systems for fresh produce has increased, water consumption, pesticide, herbicide and fertiliser use has reduced, and the spoilage and wastage of fresh produce is minimised due to advances in transportation, protection and storage (Millet et al., 2019; Zang et al., 2020; Sintim and Flury, 2017; Steinmetz et al., 2016; Zumstein et al., 2018). An increase in plasticulture, alongside strategies to minimise the environmental impact of plastic production, use and waste management in the agricultural industry, offers the potential for developing the resilience and sustainability of the UK food system and the provision of an accessible, affordable, healthy diet, whilst freeing up land to sequester carbon and restore biodiversity (The Royal Society, 2023).

The impacts of plastic covers on crop production systems are governed largely by the structural and spectral properties of the covers. Physical protection, insulation and in some cases isolating the soil from the atmosphere, reduces evaporation and increases the temperature of the soil or growing substrate (Sintim and Flury, 2017; Steinmetz et al., 2016; Liu et al., 2014; FAO, 2021). In circumstances where agricultural production is limited by water availability and temperature, plasticulture has allowed unprecedented agricultural expansion (Liu et al., 2014; FAO, 2021). The uptake of plasticulture in the UK is largely driven by the competitive advantage of producing crops for more months of the year. The extent of plasticulture in the UK is difficult to quantify and estimates are outdated by a decade. Yet, it is the shared consensus that plastic use in UK agriculture has increased and will continue to do so (DEFRA, 2011; Steinmetz et al., 2016). The soft fruit industry in particular has increased plastic use; 52 % of all soft fruit is grown under protection to maximise crop quality, yield and ease of harvest (Ridley et al., 2020).

Despite the many benefits, in-use and end-of-life agriplastics raise numerous concerns. The lack of appropriate waste management systems, accompanied by the absence of policy, regulation and enforcement has frequently led to the inappropriate disposal of agriplastics (FAO, 2021). Due to the difficulty in collecting, recycling and reusing contaminated agriplastics and the high cost of sending waste to landfill, a significant proportion of agricultural plastic waste is thought to be amassed on farm, ploughed into the soil or burnt (Sintim and Flury, 2017; FAO, 2021). Whilst agriplastic pollution is one of the main sources of plastic residues in agricultural soil, sewage sludge, processed biosolids, municipal waste and plastic-coated fertilisers, also represent significant sources of plastic residues, particularly microplastics (Nizzetto et al., 2016; Qi et al., 2021). As a result, agricultural soils contain among the highest concentrations of microplastics worldwide (Nizzetto et al., 2016).

Degradation of plastic residues in the soil releases additives and plasticizers into the environment, which can further interact with new chemical groups, resulting in toxicological effects (Qi et al., 2021). Additionally, the microplastics and nanoplastics produced are highly mobile and have been found to pass through cell membranes and accumulate in plant, animal and human tissue (Prata, 2018; Li et al., 2020a). Most recently, microplastics have been detected in human breastmilk (Ragusa et al., 2022). The effects of these particles and chemicals upon human health are largely unknown. Within agricultural soils however, macroplastics can inhibit nutrient and water transport in the soil, limiting crop growth (Liu et al., 2014), are implicated in reducing the growth rate and increasing the mortality rate of earthworms (Huerta Lwanga et al., 2016), crucially affecting soil structure and nutrient cycling.

It has been proposed that the UK government and the fresh produce industry must immediately invest in building the long-term resilience of the UK food system and health of the population against future crises (Warwick University, 2023; Benton et al., 2022). At a time when global crises, political instability and increased climate variability are threatening food production in many parts of the world, plasticulture can be increasingly important if we are to maintain, let alone increase, the domestic production and supply of fresh produce to the UK. Nevertheless, there is a tension between the potential for plasticulture to provide more available, accessible, affordable and culturally-acceptable fresh produce and the global call from NGOs and agencies such as the FAO, WWF, UNEP and IPCC to significantly and immediately reduce plastic use and the consequences of which this for an already fragile global food system (FAO, 2021; WWF, 2019; UNEP, 2021; IPCC, 2021a).

Studies have assessed the impact of individual plastic applications, mostly plastic mulch film, at a nationwide scale (Zhang et al., 2018; Li et al., 2018; Gao et al., 2019; Ma et al., 2018), yet none exist within the UK or at a global scale. Using a meta-analysis, this paper evaluates the effects of plastic crop covers on the yield of crops important to UK agriculture using a global dataset. The study investigates how the effects of plastic crop covers on yield vary across a temporal and spatial scale, between individual crops and different types of plastic application. The results from this meta-analysis can be used to better understand the role of plastic crop covers in UK crop production, global food systems and provide context-specific information to help develop future food systems for human and planetary health.

3.2 Material and Methods

3.2.1 Data collection

We conducted a meta-analysis to examine the impact of plastics on the production of crops important to UK agriculture. A comprehensive search of literature and databases was carried out to collect published peer-reviewed articles relating to the effects of plastic applications on crop yield. The article selection followed the PRISMA protocol to ensure that all relevant studies were captured and bias was reduced where possible (See Figure 3.1). Data were collected from the electronic databases Web of Science (https://apps.webofknowledge.com/), ScienceDirect (https://www.sciencedirect.com/), Google Scholar (https://scholar.google.com/), ResearchGate (https://www.researchgate.net/) and through reference screening. Keywords were used to search the titles, abstracts and keywords of articles from electronic databases till June 2022: 'plastic use', 'plastic film', 'crop yield' and 'agricultural productivity'. Search terms were tailored to individual crops depending on the type of plastic application; mulch films, high-tunnels, polytunnels, fleece and nets, and the processes that contribute to a change in crop yield; water-use efficiency, crop quality, early production, weed suppressant, chemical cost and pest, disease and weather protection. For example, 'soil solarization' was a phrase used during the literature search for the potato crop, similarly 'high tunnels' for strawberries. On both occasions, these phrases were included to minimise the loss of studies. Any duplicates that were included under the search criteria were eliminated by the eligibility criteria presented below. These search terms were included to ensure that appropriate empirical data which fitted the predetermined eligibility criteria was collected, to answer the following research question:

For 10 globally important crops (see below) where plastic is used to aid production what is the effect of plastic use on their yield, compared to a scenario where no plastic is used?

Due to the lack of data comparing yields between uncovered and plastic covered crops in the UK, we set no boundaries to where observations were collected from globally. Location has a bearing on the effectiveness of plastic use in crop production, due to the effect of different climatic conditions and growing practices (Steinmetz et al., 2016). It is therefore important to determine both a regional and global pattern of how plastic applications affect crop yield. To maximise the number of suitable studies that satisfied the eligibility criteria, without introducing bias or confounding data, observations were collected from journal articles, books, abstracts, papers, reports and conference proceedings, where appropriate.

The purpose of the analysis was to determine whether a relationship between crop yield and the application of plastic covers exists, to determine how strongly positive or negative the effect is, and the spatial and temporal distribution of the changes. Therefore, the eligibility criteria determined that data should only be collected when: (1) studies included data on one of the following crops: broccoli, cabbage, carrot, cauliflower, lettuce, potato, raspberry, strawberry, turnip and swede; (2) the study included available data on crop yield; (3) the study location and year of study were stated; (4) studies made a direct comparison between the use of plastic applications and an uncovered or natural control. If the dataset was incomplete then the data was omitted from the analysis and data was eliminated if replicated in a previous study. Studies were included regardless of the positive or negative effect of plastic treatments on crop yield.

Some crop-specific searches yielded few results that met the eligibility criteria, which was identified in a preliminary scope of the literature. Parsnips were originally included in the analysis but were later omitted due to a lack of data. Similarly, the effect of plastic upon carrot, swede and turnip yield was rarely documented, but were included in the meta-analysis on the grounds that there were sufficient observations and drew attention to a need for further research and data transparency. Observations were manually excluded based on the recognition that outlying data was either anomalous or carried significant error.

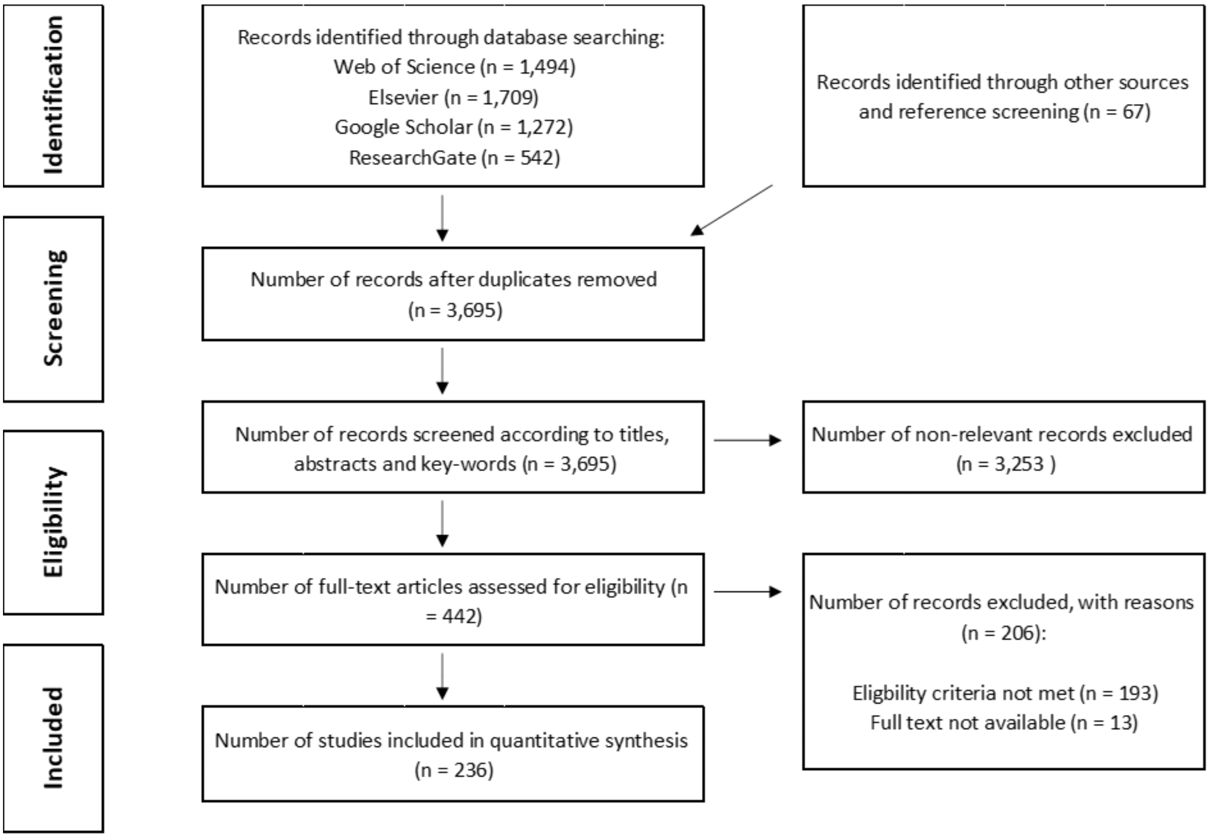


Figure 3.1. A schematic representation of the study selection process for the meta-analysis, using a PRISMA protocol.

3.2.2 Data selection and classification

The selected crops (broccoli, cabbage, carrot, cauliflower, lettuce, potato, raspberry, strawberry, turnip and swede) are important fresh produce crops in the UK. They were selected based on the largest growing area covered by plastic applications within the UK (DEFRA, 2011). Each of these crops uses different amounts and types of plastic applications to produce different desired effects, typically to increase crop quality and yield (Steinmetz et al., 2016).

Observations were collected from 37 countries and categorised by crop type, the year they were collected and the region where the observations were made. This was done to provide an insight into the strength of the relationship between crop yield and plastic use over a spatial and temporal scale.

We used results from a meta-analysis to collect observations of potato yield and plastic film mulching in China (Gao et al., 2019). The corresponding database could not be accessed to collect information about the individual studies and was therefore referenced as a single study. We adapted our search criteria to collect observations measuring potato yield within China post July-2018, working on the assumption that the aforementioned meta-analysis captured all the observations in this region prior to this date. In studies where observations were not presented in an accessible format, observations were deduced from data points used in accompanying figures (See Supplementary Figure 3.1).

3.2.3 Data analysis

Based on the eligibility criteria, 4705 paired observations from 236 studies were selected for the meta-analysis, from a possible 3,695 studies. The observations between studies were independent due to the precautions taken by the eligibility criteria. Observations within studies rarely violated independence i.e. several plastic applications were compared to the same control, where they did they were not omitted from the dataset to include as much information as possible. A random-effects meta-analysis was used to account for variance in physical environments, climatic conditions, growing techniques and socio-cultural practices within and between studies (Lajeunesse, 2011).

The natural log (InRR) of the response ratio (RR) was calculated as the effect size in this meta-analysis (Lajeunesse, 2011). The effect size represents the direction and scale of the relationship between plastic crop covers and crop yield. The effect size represents the effect of plastic use on crop yield, given by the following equations:

$$RR = \frac{\bar{X}_T}{\bar{X}_C} \tag{1}$$

$$lnRR = ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right) = ln\,\bar{X}_T - ln\,\bar{X}_C \tag{2}$$

where $\bar{X}_T$ is the mean value for crop yield where plastic applications are used, and $\bar{X}_C$ is the mean value for crop yield where no plastic applications are used. $\bar{X}_T$ and $\bar{X}_C$ were calculated for each crop and as a collective.

A random-effects model was used to calculate the mean effect sizes. Bootstrapping (4999 iterations) was used to produce bias-corrected 95 % confidence intervals (CIs) for each categorical variable; crop type, year of study, region of study and type of plastic application (See Supplementary Tables 3.1 – 3.5). When the 95 % confidence interval did not overlap zero ($P < 0.05$), we concluded that there is a significant difference in crop yield between production systems that use plastic crop covers and those without. Once the initial subgroup analysis was complete, differentiating the effect of different types of plastics used in crop production was explored within strawberry and potato production. These were the only two crops with an appropriate number of paired observations where a robust secondary subgroup analysis could be performed.

To provide a meaningful value for comparison and interpretation, changes in crop yield were given as a percentage [(RR – 1) x 100 %]; negative values indicated a decrease in crop yield when using plastic compared to no plastic, whereas a positive value indicated an increase. The frequency distribution of effect size (lnRR) was plotted to visualise the spread and variation across different studies. To test for homogeneity within the data, the effect size of individual studies was plotted against a normal distribution curve. This procedure was done for individual crops and as a collective. These procedures were performed using SPSS statistical software (IBM Statistics for Windows, Version 28.0).

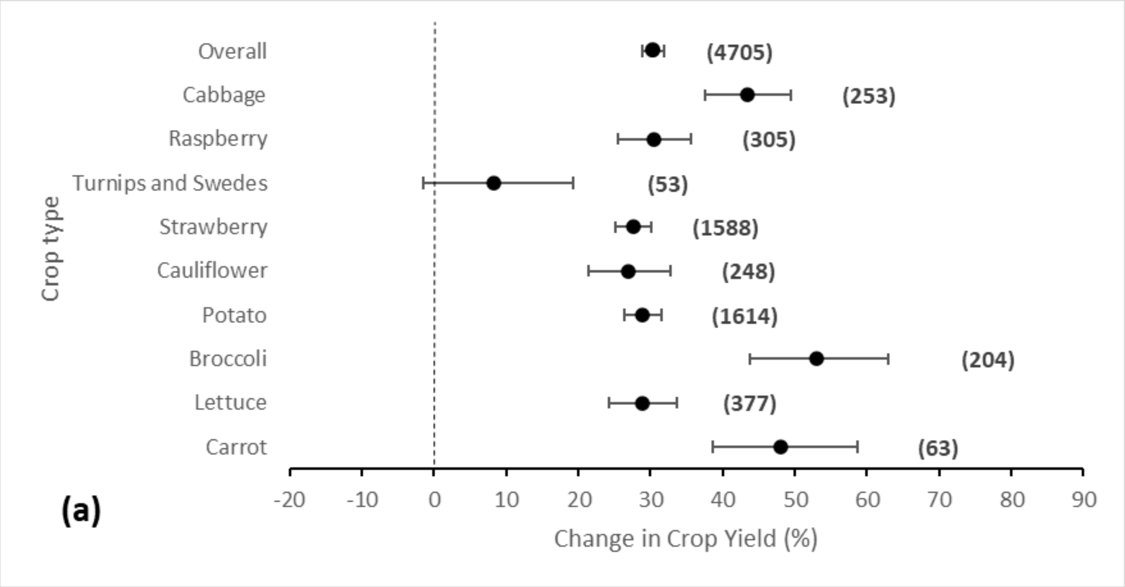
3.3 Results and Discussion

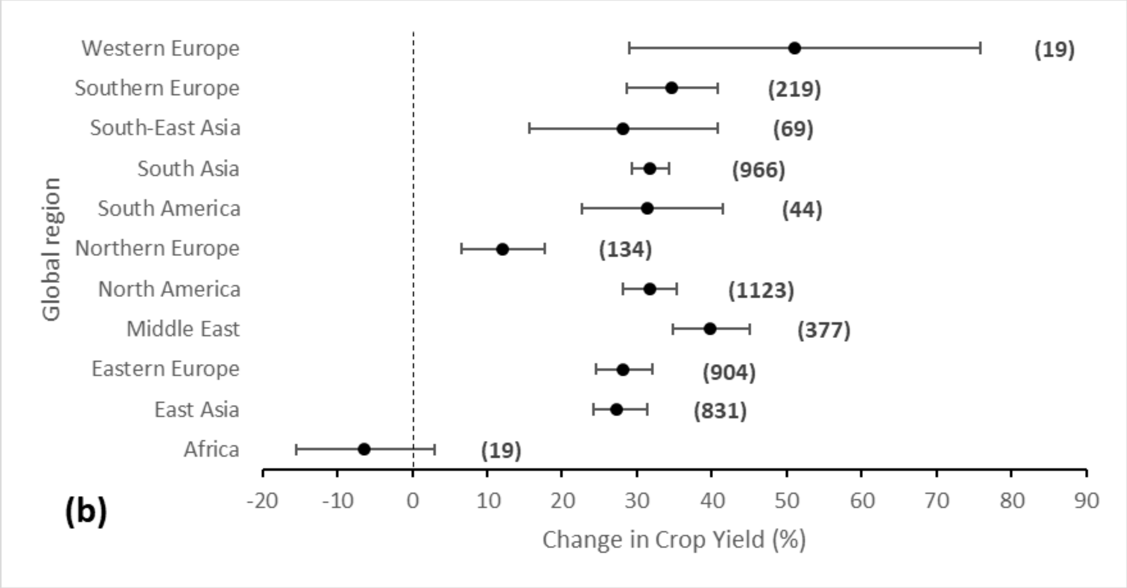
Globally, crop yields were 30.3 % (95 % CI: 28.8 %, 31.9 %) greater using plastic crop covers, compared to growing crops without (Figure 3.2a). Effect sizes were greatest amongst broccoli (53.0 %, 95 % CI: 43.8 %, 63.0 %), cabbage (43.5 %, 95 % CI: 37.6 %, 49.5 %) and carrots (48.1 %, 95 % CI: 38.6 %, 58.7 %). Effect sizes ranged between 26.9 – 30.5 % for the remaining crops, apart from turnips and swedes which had a combined effect size of 8.3 % (95 % CI: -1.5 %, 19.3 %), where the effect of plastic upon crop yield is not significant. This might be due at least in part, to the low number of observations on turnip and swede yield. For root and tuber crops, the increase in yield can be attributed to the water-saving qualities of plastic mulch film, especially for those grown in arid environments (Najafi et al., 2018), whereas soft fruit crops largely benefit from the insect, viral and weather protection that plastic applications provide, as well as improved water-use efficiency (FAO, 2021). For both crop types, the use of plastic consistently increases crop quality and yield, consuming fewer resources, requiring less land for comparable production rates and increasing profitability for farmers. Given that the least productive 20 % of farmland in the UK produces less than 3 % of calories consumed in the UK (The Royal Society, 2023), a greater reliance on plasticulture may be part of the solution to increase the production of fresh produce, whilst freeing up land for carbon sequestration and to restore biodiversity.

The use of plastic crop covers does not always equate to a corresponding increase in crop yield or more profitable production systems. 20.9 % of all observations recorded a negative or no effect on crop yield when using plastic crop covers. The potential for a plastic crop cover to improve yield is largely dependent on the temperature and water-input levels at the application location (Zhang et al., 2018; Ma et al., 2018). In a meta-analysis, potato yield in China responded best to the use of plastic film mulch when mean air temperature ranged from 15 – 20 °C (25.5 %), in comparison to < 15 °C and > 20 °C (21.2 % and 20.1 %, respectively) (Li et al., 2018). Similarly, the effect of plastic mulch film on maize and potato decreased when water input levels were higher (< 600 mm / > 600 mm and < 400 mm / > 400 mm, respectively) (Zhang et al., 2018; Li et al., 2018). Crop yields may be lower under plastic mulch film in high-temperature environments and regions where water-input is not limited, compared to non-mulched plots (Steinmetz et al., 2016; Zhang et al., 2018). The differences in the thickness and spectral properties of plastic crop covers, largely as a result of legislation and economic development in different regions, will influence yield responses for individual crops, depending on the hydrothermal regime they provide (Orzolek, 2017). To optimise the yield response and reduce the incidence of negative or negligible effects on the yield of individual crops, purposeful use of plastic crop covers, such as crop zoning, is required (Zhang et al., 2018).

Whilst reported changes in crop yield are consistent across Asia (27.3 – 31.7 %), observations made across Europe exhibit great variation (12.1 – 51.1 %) (Figure 3.2b). In Western Europe, plastic use is largely driven by the consumer demand and expectations of producing better-quality food, during most months of each year. Arid regions, such as the Middle East and parts of China are key beneficiaries of plastic crop covers. Here, applications provide protection from scorching, high winds and heavy rainfall events whilst reducing the loss of soil moisture via evaporation (Chang et al., 2013). In parallel with the development of novel irrigation techniques, plasticulture has driven an increase in agricultural productivity and reduced resource use, corresponding to improved food and eco-security in these regions. The ability to produce and sell fresh produce helps alleviate poverty in many semiarid and arid regions of China (Chang et al., 2013). In contrast, observations made in Africa have a negative effect size (-6.5 %, 95 % CI: -15.4 %, 2.9 %). However, the low number of recorded observations from this continent, and others, means that caution is needed if extrapolating this finding across such an environmentally diverse region, highlighting the need for more widespread, accessible data reporting.

Comparison of all the observations made before 1990 (21.1%, 95% CI: 14.4%, 28.8%) and those made after 2015 (34.3%, 95% CI: 31.9%, 36.7%), clearly shows the use of plastic has had an increasingly positive impact on crop yield over time (Figure 3.2c). The greater crop yield may be attributed to recent developments in polymer science, facilitating the growth of plastic intensive, high-productivity, controlled environment agriculture (CEA) and soil-less growing systems; hydroponics, aeroponics and vertical farming (Cowan et al., 2022). Soil-less growing techniques are commonly used in UK soft fruit production and offer a safer alternative to techniques where plastic is directly laid on the soil, improving the recoverability and recyclability of plastic. This reduces the risk of soil contamination, degradation and helps protect soil biodiversity, all of which are under threat from intensive agriculture (IPBES, 2019). As well as increasing crop yield, novel polymers may alter the spectral quality of incoming solar radiation to trigger morphogenetic effects, improving micronutrient content, aesthetics, taste and quality (Orzolek, 2017). Plasticulture can circumvent the negative impacts of a changing climate on crop productivity. Over the past century, an increase in crop yield has been observed on a global scale due to technological development, improvement in farming practices and plant breeding programmes (Global Food Security, 2021; Ray et al., 2013). Nevertheless, plasticulture has continued to have a significant positive effect on crop yield since the 1940's, complementary to parallel advancements in agricultural science.


Crop type
Overall (4705)
Cabbage (253)
Raspberry (305)
Turnips and Swedes (53)
Strawberry (1588)
Cauliflower (248)
Potato (1614)
Broccoli (204)
Lettuce (377)
Carrot (63)
-20 -10 0 10 20 30 40 50 60 70 80 90
Change in Crop Yield (%)
(a)


Global region
Western Europe (19)
Southern Europe (219)
South-East Asia (69)
South Asia (966)
South America (44)
Northern Europe (134)
North America (1123)
Middle East (377)
Eastern Europe (904)
East Asia (831)
Africa (19)
-20 -10 0 10 20 30 40 50 60 70 80 90
Change in Crop Yield (%)
(b)

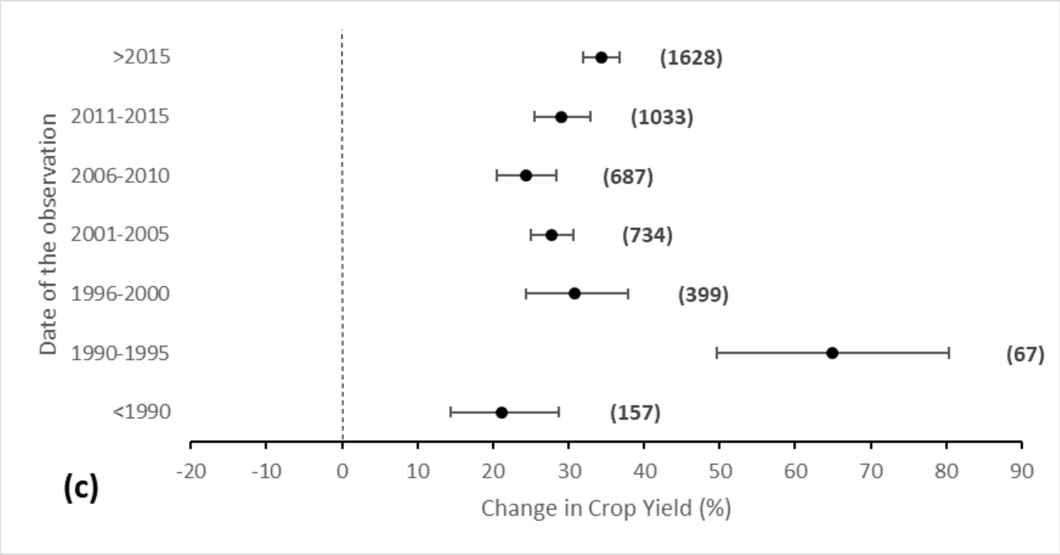
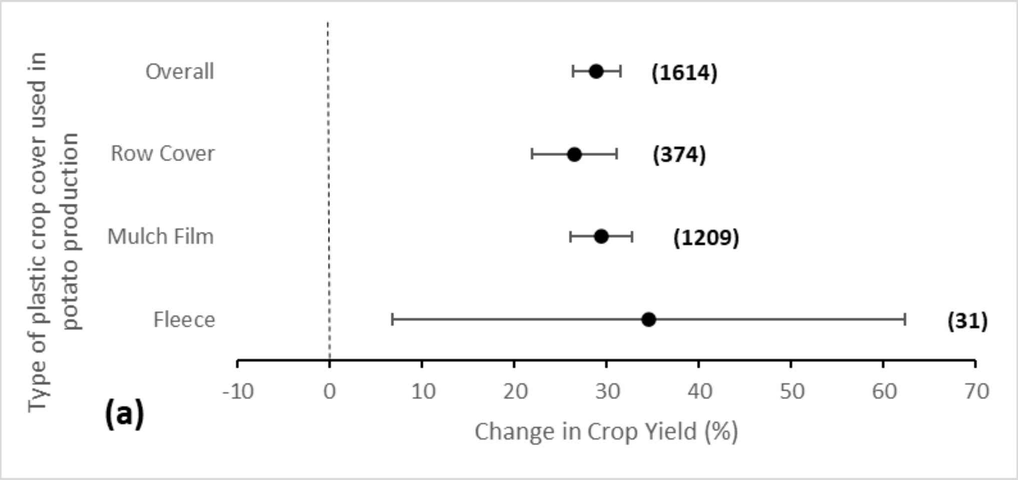

Date of the observation
>2015 (1628)
2011-2015 (1033)
2006-2010 (687)
2001-2005 (734)
1996-2000 (399)
1990-1995 (67)
<1990 (157)
-20 -10 0 10 20 30 40 50 60 70 80 90
Change in Crop Yield (%)
(c)

Figure 3.2. Increase in global crop yield under plastic crop covers by crop type, region and time. Changes in crop yield under plastic crop covers by crop type (a) region (b) and time (c). Symbols represent the estimated mean changes in crop yield for each category. Error bars represent the 95 % CI's for each category. The number of paired observations in each category is indicated in parentheses. Values below the x-axis refer to the percentage change in crop yield where plastic crop covers are used. Positive values indicate a relative increase in crop yield where plastic crop covers are used and vice versa. Where the 95 % confidence intervals intersect 0, crop yields with and without the use of plastic crop covers are not significant.

We examined the effect of different types of plastic crop covers on yields of the two crops where the number of paired observations allowed secondary subgroup analysis, potato and strawberry. All types and combinations of plastic crop cover, for each crop, corresponded to a positive impact on crop yield (Figure 3.3). Effect sizes were greatest for fleece (35.5 %, 95 % CI: 6.8 %, 62.3 %) and the combination of low and high tunnels (45.9 %, 95 % CI: 38.8 %, 53.0 %) in potato and strawberry production respectively. Whilst the use of fleece is effective at improving water-use efficiency, the risk of fungal infections is higher and may impair crop development if not treated (DEFRA, 2011). Similarities exist within strawberry production, the use of tunnels in the UK may extend the growing season of the crop, but may provide more favourable conditions for certain insects and diseases, necessitating the use of agrichemicals. Whilst changes in reported crop yield were consistent across all plastic crop covers in potato production (26.5 – 35.5 %), different types and combinations of plastic crop covers used in strawberry production displayed a large variation (6.6 – 45.9 %). The combination of plastic crop covers had greater effect sizes in comparison to conditions where one type of crop cover was used (23.7 – 45.9 %, 6.6 – 21.6 %). A combination of crop covers are often used in the UK soft fruit industry to provide effective protection against fungal infections and diseases, increase the temperature of the soil and provide protection against weather extremes (Lewers et al., 2017).

Plastic mulch film is an application used to improve the agricultural productivity of many crops. 74.9 % and 67.9 % of all plastic crop covers used in potato and strawberry production was plastic mulch film. Globally, the use of plastic mulch film is concentrated in China, covering 19.8 million hectares of arable land in 2010, resulting in a 45.5 % increase in crop yield across 51 different crop species (Liu et al., 2014; Sun et al., 2020). The expansion of plasticulture in China has been driven by an increasing demand for food by a growing population, challenging growing conditions and water scarcity. Here, plastic mulch film use is driven by the prospect of an immediate yield increase, prioritised over the long-term implications of the practise on agricultural productivity. A resource trap, where the appeal of producing more food leads to the unmeasured use of plastics, increasing the risk of soil degradation and compromising the yield benefit of using plastic, must be avoided. The use of plastic mulch is common in the UK, but since plastic residues in UK agricultural soils are largely unmapped, it is unknown how agriplastic use and waste contributes to microplastic concentrations in soil in proportion to non-agricultural sources. Given that the presence of plastic residues on soil health and function is considered net negative, the further deterioration of highly degraded soils, currently costing England and Wales £150 million a year (Graves et al., 2015), may compromise the short- and long-term domestic production of fresh produce.



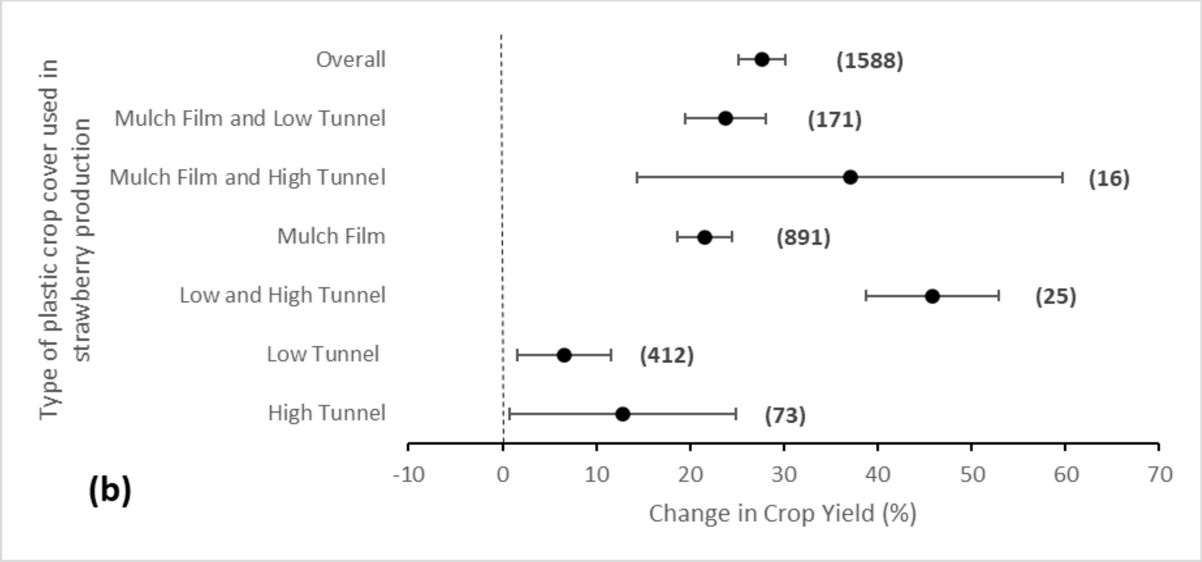


Figure 3.3 Increases in crop yield by type of plastic crop cover. Changes in the yield of (a) potato (b) strawberry under plastic crop covers. Symbols represent the estimated mean changes in crop yield for each category. Error bars represent the 95 % CI's for each category. The number of paired observations in each category is indicated in parentheses. Values below the x-axis refer to the percentage change in crop yield where different types of plastic crop covers are used. Positive values indicate a relative increase in crop yield where different types of plastic crop covers are used and vice versa. Where the 95 % confidence intervals intersect 0, crop yields with and without the use of the specific plastic crop cover are not significant.

Achieving and maintaining a resilient food system has become increasingly complex as a result of global events such as climate change, political instability, fuel shortages and COVID-19. Using the FAO's 'four dimension' approach to food security analysis (FAO et al., 2022), eliminating plastics from crop production will jeopardise the availability, access, utilisation and stability of food supply. In the UK, labour shortages alone have led to the wastage of £22 million of fresh fruit and vegetables in 2022 (NFU, 2022). Here, purposeful plastic use may extend beyond the immediate benefits of increasing crop yield and buffer impacts of labour shortages and limit post-harvest deterioration of produce. Given the increasing pressure that growers across Europe face from drought and temperature extremes, many regions may restrict the exportation of fresh produce in a bid to secure their own domestic supply negatively affecting the resilience of supply chains. Since the UK imports 47 % of vegetables and 87 % of fruit from many countries vulnerable to water scarcity and climate change, plasticulture may be an important factor in protecting UK producers from the effects of extreme weather conditions whilst extending the production season for fruit and vegetables, similarly buffering against changes in the price of and accessibility to healthy food (SHEFS, 2023a; SHEFS, 2023b). Taken together, the use of plastic crop covers, amongst other techniques, will likely help conserve natural resources, maintain yields and reduce wastage, improving food and eco-security both domestically and internationally which are essential to avoid a food system crisis. Investment in low-cost protective structures may therefore be necessary to guarantee the supply of high-quality fresh produce, resilient to any irregular supply of exports. Whilst the use of plastics presents many environmental challenges, legislation to minimise the use of plastics in agriculture may jeopardise decades of progress towards developing resilient food systems and ensuring the accessibility of healthy diets, compromising any aims to meet almost all of the UN sustainable development goals.

Understanding the key mechanisms that trigger positive yield responses from using plastic crop covers is essential to the better management of agriplastics in the UK food system. The use of plastic crop covers provide a multitude of benefits in crop production, unique to the type of plastic application. Plastic mulch films, fleece and row covers modify the soil microclimate to create favourable conditions for crop growth, reducing evaporation and increasing the temperature of the soil, or act as a method to sterilize the soil and reduce weed growth (Steinmetz et al., 2016). A combination of higher soil water availability and temperature aids seed germination and early development across multiple crops. Plastic tunnels and nets create physical protection from weather extremes, pests and frost, and offer a practical space for growers to assess, manage and pick produce once matured. The use of tunnels and mulch films has reduced the requirement for pesticide, fungicide and other chemical amendments due to sterilization and physical protection (DEFRA, 2011; Lewers et al., 2017). The motivation for using these applications is not necessarily driven by a higher yield. In China, the use of plastic mulch film is driven by the economic benefit of increased water-use efficiency, saving up to 25 % of individual farmers expenditure on irrigation (Ingman et al., 2015). Conversely, the use of plastic mulch film in the UK and other European countries is driven by the competitive advantage of producing early- and late-season yields (Cusworth et al., 2022). Under future scenarios of climate change, where the UK and other European countries are likely to experience greater periods of drought, the rationale for using plastic applications may change to prioritise resource use.

An immediate solution to reduce the impact of agriplastic pollution is to set mandatory standards of film thickness to 0.02 mm, improving the structural integrity and recoverability of the plastic crop cover (FAO, 2021). The implementation of standards should be carefully designed and well-supported, otherwise uptake of alternative materials may be unsuccessful. Under these conditions, plastic film is easier to recover, recycle and reduces plastic pollution.

However, this needs to be met with a corresponding investment into recovery and recycling equipment, facilities and networks. Progress has been made towards improving the waste management of agriplastics in the UK. APE UK, a national collection scheme, aims to increase the collection rate of agriplastics from 30 % to 70 % by 2025.

In the absence of appropriate recycling facilities, biodegradable materials offer a promising solution to plastic waste management. Biodegradable polymers and bio-based plastics, which provide comparable benefits to conventional plastics and are designed to be environmentally benign and breakdown naturally into natural compounds (FAO, 2021; UNEP, 2022; Zhang et al., 2018; UNEP, 2021; Bandopadhyay et al., 2018). Once used, biodegradable plastics are tilled into the soil and are broken down by the resident microorganisms into natural compounds. However, the complete breakdown of these applications is not always observed (Bandopadhyay et al., 2018). Whilst the bio-based components may undergo near-complete biodegradation in the presence of appropriate soil conditions, toxic additives such as plasticizers, stabilisers and lubricants do not readily degrade (Miles et al., 2017). Evidence suggests that these alternatives contribute to the existing microplastic concentrations with the soil, the effects of which are largely unexplored and uncertain (UNEP, 2021). Whilst biodegradable plastics, typically made from bio-based feedstocks such as starch, polylactic acid (PLA) and polyhydroxyalkanoates (PHA), greatly reduce the persistence and residency time of plastic residues in the environment, these materials must undergo rigorous end-of-life assessment to judge whether they do not compromise human, ecological or planetary health before widespread use.

Interestingly, the UN recommends a ’nature-positive’ approach to transforming the current food production system, involving the reintroduction of natural mulches and cover crops, which are low-cost, but raise concerns around yield reduction, variability and increased production costs (UNEP, 2022). Biodegradable plastic mulch film may align with a ‘nature-positive’ approach.

Recent evidence suggests that biodegradable films provide comparable increases in crop yield to conventional films whilst also increasing nitrogen use efficiency and mineralisation (Samphire et al., 2023). Under these conditions, fertiliser use may be reduced, an economically beneficial and nature-positive consequence of using biodegradable film.

From a UK perspective, plasticulture has been instrumental in allowing the production of a wide range of high-quality fruit and vegetables over an extended growing season and is likely to continue to form an important part of the UK production system. Without the use of plastic, the resilience, diversity and self-sufficiency of UK domestic production would be markedly reduced as would be the supply of international imports of food to the UK if restrictions on the use of plastic were imposed in other global food systems. Therefore, embracing plasticulture as a key mechanism to increase domestic production offers advantages in terms of both increased health and economic benefits. If the domestic production of fruit and vegetable increases by 50 % in 2032, the UK economy could benefit from an annual £0.5 billion increase in GDP contributions, up to £126 billion of healthcare savings and changes in land use, achieving net zero, saving £21 - £105 million and providing 131,000 permanent jobs in the industry (Warwick University, 2023). However, there are undeniable issues with plasticulture to which there is no single solution without significant trade-offs for food security. Nevertheless, with the provision of appropriate incentives, legislation, regulation and infrastructure, plasticulture may become more widely accepted in the UK. Each plastic crop cover and the importance of its use from an individual to regional scale must be individually evaluated. The UN and FAO both recognise the complexity of the issue and suggest a holistic approach to the better management of plastic use in agriculture (FAO, 2021; UNEP, 2022).

Through the use of a meta-analysis, we quantified the extent that plastic crop covers influence the yield response of ten important UK crops. We have shown that the use of plastic crop covers has significantly increased the yield of multiple crops across multiple regions and over time.

The use of plastic crop covers corresponded to a 30.3 % increase in yield across all fresh fruit and vegetable crops used in the analysis. Plasticulture is an integral part of the UK and wider global food system and has facilitated agricultural expansion and improved short-term food security, safety and nutrition in the past few decades, but at the expense of threatening long-term agricultural productivity and planetary health (FAO, 2021; UNEP, 2022). Multi-disciplinary action is needed to avoid and minimise the current and future implications of widespread plastic use (Borrelle et al., 2020; APE, 2019). Where possible, strategies should take a 'cradle to grave' approach, using the principles of the Circular Plastics Economy (Ellen Macarthur Foundation, 2021) and the 6-R's hierarchy (Refuse, Redesign, Reduce, Reuse, Recycle, Recover) (FAO, 2021) to improve the circularity of, and remediate the issues of plastic production, use and as an end-of-life material.

4. A nationwide assessment of microplastic abundance in agricultural soils: the influence of plastic crop covers within the UK

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Summary

- Agricultural soils are substantial receptors of plastic pollution, with agriplastics potentially making an important contribution to the overall microplastic load to agricultural soils. The intensive use and mismanagement of plastic crop covers, particularly plastic mulch films, nets and fleeces, represents a pollution pathway.

- In this study, we have analysed the microplastic concentrations in agricultural soils in 324 samples from 108 sites across the UK, where carrots or potatoes were grown, using a combined digestion and density separation method. Microplastics were stained with Nile Red and quantified using fluorescence microscopy.

- Microplastic concentrations ranged from 1320 – 8190 particles kg^{-1}, with a mean of 3680 ± 129 particles kg^{-1}. Where no plastic crop covers were used for potato and carrot production, a mean of 2667 ± 84 particles kg^{-1} were detected. At sites where plastic crop covers were used in the past 10 years, a mean of 4689 ± 147 particles kg^{-1} were recorded.

- There was a significant difference in microplastic abundance between sites where plastic crop covers were and were not used ($p \leq 0.001$), confirming that plastic crop covers are an important source of microplastics to agricultural soils. Further studies are

needed to investigate microplastic occurrence in the environment to better understand their impact on soil, crops and human health.

Societal Impact Statement

Agricultural soils are substantial receptors of plastic pollution. Plastic crop covers, a facet of agriplastics, may represent an important contribution to microplastic load in agricultural soils. The authors present a nationwide study of agricultural soils in the UK, comparing microplastic load between sites where plastic crop covers are and are not used for carrot and potato production. Sites where plastic crop covers were used received a higher microplastic load compared to sites where no plastic crop cover was used. The effects of microplastic pollution are largely unknown, requiring further research to determine the impact on soil, crop and human health.

4.1 Introduction

Plasticulture; the use of plastics in agriculture, is a globally important practice, originally introduced to extend the period of crop production, food availability and reduce the cost of agricultural infrastructure during the late 1940s (Le Moine and Ferry, 2019). Whilst most plastics in the agricultural sector are used for crop production; greenhouses, polytunnels, mulch films and irrigation, the use of plastic extends to the transportation, protection and storage within the industry (Cusworth et al., 2022). In modern agricultural systems the benefits that agriplastics provide within crop production systems include improved water-use efficiency, temperature control during key periods of crop development, weed suppressant, disease and pest protection, with the aim of extending the production window and improving crop yield and quality (FAO, 2021; Harrison and Hester, 2018; Orzolek, 2017; Steinmetz et al., 2016). In yield-limiting conditions, plasticulture has allowed for agricultural expansion, extension of the growing season and an increase in agricultural productivity (Le Moine and Ferry, 2019).

Globally, plasticulture is considered a relatively inexpensive means of increasing food security and developing more resilient crop production systems. In fact, global production systems have become so reliant on this material, 60 % of global vegetable and animal production may be compromised without plastic (Le Moine and Ferry, 2019).

Within the UK, the last assessment of the area covered by plastic took place in 2011 when approximately 25,900 hectares of agricultural land are covered by plastic applications (Scarascia-Mugnozza et al., 2011). The last assessment of global plastic use in agriculture suggests that the area of agricultural land covered by plastic has increased by 5.7 % a year until 2019 (Mormile et al., 2017; Steinmetz et al., 2016). The expansion of plasticulture in the UK is driven by the opportunity to produce seasonal crops for more months of the year, which provides growers with an increase in profitability at either end of the growing season (DEFRA, 2011). The use of plastic crop covers; fleeces, mulches and nets, have extended the production of brassicas, legumes, leafy, stem, root and fruiting vegetables, by raising and maintaining the temperature of the soil pre- and post-planting, extending the growing season to 11 months for certain crops (DEFRA, 2011). The early propagation and harvest of these crops creates the opportunity to cultivate multiple crops in a single growing season (DEFRA, 201; Ridley et al., 2022). An increase in the area of soft fruits covered by agriplastics; raspberries, strawberries and cherries, has coincided with a substantial increase in crop yield (DEFRA, 2011; British Berry Growers, 2017). Recently-developed polymers can manipulate the micronutrient content, aesthetics, quality and taste of a crop by changing the spectral quality of the incoming solar radiation (Orzolek, 2017; Amare and Desta, 2021). Whilst the success of these crop production systems in the UK cannot be entirely attributed to developments in polymer science and an increased uptake of agriplastics, the use of crop covers continues to be instrumental in providing protection against pests, disease and suppress weed growth. The use of plastics is deeply embedded in UK crop production systems and is likely to increase in the future following stricter resource regulations and the observed and expected impacts of climate change (Cusworth et al., 2022; Biesbroek et al., 2010). Following the Russian invasion of Ukraine and the threat to international food chains, boosting and at the least, maintaining domestic food production is critical to safeguard food security and improve food system resilience (House of Commons, 2022).

The properties and characteristics that make plastics so useful are the same characteristics that make plastic an environmental pollutant of considerable concern; persistence, durability and capability of being transported globally through a range of environmental compartments (Allen et al., 2022; Derraik, 2002). Plastics, whilst in-use and once disposed of, begin to break down via microbial, mechanical, and chemical degradation pathways (Steinmetz et al., 2016; Huang et al., 2020; Zurier and Goddard, 2021). Plastic residues; macro-, micro- and nanoplastics are, in part, released into the environment due to these degradation pathways. Whilst there is no commonly agreed definition of plastic sizes, microplastics, typically defined as particles smaller than 5 mm, but larger than 1 µm, are globally ubiquitous, having been detected in all spheres of the earth (FAO, 2021; Qi et al., 2020). During production, additives are added to polymers to tailor the properties and performance of the material to a specific application. Plasticisers are loosely incorporated into the polymer and may be released into the environment during use but raise ecotoxicological concerns as known endocrine disruptors (de Souza Machado et al., 2018). Whilst the occurrence, fate and environment impact of legacy plasticisers is understood, the impact of emerging plasticisers, which have already been detected in comparable quantities to the former, is relatively unknown (Billings et al., 2023). Current practices for the management and disposal of agriplastics in-use and as a waste product have led to the accumulation of plastic residues and plasticisers; notably microplastics, in agricultural soils (Huang et al., 2020; FAO et al., 2021; Billings et al., 2023). Whilst legislation in the UK has banned the use of microplastics in consumer products, current legislation does not capture the use of plastic in agriculture, largely plasticulture, which represents a substantial source of microplastics to agricultural soils (Mitrano and Wohlleben, 2020).

Due to the direct deposition of microplastics into soil from agriplastics, and other sources; atmospheric deposition, transport and redistribution, nearby lakes and waterways, irrigation, plastic-coated fertiliser, poultry litter, slurry, agricultural machinery and municipal waste, it is thought that agricultural soils contain the highest microplastic concentrations of any environmental compartment worldwide (Nizzeto et al., 2016; Huang et al., 2020; Sridharan et al., 2021a). Reported microplastic concentrations in agricultural soils across the world range from 0.3 – 26,630 counts kg^{-1} soil (Büks and Kaupenjohann, 2020). Many studies of microplastic concentrations in agricultural soils have been undertaken in China, where agriplastic pollution is acute (Qi et al., 2020; Liu et al., 2014; Huang et al., 2020). A study which sampled 384 sites from 19 provinces across China detected an average macroplastic concentration of 83.6 kg ha^{-1} in agricultural soils (Huang et al., 2020). Where macroplastic pollution is acute, residual plastic may compromise soil structure and inhibit nutrient and water availability (Liu et al., 2014). Decreases in crop yields of 11 – 24 % have been observed when the level of plastic residues in soil is greater than 240 kg ha^{-1} (Gao et al., 2019). Given that plastic residues are difficult to recover once incorporated into the soil, agriplastic pollution presents a long-term risk to agricultural productivity, global food security and human and planetary health (Qi et al., 2020; UNEP, 2022; FAO et al., 2021).

Whilst many studies have sought to understand the impacts of microplastic pollution in agricultural soils, many have been conducted using unrepresentative concentrations that may not reflect the true condition of agricultural soils (Qi et al., 2020). To date, there has been little attention paid to the baseline levels of microplastic concentrations in agricultural soils and how this varies between cropping systems. Here we report the results of a national level assessment of microplastic concentrations in agricultural soils within the UK. Our results show that there is a significant difference in microplastic abundance between sites where plastic crop covers were and were not used. We highlight the importance of gaining a detailed understanding of microplastic concentrations in the environment to underpin future research into the impacts of agriplastics and microplastics on soil, crop and human health.

4.2 Material and Methods

4.2.1 Site selection and sample collection

Soil samples were collected from fields where the potato or carrot crops have been grown, where plastic crop covers have or have not been used in the past 10 years. The plastic crop covers used on both crops are typically mulch film, fleece and nets, often using drip-tape irrigation in combination with these methods. To eliminate any influence on microplastic concentrations by crop type, samples were only collected from sites where different cultivars of the potato or carrot crops were grown.

A questionnaire was circulated to growers to establish land management practices at the sample sites. Before sample collection, it was determined whether any plastic crop cover was used at the chosen sample site in the past 10 years. Historic and current use of amendments and fertilisers was also recorded since these are a known source of microplastics. The project was granted ethical approval by the Faculty of Science and Technology Research Ethics Committee, Lancaster University (project ref. FST19116).

108 sites were selected across the UK, sites were selected to give a broad geographical coverage (Figure 4.1). Soil samples were collected between September 2020 – May 2022. At each site soil samples were collected from 3 randomised points within the same field.

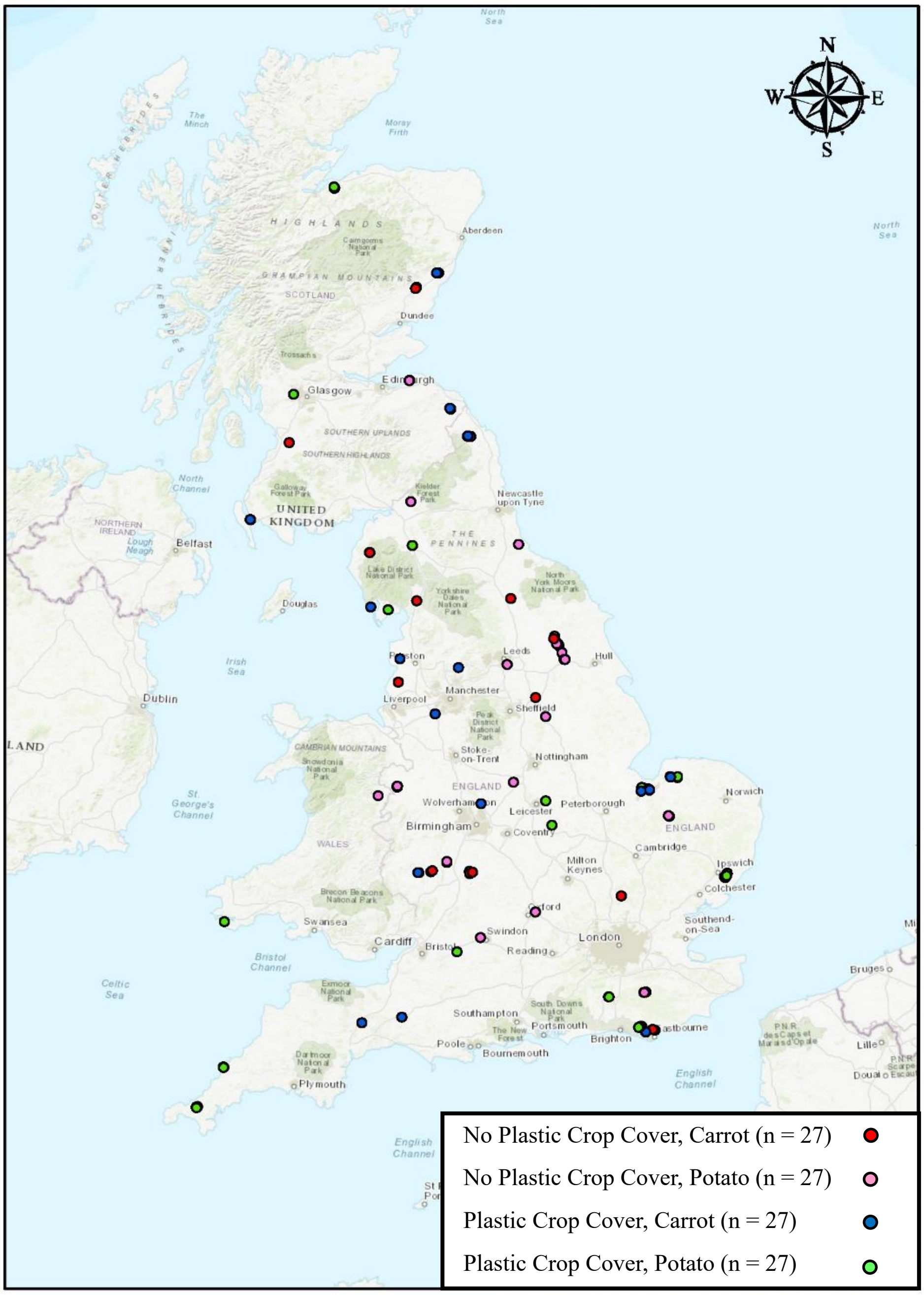

Figure 4.1. A map showing the distribution of agricultural soils sampled for microplastics across the UK in this study. Dots indicate the location of sampling sites. Red and pink dots represent sites where carrots were grown, where plastic was not and was used, respectively. Blue and green dots represent sites where potatoes were grown, where plastic was not and was used, respectively.

When collecting, transporting and analysing samples, non-synthetic clothing, such as cotton, was worn to limit contamination from synthetic fibres. Samples were collected at least 5 metres away from the field margin to limit any contamination from adjoining fields and infrastructure. Approximately 300 g of soil was taken from the top 0 – 5 cm of the soil, using non-plastic tools and transferred to aluminium trays. The aluminium trays were then sealed until sample preparation took place in the laboratory.

4.2.2 Sample preparation

The separation and extraction of microplastics from agricultural soil samples was performed using a modified version of the methods used by Shim et al (2016); Erni-Cassola et al (2017) and Maes et al (2017). Preparation and analysis of all the samples were carried out in a fume cupboard, which was cleaned frequently and where all unnecessary plastic was removed. Cotton lab coats were worn and all glassware and instruments were baked at 400 ºC for 4 h, thoroughly cleaned with acetone and carefully stored to minimise any contamination. To account for any unavoidable plastic use, three procedural blanks were run to quantify any microplastic contamination during analysis.

Samples were dried at 60 ºC for a minimum of 72 h and sieved to 1 mm into acetone-rinsed trays. The > 1 mm fraction was transferred to a separate metal tray, where any visible plastic fragments were removed and measured. Any plastic fragment < 5 mm in length was recorded. Each 100 g of the < 1 mm soil fractions was transferred to a beaker.

4.2.3 Sample treatment

Organic matter was removed from the soil samples using H_2O_2, to reduce the chance of misidentification and over-estimation of plastic contamination (Radford et al., 2021). The use of H_2O_2 has been shown to remove organic matter effectively and have a low impact on microplastic integrity (Qi et al., 2020; Radford et al., 2021; Zhu and Wang, 2020). Samples were heated to 60 ºC and effervescence closely monitored to prevent the samples from boiling over, which may further degrade existing microplastics (Zhu and Wang, 2020). An ice-bath was used to keep the temperature below 65 ºC and 5 ml of ethanol was added to reduce the surface tension of any bubbles (Rage et al., 2020). Fresh H_2O_2 was added until no natural organic material was visible or effervescence had completely subsided. The beaker was rinsed with HPLC water to re-suspend any solids that may have adhered to the beaker wall. Samples were cooled to 40 ºC and 5 ml of 0.05M $Fe(II)SO_4$ was added to the sample to decompose any residual H_2O_2 and assist in flocculating clay particles and floating lighter microplastic particles to the surface. Samples were reheated to 60 ºC and covered for 24 h.

Once the organic fraction of the sample has been removed, density separation was used to separate microplastics from the inorganic fraction of the sample. 26 % w/v NaCl solutions were added and mixed to each beaker and left to settle for 24 h. The supernatant was decanted carefully into a clean beaker and the same process repeated. The combination of H_2O_2 digestion and multiple density separations is shown to improve the recovery rate of microplastics in organic samples (Radford et al., 2021). Each fraction was filtered through a 0.45 µm glass fibre filter and beakers were rinsed with HPLC water to remove any plastic and NaOH residues. Once dried, 3 ml of a 0.5 % Nile Red solution in *n*-hexane was applied, to stain the filter paper and any microplastics on the surface. 3 ml of *n*-hexane was used to wash the filter and remove any residual Nile Red. The glass fibre filter was transferred to a microscope slide, covered with cover slips and wrapped in foil until examined under a fluorescence microscope.

4.2.4 Sample analysis

Samples were analysed using a fluorescence microscope (Leica MZFLIII Stereo Fluorescence Microscope) equipped with an integrated digital camera using GXCapture software. A 4 x 4 grid was laid over the sample and 4 randomised squares were selected for microplastic analysis. Microplastics were examined at three combinations of excitation:emission (Ex:Em) wavelength: 425:480 nm, 475:535 nm, and 510:560 nm; Nile Red-stained plastics have previously been found to fluoresce well at Ex: 450-490 nm; Em: 515-565 nm compared to red fluorescence (Ex:Em 565:630 nm), due to background staining (Erni-Cassola et al., 2017; Shim et al., 2016). Although the identification of microplastics becomes more complicated once the particle size falls below 200 μm (Shim et al., 2016), microplastics with a particle size of 20 μm can still be identified by visual inspection (Shruti et al., 2022).

Due to the presence of residual organic and inorganic material that may not have been removed by H_2O_2 digestion and density separation, which may have been co-stained by Nile-Red, it is necessary to establish strict selection criteria that relies on morphological cues and fluorescence intensity to prevent recording of any false positives (Kukkola et al., 2023; Shruti et al., 2022). A particle was identified as a microplastic if the following selection criteria were met: (1) the outline of the particle is clearly visible and has well-defined edges; (2) the particle has a 3-dimensional shape resembling a synthetic material; (3) the particle size was greater than 10 μm; (4) there is no evidence of any internal organic structures; (5) the particle clearly fluoresces in green-yellow; (6) the particle is visible and physically present in all Ex:Em combinations used (see Figure 4.2).

Given that most research suggests that any effects caused by microplastics depends on the physical presence of the particle rather than the accumulative weight, microplastic concentrations were reported as particles kg^{-1} to ensure that the research is comparable to other studies.

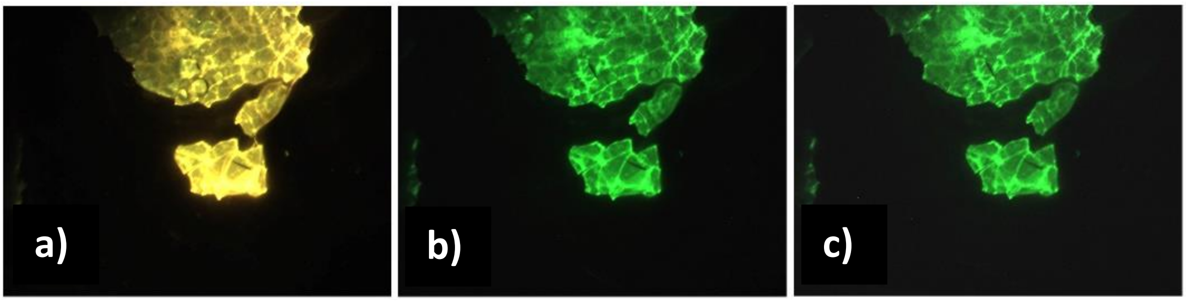

Figure 4.2. An image of microplastics found in an agricultural soil sample from a UK farm. Comparison of fluorescence from a Nile-Red stained microplastic under the fluorescence microscope using three excitation:emission filter combinations: (a) excitation 425 nm : emission 480 nm; (b) excitation 475 nm : emission 535 nm; (c) excitation 510 nm : emission 560 nm.

4.2.5 Statistical analysis and quality control

To account for any microplastic contamination during sample treatment and analysis, a triplicate of procedural blanks was performed. Blanks were found to contain 43.3 ± 2 particles kg^{-1}. Contamination accounted for ~ 1 – 2 % of the microplastic concentrations recorded from each sample. To test the robustness of the method, recovery tests were conducted using a homogenised soil sample from an undisturbed upland environment. Low-density polyethylene (LDPE) particles were procured and used to spike each sample with microplastics at 0.5 g intervals between 0.5 – 2.5g. Accordingly, recovery rates were 94.1 % ± 2.0, in comparison to other studies, which commonly report recovery rates of 90 % (van den Berg et al., 2020).

Counting 25 % of the sample and scaling up microplastic concentrations was considered valid. Analysing a subsample produced a discrepancy of ± 8 particles per sample when compared to samples that were wholly analysed.

Two-way ANOVA tests were used to determine the presence of any significant differences between groups. Data are expressed as mean ± standard error throughout. All statistical analyses were performed in SPSS (IBM Statistics for Windows, Version 28.0), using a significance level of 0.05.

4.2.6 Methodological development

Due to the complexity of agricultural systems, the comparative analysis of microplastic concentrations in agricultural environments have been difficult without a standardised, widely accepted protocol. Globally there are currently no standardised methods, procedures and appropriate quality assurance to detect and quantify microplastics in terrestrial environments which hinders the determination of risk in soils (Radford et al., 2021; Qi et al., 2020). To aid comparison between studies, the sampling approach and analytical methodology should be standardised. Given a range of budgets, equipment and time available to researchers and economies, we present an accessible, time and cost-effective method with robust selection criteria to extract, identify and quantify microplastics in complex environmental matrices such as agricultural soils. Other methods of microplastic extraction and identification exist, yet these are often more costly, less-efficient, lack high-throughput sample processing and require considerable technical expertise to perform correctly (Corradini et al., 2019; Radford et al., 2021).

The combination of multiple H_2O_2 digests and density separation steps, as used here, can reduce the limitations associated with each of these independent extraction methods and improve the recovery rate of microplastics (Radford et al., 2021).Without the use of a robust selection criteria, the visual inspection and identification of microplastics is reliant on the subjectivity of the researcher, which limits the comparability of results (Hengstmann and Fischer, 2019; van den Berg et al., 2020; Corradini et al., 2019). This reinforces the need for standardised selection criteria, as provided here, for use in future research (Shruti et al., 2022). Further method development is needed to improve comparability of results, monitor microplastic concentrations in agricultural systems and better understanding the mechanisms of their transport, persistence, degradation and environmental toxicity. Accurate, representative data is crucial to assess the impact of microplastic pollution on long-term agricultural productivity, human health and ecosystem functioning.

4.3. Results

4.3.1 Abundance of microplastics in soil

Microplastics were detected in all samples, with contamination ranging from 1320 – 8190 particles kg^{-1}. Across 108 sites and all conditions, the mean microplastic concentrations recorded in agricultural soils was 3680 ± 129 particles kg^{-1}. 2667 ± 84 particles kg^{-1} were detected in agricultural soils where no plastic crop covers were used ($n = 54$), compared to 4689 ± 147 particles kg^{-1} from sites where plastic crop covers were used ($n = 54$) (See Figure 4.3). A significant difference was found between agricultural soils where no plastic crop covers have been used, compared to sites where plastic crop covers have been used ($p \leq 0.001$). Microplastic concentrations were 175.8 % greater in agricultural soils where plastic crop covers were used.

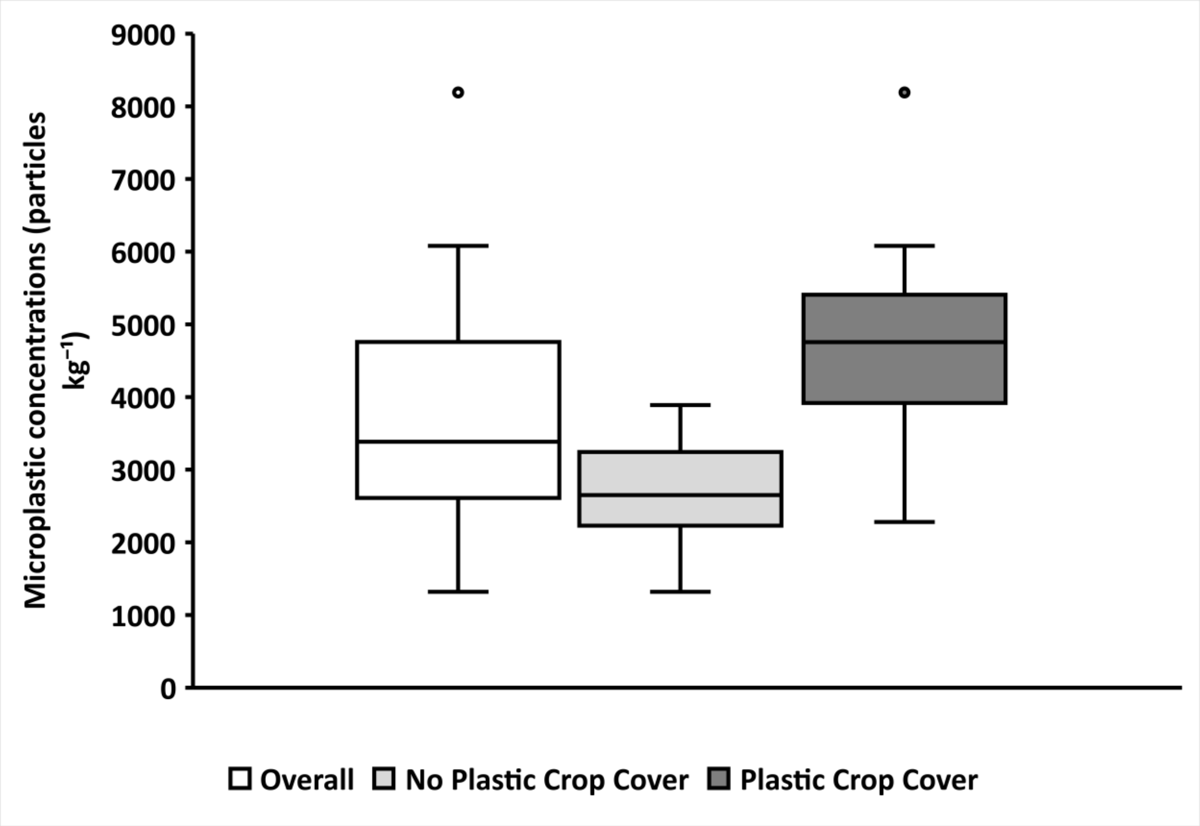

Figure 4.3. The effect of plastic crop covers on microplastic concentrations in agricultural soils from the UK. Microplastic concentrations reported as particles kg^{-1} of dried soil from all sample sites (n = 324), sites where no plastic crop covers were used (n = 162) and sites where plastic crop covers were used (n = 162). The box plot displays the values for the maximum, third quartile, median, first quartile and the minimum. Maximum and minimum values are marked by individual points or whiskers.

Where carrots were grown, 2610 ± 104 particles kg^{-1} were detected in soils where no plastic crop cover was used in comparison to soils where plastic crop covers were used for carrot cultivation, amounting to 4770 ± 212 particles kg^{-1} (n = 27, respectively). Similarly, 2720 ± 133 particles kg^{-1} were counted in soils where potatoes were cultivated without the use of plastic crop covers in contrast to 4610 ± 206 particles kg^{-1} detected where plastic crop covers were used (n = 27, respectively) (See Figure 4.4). A significant difference in microplastic concentrations was observed between soils where plastic crop covers were and were not used for carrot or potato cultivation ($p \leq 0.001$). However, no significant difference was found in microplastic concentrations between crop types when plastic crop covers were and were not used ($p = 0.517$, 0.591).

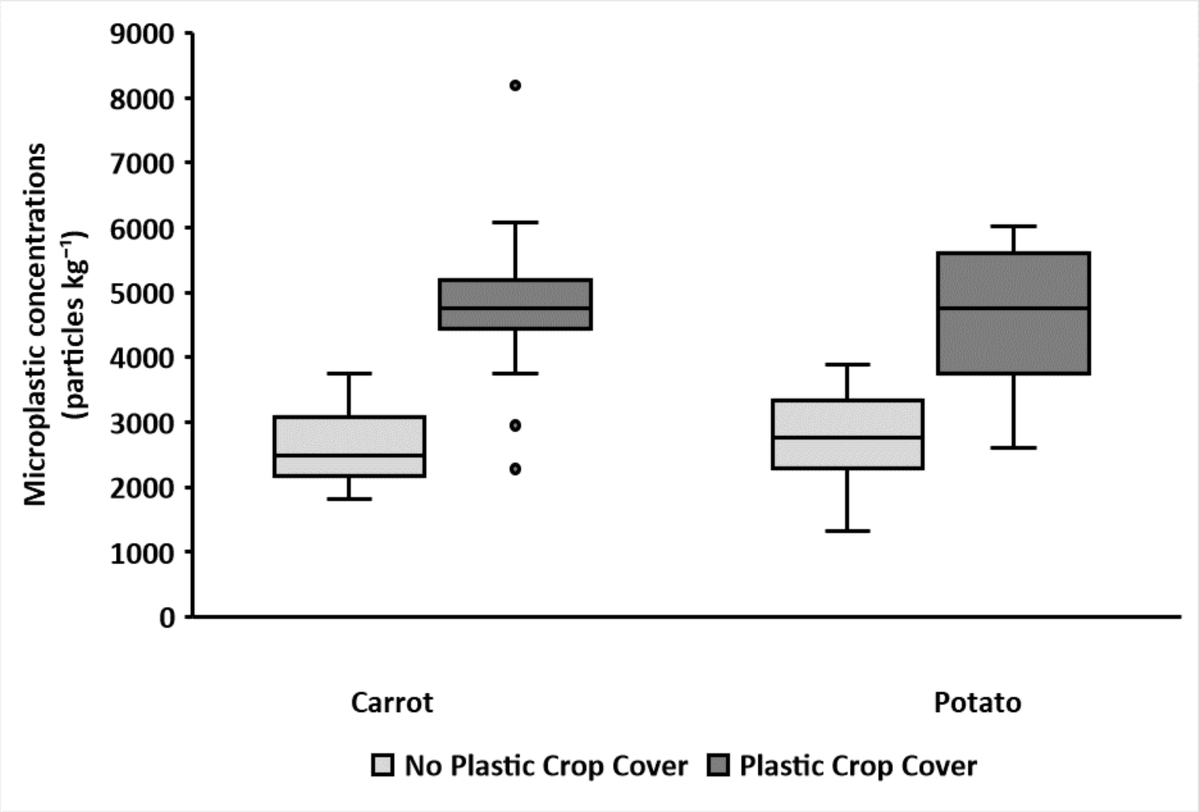

Figure 4.4. The effect of plastic crop covers and crop type on microplastic concentrations in agricultural soils from the UK. Microplastic concentrations reported as particles kg^{-1} of dried soil from all sample sites where carrots were grown, without and with the use of plastic crop covers ($n = 81$, $n = 81$) and sites where potatoes were grown without and with the use of plastic crop covers ($n = 81$, $n = 81$). The box plot displays the values for the maximum, third quartile, median, first quartile and the minimum. Maximum and minimum values are marked by individual points or whiskers.

A larger variance in microplastic concentrations was observed from sites where plastic crop covers were used, compared to sites that did not use any plastic crop covers (*SD* = 108.1, 61.8).

Although it was expected that microplastic concentrations are greater where plastic crop covers are used, microplastic concentrations from sites where no plastic crop covers were used were substantial (2610 ± 104 particles kg^{-1}). Microplastic concentrations recorded from sites where no plastic crop covers were used were comparable to some sites that used plastic crop covers. The statistical analysis of all the conditions is summarised in Table 4.1.

Table 4.1. A summary table of the statistical analysis showing the effects of plastic crop covers on microplastic concentrations found in agricultural soils.

	Microplastic concentrations (particles kg^{-1})			
	No Plastic Crop Cover		**Plastic Crop Cover**	
	Carrot	**Potato**	**Carrot**	**Potato**
Mean	2610	2720	4770	4610
Min	1810	1320	2280	2610
Max	3550	3890	8190	6030
Range	1740	2570	5910	3420
SD	54.1	69.2	110.2	107.4
SE	10.4	13.3	21.2	20.7
Count	27	27	27	27

4.4 Discussion

4.4.1 The abundance of microplastics in agricultural soils

This study demonstrates that agricultural soils are important receptors of plastic pollution. In other agricultural environments, similar microplastic concentrations have been recorded; 930 ± 740 light density particles and 1100 ± 570 high density particles kg^{-1} from sites surrounding Valencia, 2733 ± 160 particles kg^{-1} in Liangxiang Town, Northern China and 1200 – 3600 particles kg^{-1} across a range of agricultural soils in Región Metropolitana de Santiago, Chile (van den Berg et al., 2020; Zhang et al 2022b; Büks and Kaupenjohann, 2020). Taken together, these data show that microplastic concentrations in agricultural soils are amongst the highest in the terrestrial environment (Nizzeto et al., 2016). Nevertheless, microplastic concentrations are highly variable across the terrestrial environment, particularly in urban and agricultural soils, where microplastic deposition may be particularly acute, dependent upon the pollution source. 593 microplastic particles kg^{-1} were detected across 29 Swiss floodplains, 539 particles kg^{-1} in lake sediment collected from an urban lake in London, 4825.31 ± 6513 particles kg^{-1} in urban soils across Amsterdam and 870 ± 1900 particles kg^{-1} in garden soils from Mexico (Scheurur and Bigalke, 2018; Turner et al., 2019; Cohen et al., 2022; Huerta Lwanga et al., 2017). Microplastic shape distribution was recorded from a subsample of sites (n = 10). The morphology of the microplastics recorded were consistent with other studies. The shape of microplastics in soil, particularly in intensively farmed regions, has been found to be unevenly distributed. 51 % of all observed particles resemble a film, 45 % are either fragments or fibers, compared to foams and pellets, comprising less than < 10 % of all particles (Xu et al., 2022).

Variability in the sources of microplastics to agricultural soils will contribute to the range in microplastic concentrations we have observed within this study and between other observations. For example, 50,000 particles kg^{-1} have been detected in sludge applied to agricultural land in Valencia, compared to 900 particles kg^{-1} recorded in Guilin, China (van den Berg et al., 2020; Zhang et al 2022b). Likewise, chicken manure has been observed to contain 14,720 – 129,800 particles kg^{-1} (Zhang et al., 2022b), a commonly used field amendment. Contributions from non-agricultural inputs such as littering, fluvial sources and atmospheric deposition as well as indirect plastic applications such as wastewater, farmyard manure, inorganic fertiliser, compost harvesting crates and pesticide containers, amongst others, may also contribute to microplastic concentrations in agricultural systems (Zhang et al., 2022b). The amount of microplastics an agricultural system receives is also dependent on the type, amount and history of field amendments, current and historical waste management strategies and other techniques such as tilling, irrigation and grazing. The concentrations we observed are therefore consistent with agricultural soils being recipients of multiple sources of microplastic concentrations (Nizzeto et al., 2016; Huang et al., 2020; FAO et al., 2021).

4.4.2 The influence of plastic crop covers on microplastic concentrations in agricultural soils

In crop production systems where plastic crop covers were used in the past 10 years, microplastic concentrations were 175.8 % higher in agricultural soils, compared to sites where no plastic crop covers were used. Whilst these findings are supported by other studies which conclude that plastic crop covers are a significant source of microplastics to agricultural soils (FAO et al., 2021; Huang et al., 2020; Rochman, 2018; MacLeod et al., 2021; Steinmetz et al., 2016; Gao et al., 2019), most of these differences are reported from experimental plots and do not reflect the variability in nationwide practices of plasticulture.

Differences in microplastic abundance have been reported in China between sites where crop covers are used, compared to those where no plastic crop covers are used. Zhou et al., (2020) reported 571 particles kg^{-1} from sites where plastic mulch film was used, compared to 263 particles kg^{-1}, where no-mulch was used. Similar observations were made by Zhang et al., (2021), recording 376 ± 149 particles kg^{-1} at sites where plastic mulch film was used, and 754 ± 477 particles kg^{-1} at non-mulched sites. There are no comparable surveys of microplastic concentrations agricultural soils in Europe.

The range of microplastic concentrations was greater at sites where plastic crop covers were used, compared to sites without (2610 – 8190, 1320 – 3890 particles kg^{-1}, respectively). The high-variability in microplastic load to agricultural soils from plastic crop covers is dependent on the type of application, polymer structure, degradability, the time-period that plastic crop covers have been used for, continuously or intermittently, and the management of the plastic crop covers whilst in-use and as a waste product (FAO et al., 2021; Huang et al., 2020). It is difficult to discern whether the accumulation of microplastics is driven by the degradation of the plastic crop cover in-use, or once it has been used. In both cases, weather conditions and farming practices, such as tilling, may increase the fragmentation of macroplastics into microplastics within the soil (Meng et al., 2020). Agricultural soils are long-term sinks of microplastics and it is expected that the historical use of plastic crop covers contributes to current microplastic concentrations. Over time, microplastics are removed from the surface layer from runoff and vertically transported in the soil profile due to ploughing and soil biota (Sridharan et al., 2021b). Therefore, microplastics concentrations are expected to be lower at sites where plastic crop covers were last used more than 10 years ago.

The annual use of plastic crop covers combined with a slow degradation rate of plastic residues is thought to compound the concentration of microplastics in agricultural environments, much like the application of plastic-coated fertilisers, slurry and wastewater (Tian et al., 2022; van den Berg et al., 2020; Corradini et al., 2019). Plastic mulch films, fleeces and nets, a subset of plastic crop covers, are often designed to last one growing season, degrade shortly after use and become contaminated with soil, making them hard to recover and recycle. Accordingly, many plastic crop covers are burned and buried on agricultural land, a practice that used to be legal and was commonplace in the UK until the introduction of the Agricultural Waste Regulation 2006, increasing the load to agricultural soils (Kasirajan and Ngouajio, 2012). At a site where an appropriate recovery and waste management strategy combined with the use of no inorganic fertilisers, which are a notable source of microplastics (Henseler et al., 2022), 2610 particles kg^{-1} were recorded. Whereas, a site where plastic crop covers were used less frequently, but where chicken manure was used as a field amendment, microplastic concentrations were recorded at 8190 particles kg^{-1}. These are two individual sites and may not be representative so it is not clear how strongly each condition may exacerbate or mitigate the load of microplastics to agricultural soils.

Due to stricter regulations on mulch-film thickness and the provision of appropriate waste management facilities in the UK, it is expected that macroplastic and microplastic concentrations are lower in agricultural soils within the UK compared to other regions, such as China, where mulch-film thickness is largely unregulated (Büks and Kaupenjohann, 2020; Liu et al., 2014). Huang et al (2020) recorded the abundance of microplastics at sites in China where continuous mulching has taken place for 5 years as 61.9 – 102.9 particles kg^{-1}, even though macroplastic concentrations averaged 83.6 kg ha^{-1} across 394 sites. In recognition of the pollution raised by plasticulture, industry has heavily invested in the development of polymers that are made from natural or recycled sources and are biodegradable with the aim to minimise agriplastic pollution. However, when comparing two sites farmed by the same grower; one that used a conventional plastic mulch film, and the other, a biodegradable version, microplastic concentrations were comparable between sites (4880 and 4490 particles kg^{-1}, respectively). Whilst this is a single site and cannot be extrapolated this observation places uncertainty on whether many bioplastic and biodegradable films are, in fact, environmentally benign and do not contribute to microplastic loads in soil (Zhou et al., 2022; Qi et al., 2020). There is a need to isolate and individually assess how different types of plastic crop covers and management practices contribute to microplastic concentrations in agricultural soils in order to develop codes of best practice for in-use and waste management of plastic crop covers.

4.4.3 Effects of microplastics on agronomic, environmental and ecological health

Threats to agricultural productivity and long-term food security from plastic pollution are thought to be the response to acute macroplastic pollution (Zhang et al., 2020). At present, current levels of microplastic contamination, as measured in this study, do not raise parallel concerns even though negative responses of crop-soil properties; antioxidant systems, morphology and photosynthesis of crops and the reproduction, survival and weight of soil fauna, have been observed (Gao et al., 2022, Zhang et al., 2022a, Sridharan et al., 2021b). Difference in the metrics used for quantifying microplastic levels in soils (counts/pieces/particles kg^{-1}, percentage of total soil weight, mass per unit of area), together with the often unrepresentatively high concentrations of microplastics used in research, complicate comparisons between studies. As a result, to date there is no consensus on the threshold levels of microplastics which effects soil function, crop health, productivity and what the implications are for human health. Microplastic concentrations equivalent to those we observe here (1320 – 8190 particles kg^{-1}) have been reported to have limited or variable effects (Zhang et al., 2022c; Lozano et al., 2021; de Souza Machado et al., 2018). Nevertheless, microarthropod and nematode abundance has been observed to decrease concentrations of 11,361 ± 354 particles kg^{-1}, although these trends were only significant for the latter (Lin et al., 2020), whilst microplastic concentration of 1g kg^{-1} dry soil led to a 6 % reduction in crop germination, 19 % shorter shoot length alongside a 3.1 ± 1.1 % decrease in earthworm biomass (Boots et al 2019). Interestingly, the presence of high-density polyethylene led to an increase in root biomass, whereas fibres had no significant effect on root biomass or soil organic matter, suggesting that effects may be based on the shape or type of the polymer (Boots et al., 2019). Microplastic doses <0.01 % of total soil weight have been observed to have no significant effect upon cumulative CO_2 emissions from agricultural soils, microbial biomass carbon, soil dissolved organic carbon and ammonium, but significantly decreased nitrate (Zhang et al., 2022c). In contrast, at higher doses (1.0 % of total soil weight), CO_2 emissions were higher, which may be due to an increase in microbial growth, activity and an acceleration of aerobic and anaerobic metabolism (Zhang et al., 2022c). Several factors are likely to contribute to the variations in the effects observed, even when the same concentrations are used, including: (1) the experimental design of the study; (2) the shape, size and type of the polymer; (3) whether the microplastics used are virgin plastics or aged; (4) the different combinations of polymers, sorbed organic pollutants and additives used. Agricultural environments are some of the most ecologically, economically and socially important systems on Earth. Given the microplastic concentrations we have observed in this study, the probability of microplastics interacting with soil biota, food and cash crops is high. As the majority of observed effects of microplastics are negative, there is an urgent need for baseline measurements of the types and concentrations microplastics in agricultural soils, as we report here, to allow futures studies of the agronomic, ecological, and environmental and human impacts of environmental microplastics to be performed using microplastics and concentrations representative of those observed in the field.

4.5 Conclusion

This is the first nationwide study in Europe quantifying microplastic concentrations in agricultural soils and how the use of plastic crop covers influences microplastic accumulation. We show that the direct contribution of microplastics to agricultural soils from plastic crop covers is significant, resulting in microplastics concentrations 75.8 % higher than sites where no plastic crop covers are used. However, we also observed high levels of microplastics in soils even when there is no discernible use of plastic in these systems suggesting the indirect agricultural input of microplastics and contribution from non-agricultural sources is significant.

To accurately assess the contribution of direct and indirect sources of microplastics to agricultural soils it is essential to establish baseline levels of microplastics in soils, as we have done in this study, using standardised methods. This is fundamental to establishing positive and negative threshold values and determine risk from microplastics and associated additives on agronomic, environmental, ecosystem and human health. The polymeric composition of the microplastics detected in the samples was not collected. Future research should use polymer identification techniques, using FTIR or Raman, to investigate any differences in polymer composition between the conditions in this study. Together, with a deeper understanding of microplastic interactions, behaviour and transport, this will allow the development of policies to monitoring and regulate microplastic concentrations in agricultural soils.

The benefits of plastics in agriculture are extensive, such that plastic use is likely to increase during the development of more resilient food production systems. Our results, and those of other studies, show the ubiquitous distribution of microplastics in agricultural soils due to their persistence and as a result of current and historic plastic use, suggesting that concentrations will increase in agricultural soils with the increased use of agricultural plastics. Therefore, a better understanding of the effects of microplastics in the agricultural environment is urgently needed to avoid the potential of irreversible environmental harm through inaction and a lack of knowledge about the effects of this novel form of pollution.

4.6 Acknowledgements

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5. The growing legacy of plastic use

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Abstract

Since its invention, plastic has driven a revolution in behaviour in all aspects of our lives, including agriculture. Accumulation of plastic pollution in agricultural systems has been shown to have negative impacts on human health and agricultural productivity but little is known about concentrations of plastics in soils. Using a historical time series, we show increasing levels of microplastics in agricultural soils with time. This increase is significantly higher in soils that are amended with either organic or inorganic fertiliser suggesting this treatment is an important contributor to microplastic concentrations in agricultural soils over time. This study provides evidence that agricultural soils are receptors and reservoirs of microplastic pollution, a legacy which is growing over time, predating modern plasticulture.

5.1 Introduction

Plastics have revolutionised the world we live in today. Much like the industrial revolution, the introduction of plastics into everyday life is responsible for significant changes to economic and social organisation. Plastics have facilitated advancements in packaging, construction, transportation, agriculture, medicine and electronics. Approximately, 450 million tonnes of plastic are produced annually, expected to increase to 1,606 million tonnes by 2050 (Zheng and

Suh, 2019; Bergmann et al., 2022). Of all plastics created, 76 % has now become waste, 79 % of which has accumulated in landfill and the natural environment (Geyer et al., 2017).

In-use and as a waste material, plastic breaks down via microbial, mechanical and chemical degradation pathways into smaller particles; microplastics and nanoplastics (Allen et al., 2022; Steinmetz et al., 2016). Microplastic and nanoplastic pollution is considered irreversible and negatively impacts planetary and human health (Bergmann et al., 2022; Persson et al., 2022). The properties and characteristics that make plastics so versatile are the same reasons why the accumulation of the material is of growing environmental concern due to its persistence, durability and capacity for being transported globally through a range of environmental media (Allen et al., 2022). Whilst the extent and many of the effects of plastic pollution in the marine environment are well understood, this is not the case in the terrestrial environment (Allen et al., 2022; FAO, 2021).

The long-term and widespread use of plastics, combined with substandard management strategies has led to the accumulation of plastic residues (macro-, micro- and nanoplastics) in agricultural soils worldwide (FAO, 2021; Tian et al., 2022). Direct agricultural sources of plastic residues to agricultural soils include crop covers, crop housing, fertilisers and containers. Indirect agricultural sources include slurry, wastewater irrigation, organic manure and other field amendments. Other sources include atmospheric deposition from industrial emissions, vehicle tyre debris, re-suspension of dust and the deterioration of polymer-coated surfaces and structures, largely of urban origin (Tian et al., 2022; Nizzetto et al., 2016).

The release of plastic residues into the agricultural environment causes physical, chemical and biological harm, the severity of which is thought to be dictated by the polymer type, size, shape, aging, time of exposure and associated additives (Allen et al., 2022; FAO, 2021; Tian et al., 2022). Given the heterogeneity of plastic residues in the environment, it is difficult to differentiate what component or characteristic of the residue engenders a given effect. Microplastics, defined as any polymer between 1 μm to 5 mm, are an emerging concern in agricultural systems and impact agricultural productivity, directly or as a result of the additives incorporated into the polymer during production or adsorbed from the surrounding environment (Persson et al., 2022; FAO, 2021; Nizzetto et al., 2016; Horton et al., 2017; Qi et al., 2020). Additives include stabilizers, plasticizers, flame retardants and coloring agents, many of which are known endocrine disruptors which can impair the health of living organisms (Tian et al., 2022; Nizzetto et al., 2016; Qi et al., 2020).

The last decade has seen a marked expansion in microplastic research. Microplastics have been detected in every environmental compartment on earth. They have also been detected within the organs, tissues, gastrointestinal tracts and circulatory systems of multiple animal species, including humans, and have been shown to have harmful effects on biota, flora and fauna, including multi-generational impacts (Allen et al., 2022). In agricultural soils, microplastics affect the physical, chemical and biological properties of soil and negatively impact crop quality, yield and (FAO, 2021; Tian et al., 2022; Qi et al., 2020; de Souza Machado et al., 2018; Ya et al., 2021). The germination, reproduction, photosynthetic rate and growth of numerous crops, including those of commercial importance, have been shown to be inhibited (FAO, 2021; Tian et al., 2022; Ya et al., 2021). Impacts on soil biota and microorganisms are either indirect, due to changes in the soil environment or direct, due to exposure, ingestion and abrasion, affecting the survival, reproduction and abundance of mesofauna, microarthropod and nematode communities (Qi et al., 2020; Lin et al., 2020). Most of these effects are thought to worsen at higher loads of microplastic residues. However, many studies have been conducted at artificially high microplastic concentrations which have the potential to compromise agroecosystem functioning and productivity in the long-term (Allen et al., 2022; Qi et al., 2020;

de Souza Machado et al., 2018; Lin et al., 2020). Consequently, the extent, effects and severity of microplastic pollution in agricultural soils, in the short- and long-term, are largely unknown.

When assessing the effects of microplastic in agricultural soils it is important to understand whether the concentrations detected are a legacy of historical farming practices or whether they reflect current agricultural practices and wider societal plastic use. Due to the dynamism of the agricultural environment, assessing the historical contributions and concentrations of microplastics in agricultural soils is difficult, unless samples are systematically analysed from a preserved time series. Although temporal records of microplastics in peat, sediment and urban environments have demonstrated a proliferation of microplastics from the 1950's to present (Turner et al., 2019; Allen et al., 2021), changing concentrations have never been shown in agricultural soils. In this study, we used samples from the Rothamsted Sample Archive (Rothamsted Research, 2023) to determine a temporal record of microplastics in agricultural soils. Here, we provide evidence that agricultural soils are receptors and reservoirs of microplastics, and that the appearance of microplastics in agricultural soils predates modern plasticulture.

5.2 Material and Methods

5.2.1 Sample preparation

Historic soil samples collected from three different treatments (farmyard manure (FYM), inorganic fertiliser (N3(P)KMg) and no soil amendments (Nil)) across 18 different time points (1846 – 2022) from the Broadbalk winter wheat experiment at Rothamsted Research (Harpenden, Herts, UK, AL5 2JQ; 51º48′N, 0º22′W) were analysed. The samples used had been collected from the plough layer (0 – 23 cm), milled to a 2 mm and stored in sealed glass bottles or card boxes. Due to the importance of preserving the Rothamsted Sample Archive, only small samples in comparison to those used for analysis in Chapter 4, 1.5 g for each treatment at each time point, were used for analysis. However, using samples with known concentrations, recovery rates and microplastic concentrations were shown to be similar across a range of sample sizes (1.5 g, 5 g, 25 g, 50 g, 100 g), see Supplementary Table 5.1. Microplastic separation, extraction and identification from agricultural soils was adapted from the methodology outlined in Chapter 4.

5.2.2 Sample treatment

H_2O_2 was added to each soil sample and heated to 60 ºC to remove organic matter (Cusworth et al., 2023; Radford et al., 2021). To prevent samples from boiling over 5 ml of ethanol was added and an ice-bath was used to keep the temperature below 65 ºC. Once effervescence subsided and all visible organic matter was removed, samples were cooled to 40 ºC and 5 ml of 0.05M $Fe(II)SO_4$ was added. Samples were reheated to 60 ºC and covered for 24 h to allow $Fe(II)SO_4$ to decompose remaining H_2O_2 and flocculate clay particles.

Density separation was performed to separate microplastics form the inorganic fraction of the sample. 600ml 26 % w/v NaCl solutions were added, mixed and left to settle for 24 h. The supernatant was filtered through a 0.45 µm glass fibre filter. Beakers were rinsed with HPLC water to capture residual microplastics and the washings filtered. 3 ml of a 0.5 % Nile Red solution in *n*-hexane was applied to the air-dried filter paper to stain any microplastics. 3 ml of *n*-hexane was added to the filter paper and left to air-dry. The filter was transferred to a microscope slide, covered with glass slips and wrapped in foil.

During sample collection, transportation and analysis, samples were sealed in sterilised aluminum trays to minimise contamination. Preparation and analysis of samples took place in a sterilised fume cupboard. All glassware, instruments and applicable chemicals were leached with acetone and baked at 400 ºC for 4 h. Samples were analysed in triplicate along with blanks.

5.2.3 Sample analysis

A fluorescence microscope (Leica MZFLIII Stereo Fluorescence Microscope) equipped with an integrated digital camera using GXCapture software was used to analyse the samples. Microplastics were examined at three combinations of excitation:emission (Ex:Em) wavelength: 425:480 nm, 475:535 nm, and 510:560 nm; Nile Red-stained plastics have previously been found to fluoresce well at Ex: 450-490 nm; Em: 515-565 nm (Erni-Cassola et al., 2017, Cusworth et al., 2023). A particle was identified as a microplastic if the following selection criteria were met: (1) the outline of the particle is clearly visible and has well-defined edges; (2) the particle has a 3-dimensional shape resembling a synthetic material; (3) the particle size was greater than 10 µm; (4) there is no evidence of any internal organic structures; (5) the particle clearly fluoresces in green-yellow; (6) the particle is visible and physically present in all Ex:Em combinations used. Microplastics were reported as particles per weight of dry soil to ensure that the results are comparable to other studies, given that effects caused by microplastics are thought to be dictated by the physical presence of the particle rather than the accumulative mass of the particles (Allen et al., 2022; FAO, 2021; Tian et al., 2022).

5.2.4 Statistical analysis

To measure the relationship between microplastic concentrations, treatment type and time, we performed simple linear regressions with groups analysis, using dummy coding of multi-categorical predictors. Each regression was fitted to the data from 1966, when microplastics were detected in all three plots. Relationships were considered significant at the $P < 0.05$ level. Analyses were performed using SPSS (IBM Statistics for Windows, Version 28.0).

5.3 Results and Discussion

A significant increase in microplastic concentrations ≥ 10 um and particles ≤ 10 µm was observed between 1966 - 2022 in all three treatments, farmyard manure (FYM), inorganic fertiliser (N3(P)KMg) and no soil amendments (Nil) (Figure 5.1; Supplementary Table 5.2) ($R^2 = 0.546$, $F(1, 28) = 33.607$, $p \leq 0.001$). In contrast, no microplastics were detected in the samples between 1846 - 1914, consistent with the later creation of 'modern plastics' which are wholly synthetic materials (Harrison and Hester, 2018). Although particles ≤ 10 µm were present in all samples, the relatively low numbers of particles found in samples until 1966 (Supplementary Table 5.2), comparable with particle counts detected in laboratory blanks from Chapter 4, are likely the result of contamination from milling, collection and analysis. Therefore, together with the small soil sample sizes available for analysis, this introduces additional challenges when developing an accurate timeline of microplastics back to the early twentieth century (Turner et al., 2019). From 1900 – 1960, it is likely that any microplastics detected in the samples are not from agricultural sources but are instead a reflection of increased plastic use in wider society including in infrastructure, fashion and domestic use, and as a consequence of World War II (Harrison and Hester, 2018). From the mid-1960's, a substantial increase in microplastic concentrations and particles ≤ 10 µm was recorded, consistent with other sediment and archive analysis (Allen et al., 2022; Turner et al., 2019). From 1966 - 2022, microplastic concentrations in the FYM and N3(P)KMg treatments are significantly different from the Nil treatment ($R^2 = 0.8$, $F(3, 26) = 4.6$, $p \leq 0.001$) but not from one another ($p = 0.441$) indicating that these treatments directly contribute to the microplastic load in the soil beyond baseline concentrations.

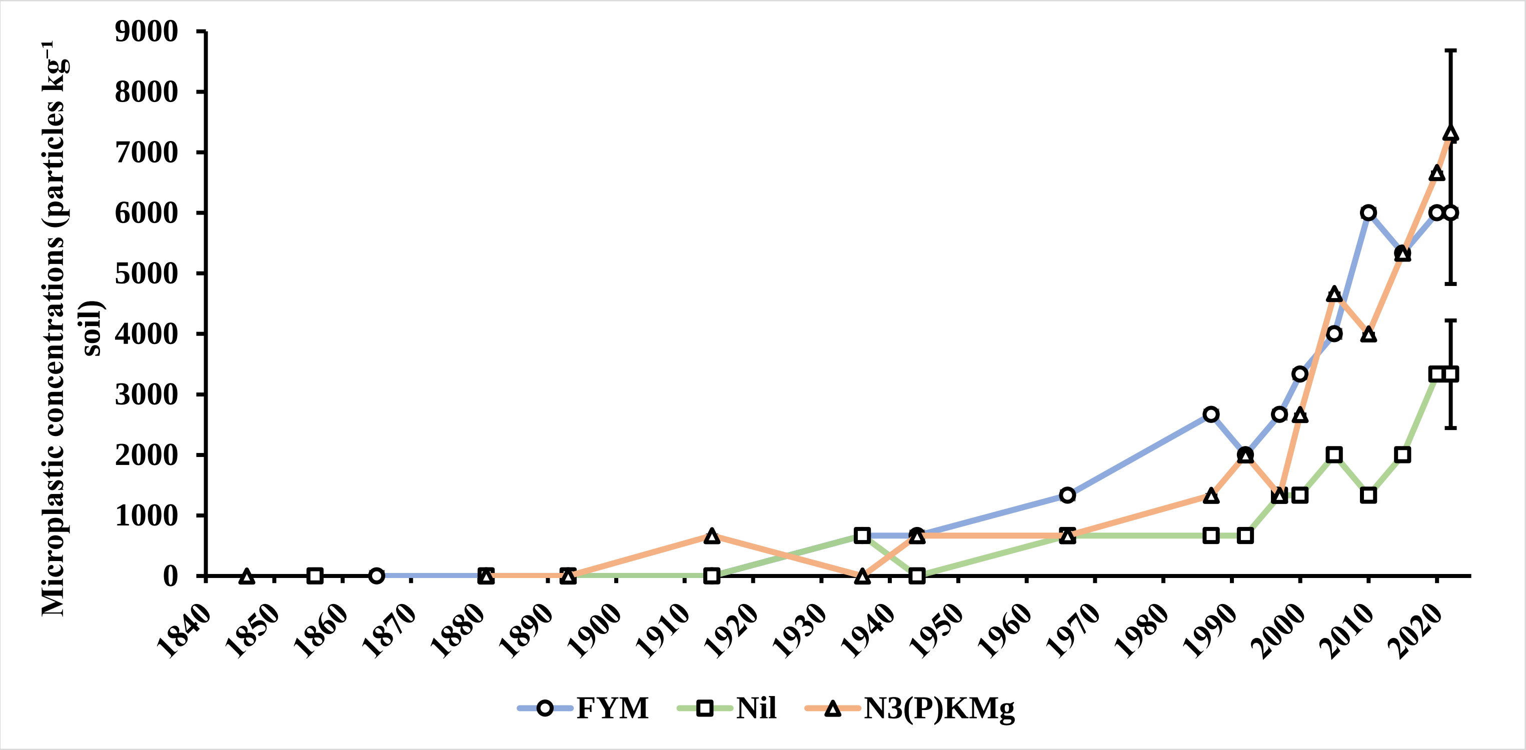

Figure 5.1 Microplastic concentrations in agricultural soils across three treatments. Microplastic concentrations (particles kg^{-1} soil) in agricultural soil samples collected from the Broadbalk winter wheat experiment from the Rothamsted Sample Archive between 1846 - 2022. Error bars represent the mean ± standard error from 2022 samples. Microplastic concentrations were recorded across three treatments **a) 2.21 – FYM**; farmyard manure at 35 t ha^{-1}, **b) 031 – Nil**; no soil amendments, **c) 081 – N3(P)KMg**; 144 kg N ha^{-1}, 35 kg P ha^{-1} triple superphosphate until 2000, 90 kg K ha^{-1} potassium sulphate, 12 kg Mg ha^{-1} Kieserite (35 kg Mg every third year between 1974 -2000).

From 1966 – 2010, microplastic load in the FYM plot increases at a gradual rate. This likely reflects the ubiquity of plastics materials on farms with the application, breakdown and distribution of plastic materials, both intentional and unintentional, being included in the farmyard manure used as an organic fertiliser (Piehl et al., 2018). Microplastic concentrations detected in farmyard manure and other comparable soil amendments are very variable, for example Wu et al., 2021 found 0 – 3780 microplastic particles kg^{-1} soil were detected across one study, partly due to the heterogeneity of farming practices, livestock feed and plastic use on farm. From 2010, microplastic concentrations in the FYM treatment plateau, irrespective of the 180 – 183 % increase in the Nil and N3(P)KMg, respectively. A plateau in microplastic loads and a relative decrease in comparison to the trajectory of the Nil treatment could be due to inputs being balanced with the vertical transport of microplastics below the sampled layer as a result of hydraulic conduits, shrink-swelling of soil and earthworm ingestion and excretion (Wu et al., 2021). Given the observed and predicted change in climate variability, particularly the increased likelihood of intense rainfall, microplastics in the plough layer are likely to be removed and discharged into the riverine and marine environment.

Microplastic concentrations were observed to increase steeply between 1997 – 2005 (+ 350 %) and 2010 – 2022 (+ 183 %) in the N3(P)KMg treatment. Between 1997 – 2005, the increase is independent of changes in the Nil treatment. This is likely linked to the increased reliance during this period on polymer-coated fertilisers (+ 45 % from 1996 - 2005), seeds and additives used to protect and control the release of nutrients to optimise resource efficiency for plant uptake (CIEL, 2022; FAO, 2021). As these coatings degrade, microplastic residues and additives are released, as a direct source to agricultural soils (Allen et al., 2022; Qi et al., 2020; Piehl et al., 2018). Annually, 22,500 tonnes of microplastics are thought to be released from fertilizers and additives (FAO, 2021). The degradation rate of the coatings is highly variable and is therefore expected to have a bearing on inter-annual microplastic load. Given this, the use of non-biodegradable polymers in slow- and controlled-release fertilisers is set to be banned in 2026 by the European Union (European Union, 2019; CIEL, 2022).

Once the FYM and N3(P)KMg decouple from the Nil treatment, it cannot be discounted that the microplastic load of the latter is wholly from non-agricultural sources; wind-blown redistribution, runoff and atmospheric deposition are known sources of microplastics (Allen et al., 2022; FAO, 2021; Tian et al., 2022; Piehl et al., 2018). The atmospheric deposition of microplastics to soil varies, ranging between 40 – 311,040 particles m^{-2} d^{-1}, between a remote mountainous catchment and an urban area, respectively (Adhikari et al., 2023). Although reported rates of microplastic deposition from the atmosphere are highly variable, it is possible to compare the proportion of microplastics in soils from atmospheric sources, compared to the microplastic load from the application of soil amendments. Given that the majority of microplastics of atmospheric origin are fibres and are typically of a lower density compared to fragments, the dominant particle morphology found in biosolids, atmospheric deposition constitutes 1 – 4 % of total soil microplastics, by mass. Whereas, by particle number, the proportion of microplastics of atmospheric origin ranges from 9 – 12 % of total microplastics (Adhikari et al., 2023). Comparing these values to Figure 5.1, it could be expected that 320 – 907 particles kg^{-1} soil, depending on the treatment, were of atmospheric origin, from the soils sampled in 2022. The proliferation in microplastic load across all treatments over time is reflective of treatment type and an increase in global plastic use, particularly the last decade. However, to provide a more detailed understanding of how the sources of microplastics and microplastic composition changed over time and between treatments, FTIR and Raman could have been used (Qi et al., 2020; Qi et al., 2021).

Microplastic pollution is a burgeoning threat to agroecosystems. Existing threats to agroecosystems due to climate variability and intensive agriculture can be exacerbated by microplastic pollution, making it more difficult to increase, let alone maintain global food production. As microplastics are vectors for pathogens and adsorb organic pollutants, the presence of microplastics in fresh produce raises concerns for food safety and human health (Ya et al., 2021; Prata and Dias-Pereira, 2023; Conti et al., 2020). The use of agriplastics is expected to increase, driven in part by a need to enhance the productivity and resilience of food systems, presenting a conflict between prioritising food security and environmental security.

Without immediate action to curb the release of microplastics into the environment, microplastic concentrations in agricultural soils are expected to keep rising, consistent with the trajectories observed in Figure 5.1. Although it has been commonly observed that responses to microplastic pollution worsen at higher concentrations (Lin et al., 2020; FAO, 2021; Ya et al., 2021; de Souza Machado et al., 2018), microplastics do not typically produce a classic dose-dependent response (Zang et al., 2020). Given that microplastic concentrations in the FYM and N3(P)KMg treatments are significantly different to the Nil treatment during 1966 – 2022, but not between one another, it does not necessarily mean the type and severity of any response to microplastic pollution is different, or for the latter, comparable. Each treatment receives microplastics from a range of different sources and therefore the type, shape, age and additive composition and corresponding ecotoxicological risk is unique to each condition. It is generally hypothesized that the translocation of smaller microplastics and nanoplastics is higher and the likelihood to trigger an ecotoxicological response is greater (Zang et al., 2020; de Souza Machado et al., 2018). Given that microplastics degrade into smaller particles and nanoplastics over time, agricultural soils with high microplastic concentrations are therefore a cause for future concern.

Multiple strategies exist to better manage plastic use and reduce microplastic pollution in agricultural soils. Solutions should focus on adjusting the design, production, supply, use and waste management of plastics (FAO, 2021). Where possible, the use of plastic should be avoided and replaced with sustainable alternative materials that provide comparable benefits.

The use of biodegradable and compostable materials could reduce microplastic load to agricultural soils. In theory, even when the complete degradation of these polymers does not occur, the build-up of microplastics from these novel polymers should not exceed the growth curves observed in Figure 5.1. Plastic product standards, regulations and certifications need further development to extend the use and post-consumer lifespan to improve the reuse, recovery and recycling of the material. In agriculture, regulating an increase in the thickness of plastic mulch film reduces the accumulation of plastic residues in agricultural soils and makes it easier to retrieve, clean and recycle (APE, 2019). To encourage the recovery, reuse and recycling of plastics, APE Europe encourages farmers to practise 'plastic-neutral farming'. Approximately 70 % of non-packaging agricultural plastics are not collected due to a lack of recycling infrastructure, contamination and processing costs (APE, 2019). Farmers are encouraged to cooperate with collection schemes and are informed how to properly sort, store and prepare plastics to improve the circularity of agriplastics. Reducing plastic use should remain a priority and at the very least, plastics should be retrieved after use to be reused, recycled or recovered.

5.4 Conclusion

This is the first study to determine a temporal record of microplastic concentrations in agricultural soils. We demonstrate the agricultural soils are receptors and reservoirs of microplastics over time, predating the widespread use of plastics in agriculture. Here, we provide evidence that sources of microplastics to agricultural soils are both agricultural and non-agricultural in origin and the application of organic and inorganic fertilisers are significant sources of microplastics beyond baseline concentrations. The impacts of microplastic pollution on the health of agricultural soils and consequently agricultural productivity are largely unquantified and unreliable, due to the lack of longer-term field trials and the use of unrepresentative concentrations in studies (Qi et al., 2020). Given that microplastic concentrations will likely continue to accumulate in agricultural soils from agricultural and non-agricultural sources, it is important to better understand the effects of microplastic inputs to agricultural systems. Future work must evaluate the long-term interactions and effects of microplastics in agroecosystems using representative concentrations. This study offers the potential for the development of scenario-based projections of microplastic concentrations for use in field trials to anticipate the future impacts of microplastic pollution in agricultural soils.

The onus of reducing microplastic pollution of agricultural soils cannot be placed on the agricultural industry alone. Given that much of the microplastic pollution of agricultural soils is of industrial, commercial and urban origin, multidisciplinary action is required to reduce future microplastic pollution of agricultural soils. Adopting the principles of the 6-R framework; refuse, redesign, reduce, reuse, recycle and recover (FAO, 2021), will be necessary to reduce the release of microplastics into the environment and identify alternative materials with a reduced planetary impact.

The legacy of plastic use in agricultural soils from agriculture and other industries is irreversible. Given the increasing pressure on global food systems, acute microplastic pollution may pose a direct threat to agricultural productivity, food security and food safety. With no immediate solution to remediate microplastic pollution on the horizon, it is critical to reassess our relationship with plastic use in agriculture and beyond.

5.5 Acknowledgements

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6. The distribution of microplastics in soil and their effect on crop and soil health

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6.1 Introduction

Plastics, a prominent marker of the Anthropocene, are synonymous with modern society. The global use of plastics is driven by the versatility, durability and low cost of the material (Zalasiewicz et al., 2016). The use of plastics in agriculture, much like other sectors, has revolutionised the industry. Globally, agricultural systems have benefited from plastic use since the 1940s, providing benefits for crop production, transportation, protection and storage. Agriplastics provide protection against weeds, insects and weather damage, increase soil and air temperature, reduce evaporation losses and may be wavelength-selective, enhancing the nutritional profile of crops, increasing crop yield and reducing resource use, food losses and waste (Sintim and Flury, 2017; FAO, 2021; Gao et al., 2019).

Despite these advancements, the disposability of plastic and a lack of appropriate waste management infrastructure has contributed towards the creation and accumulation of plastic waste in the environment (Geyer et al., 2017; Borrelle et al., 2020). Due to aging, contamination and poor recoverability of many agriplastics, the proportion of these materials destined for landfill or disposed in the natural environment, often at the location of use, is high (Sintim and Flury, 2017; FAO, 2021; APE, 2019). Exposed to multiple degradation pathways, plastic residues degrade into micro- and nanoplastics, the former, thought to pose a greater ecotoxicological risk (Qiu et al., 2020).

Agricultural soils are receptors and sinks of microplastics from direct and indirect agricultural sources; plastic mulch film, wastewater irrigation, compost, biosolids and fertilisers, as well as atmospheric fallout and runoff from non-agricultural sources; textile fibers, artificial surfaces, landfill and domestic effluents, largely of urban origin (Nizzetto et al., 2016; Qiu et al., 2020; Tian et al., 2022). Aggregation with soil particles, trophic transfer, bioturbation and tilling, all contribute to the retention and movement of microplastics in agricultural soils, where microplastics accumulate over time (Tian et al., 2022; Horton et al., 2017; Rillig et al., 2017b). It is expected that these environments contain some of the highest microplastic concentrations worldwide (Nizzetto et al., 2016; Allen et al., 2022).

The presence of microplastics may change the physical properties of the soil; bulk density, aggregate size and water holding capacity, the structure, function and activity of soil communities, nutrient and water availability and root penetration, resulting in changes to nutrient cycling, CO_2 fluxes, organic matter decomposition and agricultural productivity (Tian et al., 2022; Lin et al., 2020; Zhang et al., 2022a; Zang et al., 2020; Li et al., 2020a). Microplastic uptake by a range of soil biota and plants raises further ecotoxicological and phytotoxic concerns. The role of earthworms in microplastic transport is well-established, however it remains unclear if crop and soil type promote the downward movement of microplastics via mechanisms such as root adhesion, biopore production or soil aggregation (Rillig et al., 2017a; Wu et al., 2020). The risks posed by microplastics deeper in the soil profile remains to be fully assessed although microplastics in subsoils may act as carriers of soil contaminants, compromise groundwater quality and pose unique environmental risks (Ren et al., 2021; Rillig et al., 2017a).

Many studies have explored the effects of microplastics in agroecosystems including impacts on crop, soil, biota and microorganism health, many of which show a negative response to the presence of microplastics (Zhang et al., 2022a). 83 % of the reported interactions between microplastics and soil fauna, vegetation and microbiota are negative, whereas negative impacts on crop production are recorded in 63 % of studies (Pérez-Reverón et al., 2022). The effects vary depending on polymer type, shape, dose, exposure time and individual sensitivities to microplastics (FAO, 2021; Gao et al., 2019; Zang et al., 2020; Zhang et al., 2022a; Li et al., 2020b). However, to date there has been lack of longer-term experiments and/or studies using environmentally representative concentrations of microplastics and therefore many impacts of microplastic pollution on agroecosystems remain to be determined (Qi et al., 2021). This study explores how microplastics impact agroecosystems, at environmentally relevant concentrations. The aim of this study is to determine how microplastics affect: 1) soil microbial community; 2) crop nutrient availability; 3) crop growth; and, in turn, how the distribution of microplastics in the soil profile is dictated by crop and soil type.

6.2 Material and Methods

6.2.1 Experimental design and set-up

The soil types used for the mesocosm experiment were procured from UK suppliers (Soil A - Beaver Compost; Soil B - Bailey's of Norfolk, UK). Soil A had a silty loam texture, an organic matter content of 4.9 % and pH 7.1. Soil B had a sandy loam texture an organic matter content of 1.5 % and pH 7.2. The soil was transported and stored in polypropylene bags until the mesocosm was set-up. Both soils were homogenised and screened manually in field-moist conditions for earthworms, plastic debris, organic residues and other constituents that may influence movement and distribution of microplastics. Soil was tested for baseline microplastic concentrations using the methods below. Soil A and B had baseline microplastic concentrations of 1407 and 1670 particles kg^{-1}, respectively.

An outdoor mesocosm experiment was set up at Hazelrigg Weather Station, Lancaster University, UK from May 21, 2021 till October 21, 2022. The two soils were combined with two crops and plastic additions in a fully factorial design. The two crops were a leguminous crop (*Vicia faba*) and a non-leguminous crop (*Triticum aestivum*), with an additional no-crop control. Pots were either spiked at environmentally relevant concentrations (~ 400 particles 100 g^{-1}) or unspiked (Figure 6.1). Given that polyethylene (PE) is used in a large proportion of agriplastics and are commonly found in soil (Tian et al, 2022; Zhang et al, 2022), clear PE microspheres (500 – 600 um; 0.96 g cc^{-3}; Cospheric, Santa Barbara, USA) were used to spike pots.

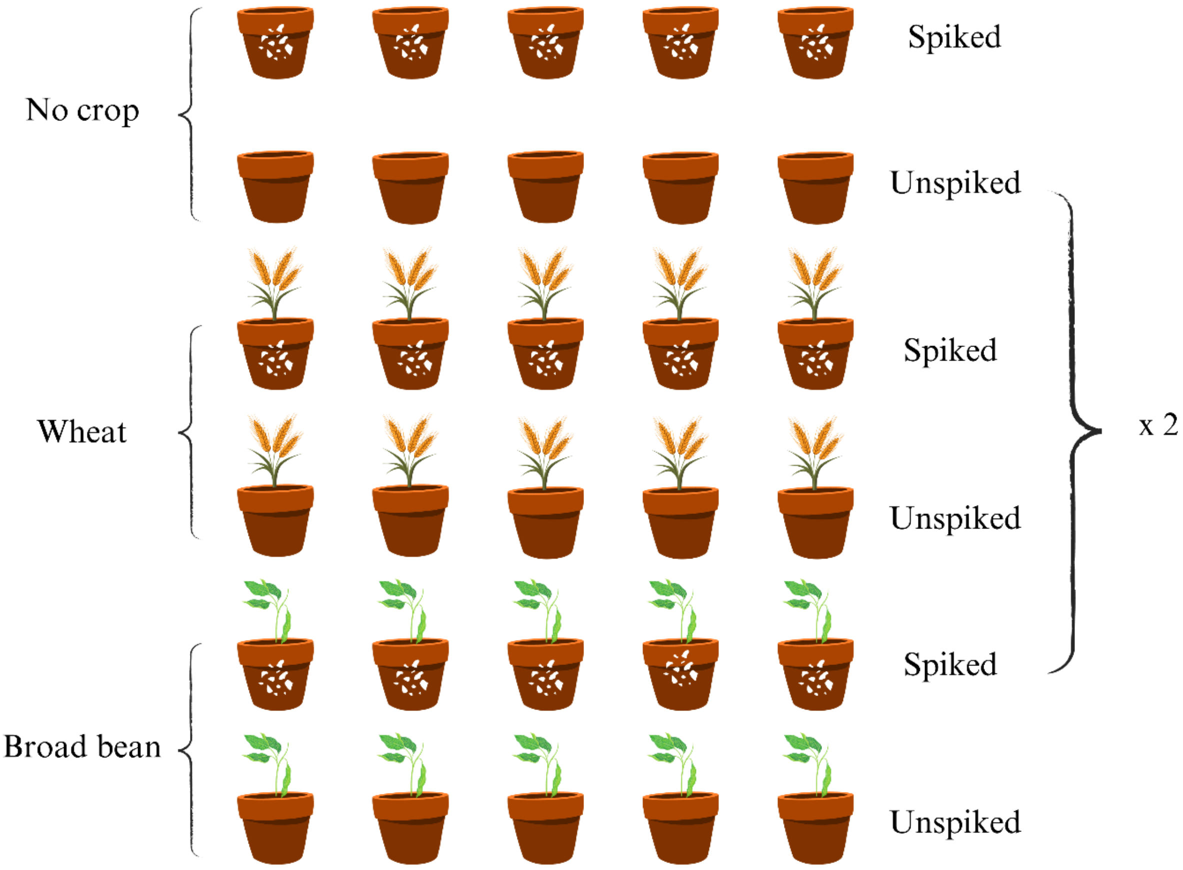

Figure 6.1. Mesocosm experiment design. All eight treatments were repeated for each soil type.

Round terracotta pots with a surface diameter of 39 cm and a height of 34 cm were used for the experiment. Each pot was filled with 40 kg of homogenised and screened soil. PE particles were mixed into the topsoil (0 - 5 cm) at a rate of ~ 400 particles 100 g^{-1} based on the findings of Cusworth et al., (2023). 5 g of broad bean (*Vicia faba*) or wheat (*Triticum aestivum*) seeds were sown in each planted pot and watered regularly. Throughout the experiment, the use of plastic was limited to reduce the risk of microplastic contamination. A wire mesh was secured over the pots to reduce disturbance from fauna and the topsoil tilled by hand after harvest to mimic agroecosystem conditions. Any pots noticeably disturbed were removed from further analysis.

6.2.2 Sampling procedure

Once the first cycle of crops matured (September 12, 2021), shoot length, leaf count, leaf area and chlorophyll content were measured in field. From each pot, 10 g of fresh weight soil from the topsoil was collected for pH analysis. The topsoil (0 - 5 cm) was tilled and left bare over winter. Crop were resown on May 23, 2022 and exposed to the same conditions as the first cycle. After the second harvest (October 21, 2022), the mesocosms were destructively sampled by hand to record root length and dry biomass, in addition to the previously described measurements. At soil depths 5, 10 and 15 cm, 150 g of soil was collected for microplastic analysis, microbial C, N and phospholipid fatty acid (PLFA) extraction.

6.2.3 Soil analysis

A pH meter (Mettler-Toledo, SevenCompact S220) was used to determine the pH of the soil samples using a 1:2.5 (w/v) ratio of soil to distilled water, once mixed on an orbital shaker for 30 min and left for 12 h to settle.

Microbial biomass carbon and nitrogen were determined using the chloroform fumigation-extraction method (Brookes et al., 1985). From each mesocosm, two 5 g subsamples were taken; one was fumigated for 24 h with gaseous $CHCl_3$ and the other not. 25 ml of 0.5 M K_2SO_4 was added to each sample shaken for 30 min. Organic carbon and nitrogen concentrations were determined using a Shimadzu total organic carbon analyser (Shimadzu Corporation, Kyoto, Japan). An extraction efficiency of 0.45 was used (Brookes et al., 1985).

Phospholipid fatty acid analysis of the soil microbial community was performed at the end of the second growing cycle. 1.5 g of topsoil were sieved and freeze-dried according to a modified Bligh-Dyer method (Bligh and Dyer, 1959). Phospholipids were extracted twice from each sample using a chloroform-methanol-citrate buffer mixture at a volume ratio of 1:2:0.8. The extracted phospholipids were methylated using mild alkaline methanolysis and washed with hexane. Methyltridecanoate (13:0) and methylnonadecanoate (19:0) were added as an internal standard. The PLFAs were analysed on a gas chromatograph equipped with a flame ionization detector (Agilent GC-6890 GC-FID) and identified using a MIDI Sherlock Microbial Identification System. The fatty acid nomenclature was that proposed by (Peterson and Klug, 1994). PFLAs with a carbon chain greater or equal to 14 and less than or equal to 19 were included for analysis. The sum of i15:0, a15:0, 15:0, i16:0, 16:1ω5,7, 7me17:0, i17:0, a17:0, 7cy17:0, 18:1ω7 and 7,8cy19:0 was used to represent bacterial PLFAs and the sum of 18:2ω6,9 and 18:1ω9 was used to represent fungal PLFAs. Total PLFAs and fungal:bacterial ratio was calculated. PLFA abundance was expressed as nmol g^{-1} dry soil in each sample.

6.2.4 Crop analysis

After each growing cycle, shoots were cut at the base of the stem, length measured, weighed and oven-dried at 60 ºC for 48 h to determine dry biomass. Roots were removed from the pots after the second growing cycle by gently shaking the pot to loosen the soil allowing extraction of the root mass followed by gentle washing under running water. Root biomass was measured and oven-dried with shoots to determine dry biomass. Leaves were cut off and leaf area measured using a LI-3100C leaf area meter (LI-COR Biosciences, USA). From these measurements, average leaf area and the root:shoot ratio for length and biomass was calculated. Plant chlorophyll content was measured in field using a Konica Minolta SPAD-503Plus meter (Richardson et al., 2002). The relative leaf chlorophyll content is determined by measuring leaf absorbance in near-infrared and red regions (650 and 940 nm). The absorbance values are automatically converted to a SPAD (Soil Plant Analysis Development) value by the instrument which provides an estimation of the relative content of chlorophyll in the sampled leaf (Richardson et al., 2002).

6.2.5 Microplastic sampling and analysis

Microplastic concentrations from soil depths 5, 10 and 15 cm were determined from each mesocosm. 100 g of soil, dried at 60 ºC for at least 72 h and hand sieved to 1 mm in acetone-rinsed trays, was used for microplastic analysis. Microplastic separation, extraction and identification followed the methods outlined in Chapter 4. To minimise contamination, samples were sealed in sterilised aluminum trays until analysis.

Microplastics present in the soil prior to the start of the experiment were identified and quantified based on the selection criteria outlined in Chapter 5, whereas the PE microplastics used in the study were easily identifiable without the use of a pre-determined selection criteria. Microplastic concentrations at each depth were expressed as particles 100 g^{-1} dry soil.

6.2.6 Statistical analysis

Each variable was tested for normality using the Shapiro-Wilk test and homogeneity of variances using Levene's test to check the assumptions for analysis of variance (ANOVA). Where required, data with non-normal distributions were log transformed to meet the assumptions for ANOVA. Differences in soil properties, soil microbial community and crop properties were analysed using one-way ANOVA, using the factors 'soil', 'crop' and 'plastic'. Principal component analysis (PCA) was used to further analyse the soil microbial community using PLFA fingerprints; total PLFA, total fungal, total bacterial, fungal:bacterial ratio, Gram +'ve, Gram $^{-}$'ve and Gram +'ve:$^{-}$'ve ratios. Two principal components were selected for analysis: PC1 (61.5 %) and PC2 (16.7 %). All differences were considered significant at the $P < 0.05$ level. Analyses were performed using SPSS (IBM Statistics for Windows, Version 28.0) and results presented as 'mean ± standard error'.

6.3 Results

6.3.1 Effects of microplastics on soil properties and microbial communities

The addition of microplastics significantly increased soil pH compared to unspiked soils across all treatments ($p < 0.05$) apart from the 1st year NC_A and BB_B ($p = 0.195$ and 0.062, respectively) Soil pH in spiked treatments was observed to be an average of 2.96 % higher than unspiked treatments over a two-year period.

The addition of microplastics did not have a significant effect on overall microbial biomass carbon or nitrogen ($p > 0.05$). However, significant changes in microbial biomass carbon were observed in individual treatments (WH_A, $p = 0.032$ and WH_B, $p = 0.040$). Microbial biomass carbon was significantly higher in the spiked WH_A treatment (+ 36.4 %) but declined in the spiked WH_B treatment (- 19.1 %). Microbial biomass carbon was observed to increase in the spiked NC_A, NC_B and BB_B treatments (+ 19.5 %, + 5.5 %, + 5.2 %) and decline in BB_A (- 35.3 %), however, none of these observed changes were significant.

There was no significant difference in total PLFAs due to the addition of microplastics ($p = 0.574$). Only one individual treatment showed a significant affect (WH_A, $p = 0.032$), where the addition of microplastics reduced total PLFAs by 38.3%. Similarly, when considering all treatments together no significant changes in fungal:bacterial ratio, total bacteria and fungal PLFAs, Gram +'ve, Gram $^{-}$'ve and Gram +':ve^{-}'ve ratios were recorded ($p > 0.05$). However, as with total PLFAs, significant changes in total bacteria, Gram +'ve and Gram $^{-}$'ve were recorded in the WH_A treatment ($p = 0.037$, 0.050, 0.047). Bacterial abundance was significantly lower in the spiked WH_A treatment, compared to the control (- 43.9 %, - 33.5 %, 40.2 %) (Table 6.1, Figure 6.3).

Principal component analysis (PCA) of the effects of microplastic treatment on soil microbial communities revealed that 80.7 % of the total variance could be explained by the first two principle components (PC), of which PC1 and PC2 explained 56.2 % and 24.6 %, respectively (Figure 6.2). Gram +’ve and Gram ⁻’ve were more related to PC1, separating the responses of spiked treatments amongst crop types. Total PLFA and fungal:bacterial ratio were more related to PC2, separating the spiked treatments from the unspiked, control treatments. However, considerable overlap exists between spiked and unspiked treatments, partly due to the large intra-group variance in both treatments (Figure 6.2).

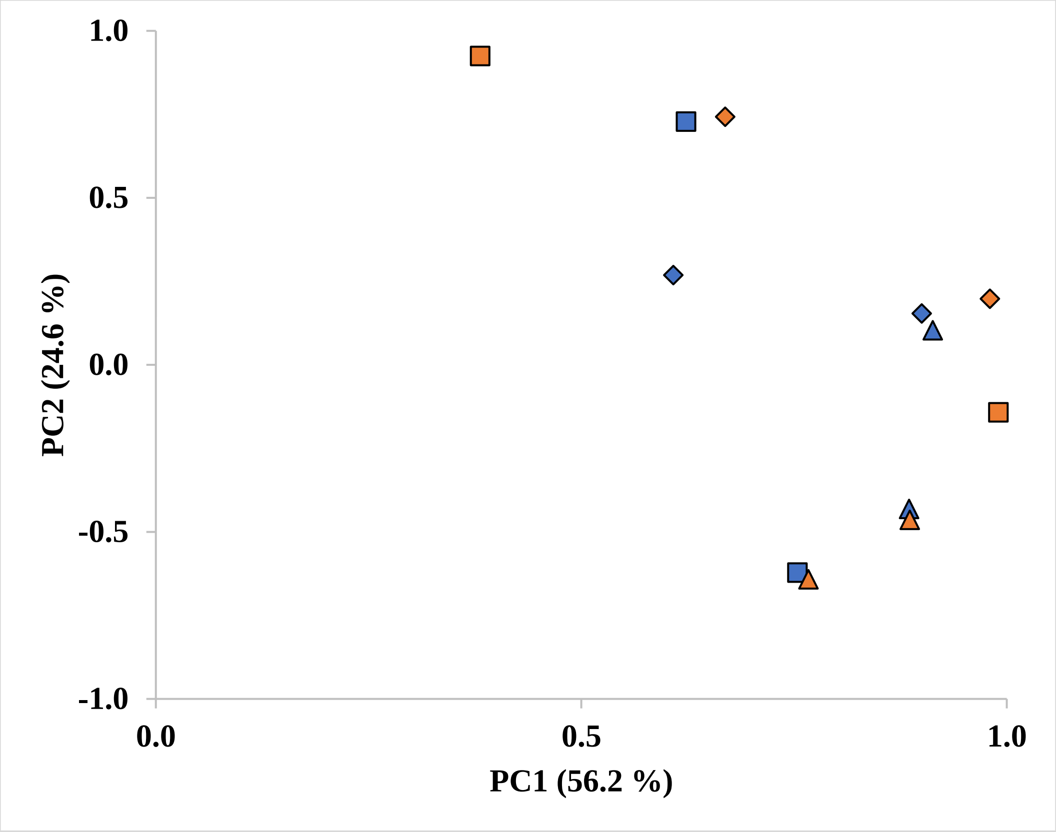

Figure 6.2. Principal component analysis (PCA) of microbial PLFA profiles from no crop (triangles), wheat (squares) and broad bean (diamond) treatments, as well as unspiked (blue markers) and spiked (orange markers) treatments. A table of values is provided in Supplementary Table 6.1.

Table 6.1. The influence of microplastic addition on soil properties and microbial communities. P-values < 0.05 are marked in bold and represent significant differences between spiked and unspiked treatments. Arrows indicate the direction of any significant differences. Treatment abbreviations are No Crop Soil A (NC_A), Wheat Soil A (WH_A), Broad Bean Soil B (BB_A), No Crop Soil B (NC_B), Wheat Soil B (WH_B) and Broad Bean Soil B (BB_B).

Treatment	NC_A	WH_A	BB_A	NC_B	WH_B	BB_B
Soil pH	**0.037**^{b} ↑	**< 0.001**^{a,b} ↑	**< 0.01**^{a,b} ↑	**< 0.02**^{a,b} ↑	**< 0.02**^{a,b} ↑	**0.012**^{b} ↑
Microbial biomass C	*0.448*	**0.032 ↑**	*0.139*	*0.734*	**0.040 ↓**	*0.594*
Microbial biomass N	*0.725*	*0.353*	*0.540*	*0.187*	*0.119*	*0.764*
Total PLFA	*0.349*	**0.032 ↓**	*0.956*	*0.448*	*0.590*	*0.564*
Total fungal	*	*0.810*	*0.294*	*0.228*	*0.407*	*0.652*
Total bacterial	*	**0.037 ↓**	*0.961*	*0.604*	*0.963*	*0.668*
fungal:bacterial	*	*0.286*	*0.349*	*0.660*	*0.328*	*0.260*
Gram +'ve	*	**0.048 ↓**	*0.974*	*0.934*	*0.799*	*0.647*
Gram -'ve	*	**0.047 ↓**	*0.943*	*0.267*	*0.769*	*0.724*
Gram +'ve:Gram -'ve	*	**0.025 ↓**	*0.839*	*0.095*	*0.144*	*0.804*

Note: Letters indicate significance differences over different years: a) year 1 b) year 2. An * indicates where a p-value could not be generated due to analytical errors.

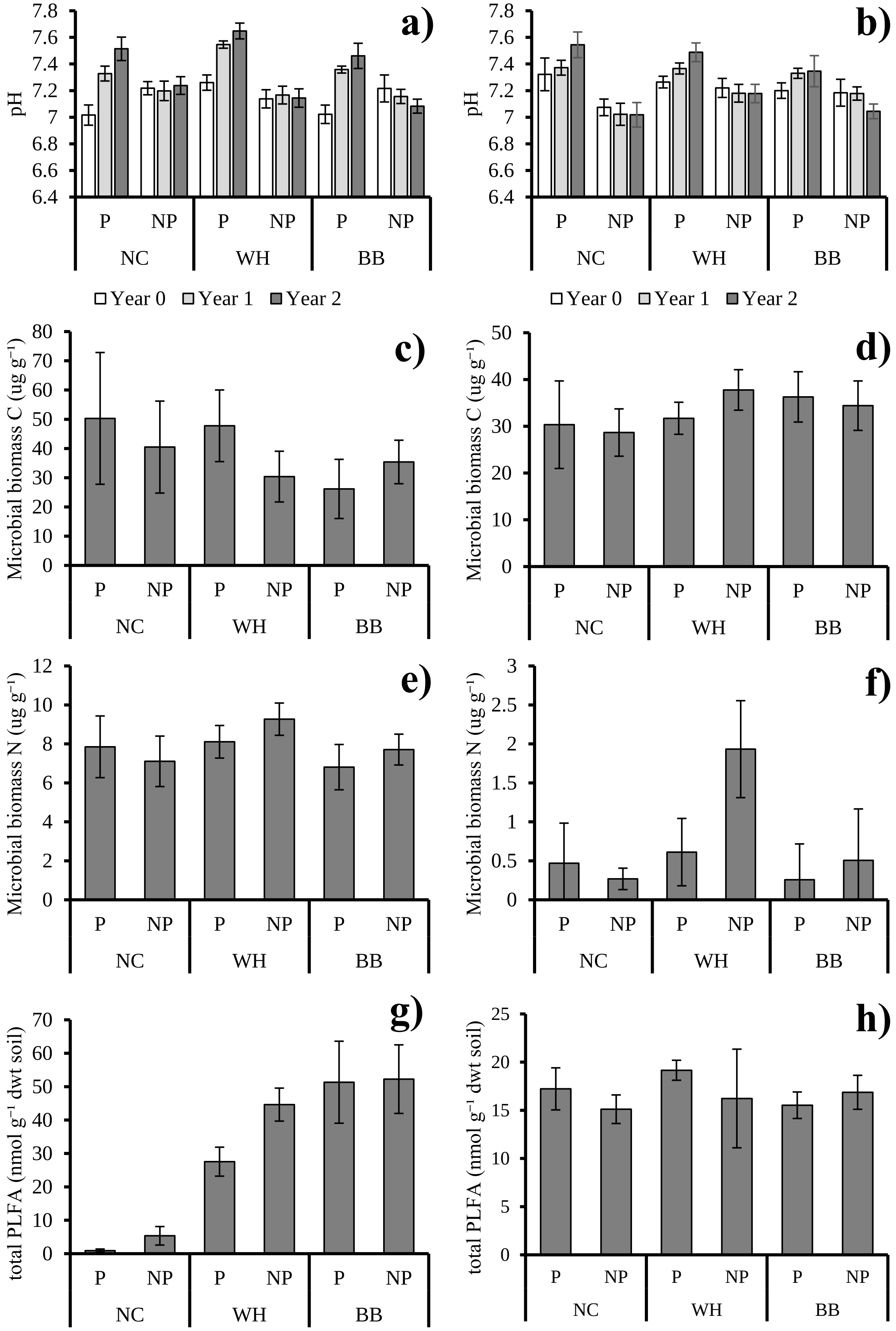
a)
pH
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
P
NP
P
NP
P
NP
NC
WH
BB
□ Year 0 □ Year 1 ■ Year 2
b)
pH
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
P
NP
P
NP
P
NP
NC
WH
BB
□ Year 0 □ Year 1 ■ Year 2
c)
Microbial biomass C (ug g⁻¹)
80
70
60
50
40
30
20
10
0
P
NP
P
NP
P
NP
NC
WH
BB
d)
Microbial biomass C (ug g⁻¹)
50
40
30
20
10
0
P
NP
P
NP
P
NP
NC
WH
BB
e)
Microbial biomass N (ug g⁻¹)
12
10
8
6
4
2
0
P
NP
P
NP
P
NP
NC
WH
BB
f)
Microbial biomass N (ug g⁻¹)
3
2.5
2
1.5
1
0.5
0
P
NP
P
NP
P
NP
NC
WH
BB
g)
total PLFA (nmol g⁻¹ dwt soil)
70
60
50
40
30
20
10
0
P
NP
P
NP
P
NP
NC
WH
BB
h)
total PLFA (nmol g⁻¹ dwt soil)
25
20
15
10
5
0
P
NP
P
NP
P
NP
NC
WH
BB

Figure 6.3. The influence of microplastic addition on soil properties and microbial communities, including a) soil pH (silty loam), b) soil pH (sandy loam), c) microbial biomass C (silty loam), d) microbial biomass C (sandy loam), e) microbial biomass N (silty loam), f) microbial biomass N (sandy loam), g) total PLFA (silty loam), and h) total PLFA (sandy loam). The data is representative of samples collected at the end of the mesocosm experiment, unless otherwise stated. Values are represented as mean ± standard error (n = 5). Treatment abbreviations are No Crop (NC), Wheat (WH), Broad Bean (BB), as well as spiked treatments (P) and unspiked treatments (NP).

6.3.2 Effects of microplastics on crop properties

Considering all treatments together, the addition of microplastics did not have a significant effect on crop properties compared to the control ($p > 0.05$). However, significant changes to crop properties were observed in individual treatments (Table 6.2, Figure 6.4). Over two years, shoot biomass and shoot length were lower in spiked *Triticum aestivum* treatments across both soil types, apart from the 2nd year WH_B treatment, where shoot biomass was significantly greater ($p = 0.022$, + 38.9 %). A decrease in shoot length was only significant in the 1st year WH_B treatment ($p = 0.031$, - 9.1 %) and the 2nd year WH_A treatment ($p = 0.033$, - 16.5 %). Shoot biomass and shoot length were initially suppressed in all of the spiked *Vicia faba* treatments compared to the control, but were greater in the second year. These changes are only significant in the spiked 2nd year BB_A treatment ($p = 0.014$, + 34.9 %, $p = 0.036$, + 29.5 %).

Root biomass and length were greater in the spiked treatments compared to the unspiked control across all crop and soil types, however these differences were only significant in the 2nd year BB_A treatment ($p = 0.012$, + 24.8 %, $p = 0.004$, + 47.4 %) (Table 6.2, Figure 6.4). Although shoot:root biomass and length were greater in all spiked treatments, none of the differences observed were significant ($p > 0.05$). Leaf chlorophyll content readings were higher in the spiked *Vicia faba* treatments, but only significant for the 1st year BB_A treatment (p =

0.044, + 21.5 %). The opposite was observed in all the spiked *Triticum aestivum* treatments, but only significant for the 2nd year of the spiked WH_A treatment (p = 0.029, - 16.1 %) (Table 6.2, Figure 6.4). The addition of microplastics showed no significant effect on average leaf area (p > 0.05).

Table 6.2. The influence of microplastic addition on crop properties over a two-year period. P-values < 0.05 are marked in bold and represent significant differences between spiked and unspiked treatments. Arrows indicate the direction of any significant differences. Treatment abbreviations are No Crop Soil A (NC_A), Wheat Soil A (WH_A), Broad Bean Soil B (BB_A), No Crop Soil B (NC_B), Wheat Soil B (WH_B) and Broad Bean Soil B (BB_B).

	Year 1				**Year 2**			
Treatment	WH_A	BB_A	WH_B	BB_B	WH_A	BB_A	WH_B	BB_B
Shoot biomass	*0.206*	*0.780*	*0.142*	*0.947*	*0.228*	**0.014** ↑	**0.022** ↑	*0.837*
Root biomass	*	*	*	*	*0.838*	**0.012** ↑	*0.804*	*0.907*
Shoot length	*0.057*	*0.415*	**0.031** ↓	*0.947*	**0.033** ↓	**0.036** ↑	*0.120*	*0.832*
Root length	*	*	*	*	*0.531*	**0.004** ↑	*0.491*	*0.822*
Shoot:Root biomass	*	*	*	*	*0.485*	*0.937*	*0.317*	*0.652*
Shoot:Root length	*	*	*	*	*0.107*	*0.187*	*0.117*	*0.798*
Average leaf area	*0.249*	*0.070*	*0.488*	*0.459*	*0.095*	*0.609*	*0.828*	*0.191*
Leaf chlorophyll content	*0.069*	**0.044** ↑	*0.831*	*0.053*	**0.029** ↓	*0.474*	*0.089*	*0.151*

Note: Cells marked with * do not contain p-values as measurements were not made till the end of the second growing season.

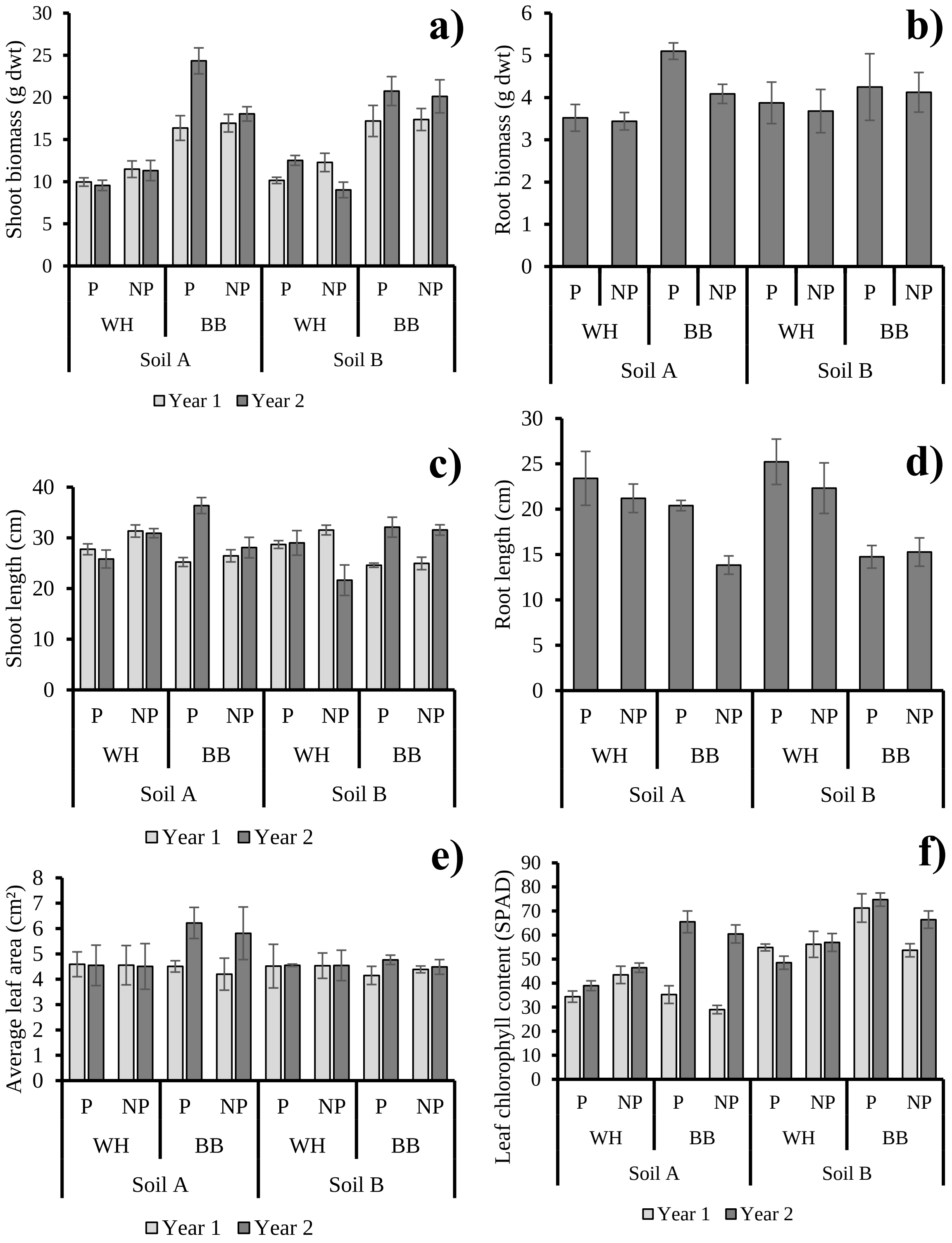

Figure 6.4. The influence of microplastic addition on crop properties, including a) shoot biomass b) root biomass, c) shoot length, d) root length, e) average leaf area, and f) leaf chlorophyll content. The data is representative of samples collected at the end of the mesocosm experiment, unless otherwise stated. Values are represented as mean ± standard error (n = 5).

Treatment abbreviations are Silty loam (Soil A), Sandy Loam (Soil B), Wheat (WH), Broad Bean (BB), as well as spiked treatments (P) and unspiked treatments (NP).

6.3.3 Effect of soil and crop type on the distribution of microplastics in the soil profile

The distribution of microplastics were significantly affected by crop type compared to the uncropped control ($p < 0.05$). Microplastic concentrations were comparable within the topsoil, at a depth of 5 cm ($p = 0.880$), ranging between 335 ± 33 – 342 ± 28 particles 100 g^{-1} dry soil. At a depth of 15 cm and 30 cm, microplastics concentrations were significantly higher in BB treatments (304 ± 21 and 260 ± 15 particles 100 g^{-1} dry soil) compared to NC treatments (266 ± 17 and 232 ± 19 particles 100 g^{-1} dry soil) ($p \leq 0.001$, $p = 0.004$). Microplastic concentrations were greater in WH treatments at a 15 cm and 30 cm depth (282 ± 25 and 301 ± 38 particles 100 g^{-1} dry soil), this difference was only statistically significant at 30 cm ($p = 0.130$, $p \leq 0.001$). Microplastic concentrations in WH pots were significantly higher than BB treatments at a depth of 30 cm ($p = 0.012$, 301 ± 38 and 260 ± 15 particles 100 g^{-1} dry soil, respectively). Although microplastics were more abundant at a depth of 15 cm in BB treatments (304 ± 7 particles 100 g^{-1} dry soil) compared to WH mesocosms (282 ± 25 particles 100 g^{-1} dry soil), this difference was not significant (Supplementary Table 6.2).

Soil type was a determining factor of microplastic distribution. No significant changes between soil types were observed at a 5 cm depth but were significant at a 15 cm depth ($p = 0.005$) (A = 297 ± 23, B = 270 ± 20 particles 100 g^{-1} dry soil) (Supplementary Table 6.2). A clear, but non-significant difference in microplastic concentrations was observed at a 30 cm depth between soils, + 23 microplastic particles 100 g^{-1} dry soil were recorded in the silty loam (A) compared to the sandy loam (B) (Figure 6.5).

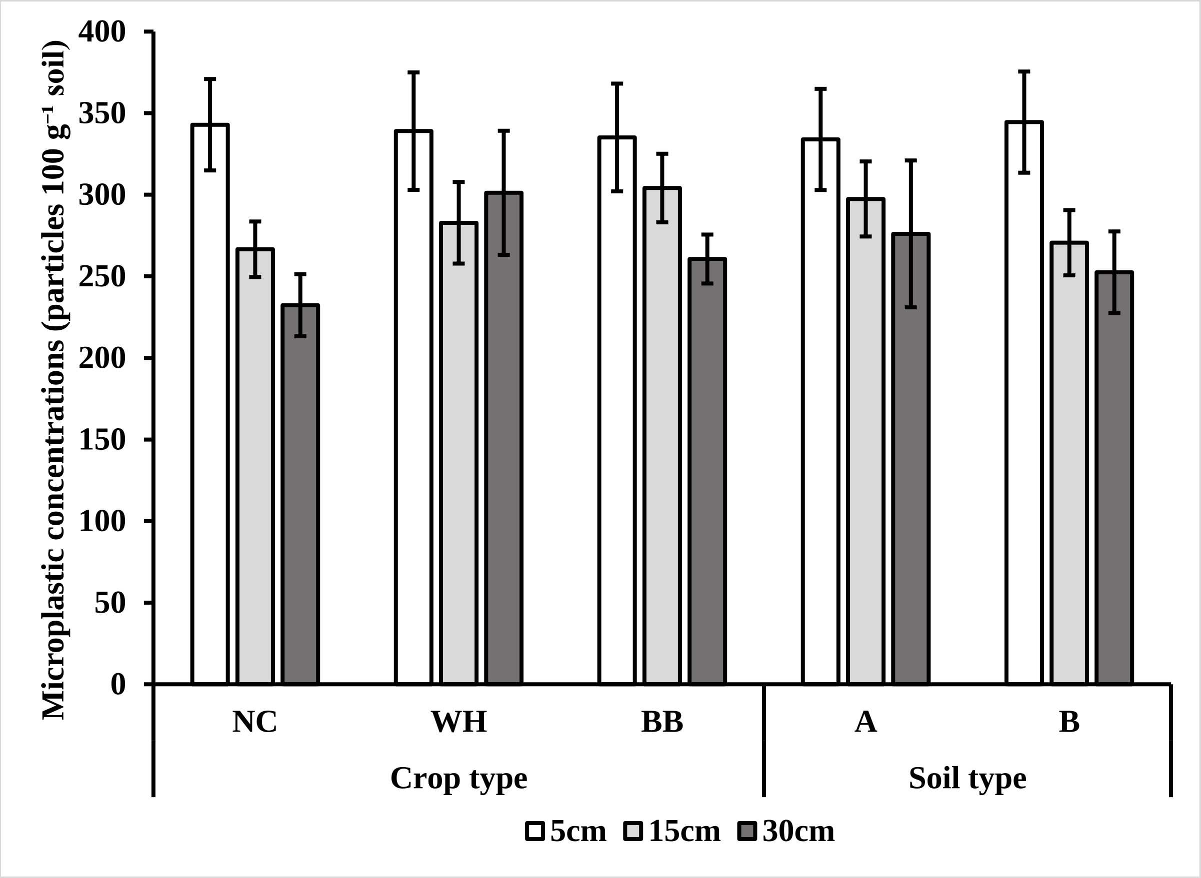

Figure 6.5. The influence of crop and soil type on the distribution of microplastics in the soil profile. Microplastic concentration values are expressed as particles 100 g^{-1} and presented as mean ± standard error (n = 60). Treatment abbreviations are No Crop (NC), Wheat (WH), Broad Bean (BB), Silty Loam (A) and Sandy Loam (B).

6.4 Discussion

6.4.1 Soil pH response to microplastics

The addition of microplastics had a significant effect on the soil pH, regardless of soil or crop type (see Table 6.1, Figure 6.3). An increase in soil pH in response to microplastics has also been reported by Zhao et al., (2021) who found that microplastic films, foams and fragments increased soil pH after 3, 11 and 31 days of exposure. Although the present study recorded significant increases to soil pH, other studies have reported a decrease or non-significant effects in soil pH (Wang et al., 2022). However, changes in soil pH are dictated, in part, by polymer type, shape and exposure time, complicating comparisons between studies (Zhao et al., 2021; Boots et al., 2019; Li et al., 2020b). Species-specific changes in soil pH in response to growth in microplastic-containing soils have been previously recorded, although such differences were not observed in the present study (Zhao et al., 2021b). Changes to soil pH, such as those resulting directly from microplastic treatment, affect the structure and composition of soil microbial communities, which play an important role in soil nutrient cycling, plant growth and root development (Boots et al., 2019). Alternatively, the addition of microplastics may indirectly affect soil pH by changing the structure of microbial communities (Zhao et al., 2021; Wang et al., 2022; Li et al., 2022).

The physical presence of microplastics may change the soil structure, increasing aeration, porosity and reducing soil bulk density which may increase soil pH (de Souza Machado et al., 2018; de Souza Machado et al., 2019). During degradation, microplastics may release compounds which alter the chemical properties of the soil. In theory, the degradation of polylactic acid (PLA) may lower soil pH due to leaching of acidic chemical compounds. However, studies have shown the addition of PLA has no significant effect and may even increase soil pH (Reay et al., 2023; Wang et al., 2020). The microplastics used in this study were pristine polyethylene spheres, a highly recalcitrant polymer with a low degradation rate. The release of biproducts from microplastic degradation is unlikely to generate a significant effect unless the mesocosms have a lower tolerance and buffering capabilities to the addition of microplastics, in which case the response to biproducts may be heightened (Chu et al., 2023). Pristine microplastics have been shown to have a greater effect on soil pH than weathered microplastics, although the mechanisms behind these changes are unknown (Shi et al., 2022). The present study was not designed to monitor degradation or bi-products of the PE microplastics. Therefore, further research is required to fully understand the mechanisms responsible for changes in soil pH.

6.4.2. Microbial community response to microplastics

Considering all the treatments together, the changes in total soil microbial biomass (as determined by microbial biomass carbon, nitrogen and PLFAs) and overall soil community structure (determined by PLFAs) across all treatments were not significant (Table 6.1). No changes in overall microbial abundance or composition have also been reported at microplastic concentrations of 39,172 particles kg^{-1} and 1000 g m^{-2}, much higher than observed in field conditions (Schöpfer et al., 2022; Lin et al., 2020; Brown et al., 2022).

However, when comparing individual treatments, significant changes in microbial biomass and PLFA assemblages were recorded. In individual wheat treatments (WH_A and WH_B), significant bidirectional differences in microbial biomass C were recorded in response to the addition of microplastics. Microbial biomass C increased in the silty loam (Soil A), whereas a decrease was observed in the sandy loam (Soil B). Microplastics are thought to have a greater impact on the physical structure of coarser soils, affecting soil aggregate formation, stability and porosity, which may increase aeration and positively impact the soil microbial community (Rillig et al., 2021; Rauscher et al., 2023).

Microbial biomass C has been reported to increase, decrease and remain unchanged following the addition of microplastics in cultivated treatments (Blöcker et al., 2023; Rauscher et al., 2023; Brown et al., 2023). Decreases in microbial biomass may be the result of physiochemical changes to the soil structure or upregulated stress responses from crops (Zantis et al., 2023; Wang et al., 2022). Levels of alicyclic acid and phenolic compounds from wheat crops increase when exposed to microplastics, affecting microbial biomass structure (Zantis et al., 2023). Ultimately, microbial community responses are complex and depend on how resistance and resilient existing communities are to disturbance (Wang et al., 2022). Increases in microbial biomass may be the result of an increase in bioavailable carbon following degradation of microplastic particles. However, the microplastics used in this study were pristine and are unlikely to have produced any bioavailable metabolites, developed biofilms or leached additives over the time course of the study.

The relatively low microplastic concentrations used compared to other studies, the purity of the microplastics and the short exposure time relative to field conditions could explain why only a few significant changes were detected in soil microbial biomass C and N (Schöpfer et al., 2022; Brown et al., 2022). When the mesocosms were sampled, moisture values were low, explaining why some values were lower than expected. Cycles of drying and rewetting can affect the soil microbial community and has been shown to reduce the abundance of many microbial groups (Sun et al., 2017).

Small and bidirectional changes in the soil microbial community structure, which were not significant, were observed in spiked treatments, as indicated by PLFA analysis, consistent with findings from Judy et al (2019) and Ya et al (2022). Although total PLFAs were reduced by 11.2 % in spiked treatments, the direction of effect varied between treatments. These changes were only significant for one individual treatment (WH_A), not when grouped. No distinct pattern was observed between crop or soil type in this study. In the WH_A treatment, a significant decrease in total PLFAs, total bacteria, Gram +’ve, Gram $^{-}$’ve and Gram +’ve:Gram $^{-}$’ve ratio was recorded. These changes to the PLFA fingerprint indicate that soil carbon cycling is suppressed (Chen et al., 2023). The presence of microplastics can inhibit the growth of sensitive bacteria such as *Nitrospirales*, *Alphaproteobacteria* and *Agrobacterium*, reducing soil microbial activity and functioning (Gao et al., 2021; Zhang et al., 2022a). Alternatively, the physical presence of microplastics may clog soil pores, restricting water flow and aeration. A shift in the distribution of anaerobic and aerobic microbes may be responsible for a decrease in Gram +’ve and Gram $^{-}$’ve bacteria, implying that relative C availability is reduced (Wang et al., 2022; Li et al., 2020b).

Nonetheless, an increase in total PLFAs and bacterial abundance have been observed in other studies, attributed to an increase in growth sites on the surface of microplastics (Chen et al., 2023), facilitating the growth of rapid-colonising bacteria and tolerant microorganisms that thrive in a soil-microplastic complex (Gao et al., 2021; Zhang et al., 2022a; Li et al., 2022). In accordance with this study, changes in response to microplastics have been found to be more pronounced in bacteria assemblages compared to fungi (Wang et al., 2022). The simultaneous increase in microbial biomass C and a decrease in total PLFA within the WH_A treatment presents contradictory results which cannot be easily explained.

6.4.3 Crop properties in response to the addition of microplastics

The addition of microplastics had limited effects on the growth of *Vicia faba* and *Triticum aestivum* (Table 6.2, Figure 6.4). Whilst changes in shoot and root biomass that were species-dependent were observed, as supported by Zantis et al., (2023), these differences were only significant for a few of the individual treatments.

Apart from the WH_B treatment in the 2nd year, a non-significant decrease in shoot biomass and length was observed in all wheat mesocosms treated with microplastics by 13.2 – 17.3 % and 9.1 – 16.5 %, respectively. If microplastic concentrations are substantial enough to change soil structure, the resultant changes in nutrient availability and water holding capacity will likely cause crops to adjust the metabolism and growth of the root and shoot network to restore balance. Increased root growth to increase water and nutrient transport and uptake, may have an inhibitory effect on shoot development (Meng et al., 2021; Boots et al., 2019; Zantis et al., 2023). In combination with the potentially toxic effects of microplastics, shoot biomass and length may be suppressed by 13 – 53 % (Li et al., 2022; Liu et al., 2022).

Root biomass was between 3.0 – 24.8 % greater in all spiked treatments, but only significant in one treatment (BB_A). These observations are contrary to Jia et al., (2023), who suggests that microplastic-root interactions are overwhelmingly negative due to direct and mechanical damage. In response to microplastic exposure, root growth may increase to reduce interference and improve nutrient uptake (van Weert et al., 2019). Alternatively, an increase in root biomass and length could be due to a reduction in soil bulk density and aggregate stability caused by microplastics, improving root penetration and development (Li et al., 2022; Liu et al., 2022). An immediate response to the addition of microplastics could decrease above-ground biomass due to the preferential energy allocation to root development (Liu et al., 2022), as observed in the 1st year of all spiked treatments (1.0 – 17.3 %). If changes to the root network are immediate, mycorrhizal associations and water availability could improve within a season, translating to an increase in shoot biomass (Li et al., 2022). An increase in shoot biomass was observed across all 2nd year treatments (3.1 – 38.9 %) apart from the WH_A treatment, consistent with the measurements from the previous year.

Relative chlorophyll content was higher in all of the spiked broad bean treatments (8.3 – 32.8 %), the opposite was observed for spiked wheat treatments (- 2.3 - -20.8 %). The mechanisms behind these changes are largely unknown. It is likely that these differences are the product of physiochemical changes to the soil or an indication of direct microplastic-induced stress (Boots et al., 2019). Metabolites released as a biproduct of microplastic degradation may account for a decrease in shoot biomass, length and relative chlorophyll content (Meng et al., 2022). Differential responses to metabolites have been observed, whilst relative chlorophyll content has been observed to decrease in lower plants, no change was observed in higher plants (Boots et al., 2019).

Microplastics may be taken up by crops and accumulate in plant tissue (Roy et al., 2023; Li et al., 2020a). Given the size of the microplastics used in the study (500 – 600 um), it is unlikely that active transport of microplastics into plant tissue is a mechanism responsible for any of the observed changes. Direct effects of microplastic exposure are unclear, impaired hormonal regulation and excessive production of reactive oxygen species are proposed consequences of microplastic-induced changes to leaf physiology and root pore blockages (Roy et al., 2023; Jia et al., 2023). Microplastics may block root and cell pores, disrupting, limiting nutrient and water uptake, limiting physiological performance. Inadequate nutrient availability has cascading impacts on germination, morphology, growth and photosynthesis (Roy et al., 2023). However, it is well established how changes to the soil environment affect crop development and growth and what the mechanisms are that govern such changes. The observed effects on root and shoot biomass, length and leaf chlorophyll content are likely to be the result of indirect changes to soil structure, aggregate stability, water holding capacity and nutrient availability due to microplastic exposure (Schöpfer et al., 2022; Jia et al., 2023). Generally, the frequency and magnitude of indirect effects are thought to be dictated by certain thresholds (Lin et al., 2020), however it was observed by Brown et al., (2022) that responses to microplastic amendments are not necessarily dose-dependent.

6.4.4. Distribution of microplastics in the soil profile in response to soil and crop type

Significant differences in microplastic concentrations at different soil depths were recorded (Figure 6.5), indicating that the distribution of microplastics in a soil profile is greatly affected by soil and crop type. As expected, no differences were observed in the microplastic concentrations of unspiked treatments as the soil was homogenised before the experiment was conducted. Regardless of crop type, microplastics in the topsoil were comparable. At depths of 15 and 30 cm, microplastic concentrations were higher in cropped treatments, compared to the uncropped control (293.4 – 280.9 and 266.5 - 232.3 particles 100 g^{-1} dry soil, respectively). As suggested by Rillig et al (2017), the production of biopores from plant roots may facilitate the downward movement of microplastics in the soil profile. As a root network develops, the movement, expansion and extraction of water from the roots can contribute to microplastic movement (Ren et al., 2021; Li et al., 2020b). If the root network is deeper, as is the case with wheat in comparison to broad bean treatments (23.0 and 16.1 cm), it is expected that the movement of microplastics is more extensive in the former, as observed (see Figure 6.5). Biological mechanisms responsible for microplastic transport in soils are well established. Earthworms, directly and indirectly increase the movement of microplastics in the soil profile through attachment, ingestion, egestion, casting activity, burrowing and production of biopores (Rillig et al., 2017b; Huerta Lwanga et al., 2016). Even though the soil was screened for earthworms and other macrofauna, it is possible that soil fauna could be partly responsible for microplastic transport in this study.

Soil type was a determining factor of microplastic movement in the soil profile. No significant difference was observed in the topsoil, but at depths of 15 and 30 cm, microplastic concentrations were higher in the silty loam than the sandy loam (9.0 % and 8.5 %, respectively). The physiochemical properties of the soil; organic matter, soil pH, porosity and surface heterogeneity are partly responsible in governing the movement of microplastics (Li et al., 2020b; Ren et al., 2021). The hetero-aggregation of microplastics with organic matter may increase the downward movement of microplastics in the soil profile (Wu et al., 2020). Given that the silty loam had comparably higher organic matter, more bonds are formed between microplastic particles and the organic fraction of the soil via electrostatic attraction, aiding soil aggregate formation (Ren et al., 2021). Even though the sandy loam has a greater porosity, the distribution of microplastics at deeper layers were considerably lower than the silty loam. Microplastic transport in soil is complex and perhaps these observations were the result of the deposition of particles on the surfaces of larger soil particles (collision and attachment), particles that are too large to enter soil pores (pore exclusion), restricted particle mobility in soil pores too small for passage, causing the retention of more microplastics in the upper layers of the soil (straining) (Li et al., 2020b). Similarly, polymer type, shape, size, density and charge are determining factors in distribution due to unique soil-microplastic interactions (Wu et al., 2020; Ren et al., 2021; Rillig et al., 2017a). Micropsheres, as used in this study, are more likely to migrate to greater depths compared to fibers, which are easily entangled and entrained in clod formations (Li et al., 2020b; Zhang et al., 2019). Microplastics used in this study were pristine and do not necessarily represent the characteristics and heterogeneity of microplastic in the field, so results need to be interpreted with care. Tilling was restricted to the topsoil and mesocosms were only destructively sampled after the second growing season to ensure the soil profile was preserved and any observations made on microplastic transport were the result of soil and crop driven mechanisms. Farming practices such as harvesting, tilling and irrigation may distribute microplastics to deeper soil layers, or reintroduce particles into the topsoil that were entrained in clods.

Considering that the movement and distribution of microplastics in the soil profile is, in part, governed by soil and crop type, it must be further explored how microplastics in agroecosystems are preferentially released or retained. Each scenario raises unique ecotoxicological effects, not only on the agroecosystem, but on the wider environment. Accumulation in agricultural soils could directly impact long-term agricultural productivity, whilst the release of microplastics could cause cascading effects on aquatic environments, especially if particles develop biofilms or sorb volatile compounds.

6.5 Conclusion

This study demonstrates how microplastics can directly affect agroecosystems, but also how agroecosystems affect the movement, distribution and ultimately, fate of microplastics. Whilst the direction of effect was not entirely consistent with existing research, this study nevertheless adds to the growing body of evidence that microplastics are not environmentally benign and are capable of directly and indirectly affecting agroecosystem functioning. Whilst most of the differences in soil and crop properties in response to the addition of microplastics were not significant, changes were substantial enough to assume that the effect of microplastics in these environments may be significant over the long-term.

The concentrations used in this study are some of the lowest used in microplastic research, compared to the use of artificially high concentrations in other studies (Lenz et al., 2016; Green et al., 2017; Qi et al., 2021). Although the effects of microplastic pollution are not necessarily dose dependent (Brown et al., 2022), the use of vastly different microplastic concentrations makes it difficult to compare the outcomes from other studies. Following the results of Chapter 4 and 5 and predictions that global plastic use will continue to increase (Zheng and Suh, 2019), it is likely that many of artificially high concentrations will be typical of many environments, but are generally not reflective of the current environment.

The microplastics used in this study were considered pristine, contained no additives and were not subject to any prior degradation. In field conditions, microplastics are weathered, may have adsorbed toxicants and have been exposed to the environment for a greater period of time. The observed effects of microplastics in this study are likely to be the result of the physical interactions with the particle rather than a function of any sorbed or leached contaminants of biological or artificial origin. Although microplastics used in this study were PE, one of the most common polymers found in agricultural soils, the presence and effects of polyvinylchloride, polypropylene and polyethylene terephthalate are equally important polymers (de Souza Machado et al., 2019; Li et al., 2020b). The input of microplastics to agricultural soils is progressive and dependent on the type, rate and application of field amendments and the contribution from atmospheric, fluvial and wind-blown deposition. Given the range and magnitude of microplastic transport to agricultural soils, microplastic inputs to this system may be considered quasi-constant, which influence the direction and scale of a response.

7. General Discussion

This thesis has been crucial to comprehensively assess the use of plastics in agriculture in current and future food systems. Throughout the thesis, it is overwhelmingly clear that plastic use is deeply rooted in agricultural systems globally. It is difficult to comprehend how social, economic and cultural development would be different without the invention of plastics and how the use of the material may influence future development.

Global food systems are under threat from recent geopolitical upheaval, market disruption and the prospect of more challenging growing conditions as a result of climate change in the future. Vulnerabilities in the UK food system have been exposed, most recently during the COVID-19 pandemic and the Russian war in Ukraine (Garnett et al., 2020). The UK food system is reliant on an extended food supply chain, importing produce from nearly 200 countries (Benton, 2017). In turn, the UK is highly vulnerable to disruption and unprepared for external shocks to the food system in the future (Chatham House, 2022). The use of plastic in domestic production buffers against some of these external shocks, guaranteeing the supply of healthy, accessible and high-quality produce.

Whilst the use of plastics in global production systems have enabled progress towards many of the UN's Sustainable Development Goals (SDGs), it has compromised achieving some of these goals in the long-term. Much like other industries, there has been a global call to reduce plastic use in agriculture due to the adverse effects and risks associated with its use (FAO, 2021; WWF, 2019; UNEP, 2021; IPCC, 2021a). An immediate and active approach to reduce the reliance and use of plastics has been observed across industry. In agriculture, the response to this global call has not been as urgent. In many regions, the uptake and use of agriplastics continues to increase, particularly in areas where population increase is steep (FAO, 2021). Globally, agricultural systems continue to favour the short-term benefits of increased crop yield and quality over the risk of compromising long-term agricultural productivity.

According to the planetary boundaries model, where plastics (macro-, micro- and nanoplastics) are classified as novel entities, the only safe operating space is part of a scenario where no plastic exists or is judged to be environmentally inert (Persson et al., 2022). Removing plastics from agriculture is possible, but the immediate effects on global production systems would significantly affect crop yield, as highlighted in Chapter 2. Removing plastic from agricultural production systems, through use of policies, regulations and bans disproportionally affects users from many demographics. Unable to use plastic, many smallholder production operations, particularly in semi-arid and arid regions, would not be successful in meeting the dietary needs of the local population (Zhang et al., 2020). As illustrated in Chapter 3, the use of plastics is deeply entrenched in South and East Asian production systems, where the use of plastic has been a major component of poverty alleviation and resource-use efficiency (Gao et al., 2019; Chang et al., 2013).

In the UK, the use of plastics has promoted the production of seasonally-restricted crops for more months of the year which has driven consumer expectations of year-round supply of better-quality fresh produce. Given that 23 % of fruit and vegetables consumed in the UK are produced domestically (Benton et al., 2017), removing plastic use from domestic agriculture could reduce the yield of important crops by a third, increasing the reliance on international imports, as outlined in Chapter 3. Reducing plastic use in the UK would compromise aims to transform the food system into a localised, communal food system that aligns with social and environmental sustainability, as outlined in the GFS scenarios (Global Food Security, 2021). Restricting access to readily available, nutritious food and eating ‘seasonally’ would require a significant undertaking to reconfigure deeply entrenched societal behaviors and expectations.

Without plastic, agricultural intensification will become more widespread to maintain or even increase food production, to face the challenge of feeding 2 billion more people by 2050 (Hofmann et al., 2023). Given that agricultural systems are already responsible for 29% of GHG emissions, 75% of deforestation, 33% of land-use and 70% of all freshwater withdrawals globally, the implications are increasing food production will further compromise progress towards the UN's Sustainable Development Goals (SDGs) (Hofmann et al., 2023). Whilst Chapter 3 provides new evidence that plasticulture can address the existing issues with the UK food system and improve the accessibility, affordability and availability of nutritionally-rich produce, the life-cycle of agriplastics must be urgently transformed.

As highlighted in Chapter 4, 5 and 6, the use of plastics in agriculture is problematic. The production of plastics is both resource and energy intensive (Zheng and Suh, 2019). In-use and as a waste material, plastics degrade into smaller residues and leach additives bound to the polymer during production (Steinmetz et al., 2016). The incomplete collection of agriplastics, due to inappropriate waste management, both intentional and unintentional, is a significant contributor to the accumulation of plastic residues in agricultural soils, particularly microplastics. Microplastic concentrations were 175.8 % greater in agricultural soils where plastic crop covers were used. Plastic crop covers, particularly plastic mulch films, are significant sources of microplastics in-use and as a waste material to agricultural soils, as identified in Chapter 4. The results from the nationwide survey are crucial to understanding how agricultural systems are receptors of microplastics from plasticulture. Chapter 4 is the first nationwide survey of microplastic concentrations in UK agricultural soils and will be essential to better manage and reconfigure the life-cycle of agriplastics. Additionally, irrigation, fertiliser and the application of other soil amendments are indirect sources of microplastics to agricultural soils, highlighted in Chapter 5. However, sources of microplastic pollution are not exclusive to agriplastics. From the results of Chapter 5, widespread plastic use over time has contributed to the accumulation of microplastics in agricultural soils, increasing from 1966 - 2022. Chapter 5 provides the first evidence that microplastics accumulate in agricultural soils over time from agricultural and non-agricultural sources. Given that agricultural soils are receptors of microplastic pollution from multiple sources, the results from Chapter 4 and 6 are crucial to comprehensively assess risk to long-term agroecosystem functioning and better manage plastic use in agriculture.

Current research indicates that microplastic pollution in agricultural soils affects the physical, chemical and biological properties of soil (Zhang et al., 2020; Tian et al., 2022; Allen et al., 2022). Whilst the reported effects of microplastics are overwhelmingly negative, studies have credited microplastics with nutrient enrichment and improving microbial functioning in soil Blöcker et al., 2023; Rauscher et al., 2023; Li et al., 2020a). The presence of microplastics and associated additives in agricultural soils negatively affects soil quality and health, reducing water and nutrient transport, impacting crop quality and yield. Using the microplastic concentrations determined in Chapter 4, the results of mesocosm experiment in Chapter 6 indicate that microplastics could be responsible for changes to soil and crop health in the long-term, contributing to the current evidence base that microplastics are a future threat to agroecosystem functioning. Similarly, the biological impact of microplastics in soils is unpredictable, but overwhelmingly negative. Microplastics on the smaller edge of the spectrum (< 100 um), are found to impact macro-, meso- and microfauna behaviour, physiology, hormonal function and survival (Zang et al., 2020; Lin et al., 2020). Bioturbation, ingestion and egestion of microplastics are mechanisms for microplastic transport in the soil profile (Rillig et al., 2017b; Rillig et al., 2019) which is partly influenced by crop and soil type, as shown in Chapter 6. Heavy metals and toxicants may adsorb to microplastics, as well as the development of biofilms on the surface of the particle. The accumulation of microplastics in the terrestrial environment also has unknown impacts on food safety, of which the impacts on human health are unclear. As microplastics are transported through the soil profile and even distributed to other environments, ecological and human health may be at significant risk.

Given that microplastic pollution in agricultural soils is expected to worsen over time, as shown in Chapter 5, it is vital to develop a comprehensive understanding of microplastic behaviour and transport in agroecosystems over the long-term. The scale, type and rate of microplastic pollution in agricultural soils is difficult to predict, monitor and model. Even at environmentally relevant concentrations, studies cannot fully capture the complexity of microplastic behaviour and interactions in agricultural soils, as highlighted in Chapter 6. As such, we have limited and varied knowledge of the responses to microplastics in the terrestrial environment, particularly agricultural soils. We conclude that microplastics present a short- and long-term effect on agroecosystems and action is required, not only to reduce the input of microplastics to agricultural soils, but to better manage the legacy of plastic pollution in these environments.

For a future food system to be resilient to external shocks and achieve human and planetary health, sustainable plasticulture must be a pillar of agricultural development. Adopting the 6-R's; refuse, redesign, reduce, reuse, recycle and recover, an approach proposed by the FAO, whilst considering the social, economic and cultural differences in food production by region is essential (FAO, 2021; Hofmann et al., 2023). Most of the emissions associated with plastics are attributed to the production using non-renewable resources. Using renewable energy sources and sustainably sourced raw materials are solutions to making plastic production ‘Net Zero’. Plastics should be designed to optimise recovery, reuse and recycling where possible. In cases where the complete recovery of plastics is not possible, plastics should designed to be environmental inert and biodegrade in a reasonable, defined timescale under realistic environmental conditions (Hofmann et al., 2023). The use of biodegradable plastics is essential to reduce and potentially prevent the accumulation of microplastics, the legacy of historic plastic use from agricultural and non-agricultural sources, as highlighted in Chapter 4 and 5. To avoid further contribution to the ecotoxicological load in agricultural soils from legacy plastic use, the use of environmentally inert polymers and additives is essential.

To underpin and enforce these changes to plastic production, use and waste management in agriculture, appropriate regulatory framework and incentives must be encouraged. The findings of this thesis are key to shaping policies that are legally binding and hold regions from a local-international scale responsible for breaches to codes of best practice. Ensuring that actions to encourage sustainable plasticulture are positive and targets are being met, long-term monitoring of plastic residue concentrations, fate, transport and toxicity in agricultural soils must be encouraged. To mitigate the past, current and future impacts of plasticulture, much of which are not fully understood or quantified, a multi-faceted, multi-disciplinary, responsible and holistic approach to managing plastic use in agriculture is crucial.

7.1 Future Research

This thesis has met the original aims and objectives and contributed to the growing base of plasticulture research. Throughout the thesis, opportunities for future research are highlighted, many of which of essential to comprehensively assess the production, use, management and fate of plastics in agriculture. It is essential that any future research does not operate in individual silos. Interventions must be multidisciplinary, collaborative and engage with a range of stakeholders from a local to international scale, as highlighted in Chapter 3. Here, a few interesting areas of future research are listed:

1. To what extent do different agricultural systems retain or redistribute microplastics?

Chapter 4 and 5 found that agricultural soils are receptors of microplastic pollution from agricultural and non-agricultural sources over time. Combined with the findings from Chapter 6, which indicated that soil and crop type influence the movement of microplastics in the soil profile, it is clear that agricultural soils are sinks of microplastics and sources of microplastics to other environments. However, the rate at which microplastics are retained or released from these environments is unknown. Given that many agricultural landscapes border or are strongly linked to major water courses the release of microplastics from agricultural soils, which may be a vectors for entities of ecotoxicological concern, represent a currently unquantified risk. Therefore, it is vital to identify and understand how farming practices and other agricultural conditions affect microplastic transport to determine risk for agroecosystems and surrounding environments.

2. Can assessments of soil quality provide an accurate estimation of microplastic concentrations, characteristics and transport from different soils?

Chapter 6 highlighted that agricultural systems respond to microplastic pollution differently, expressing a range of positive and negative effects. Even though existing research reports bidirectional effects in agroecosystems, the implications of microplastics in agricultural soils are overwhelmingly negative, even at realistic concentrations. Although it is well-established that microplastics in agroecosystems are strongly linked to measures of soil quality, it is unexplored how soil quality assessments can be used as an indicator of microplastic concentrations, characteristics and transport in agricultural soils.

3. **Opportunities to determine future trajectories of microplastic concentrations in agricultural soils**

Throughout the thesis and wider research it is accepted that long-term monitoring of environments is key to better understanding microplastic fate and risk in agricultural systems. The benefit of long-term monitoring and archives is evident in Chapter 5, enabling the retrospective analysis of microplastics in agricultural soils. Using existing networks and archives, it may be possible to model future trajectories of microplastics in agricultural soils, an area of research currently unexplored. The potential to model changes microplastic concentrations over time is key to identify areas where microplastic pollution may be particularly acute and to better assess the long-term risk to agroecosystem functioning.

4. How does plasticulture fit into future food-system change?

The benefits of plastic use in agriculture are well-established on a global scale, as highlighted in Chapter 3. It is not well understood how plastic applications are used on a local scale outside of commercial enterprises and the potential for these applications to increase the localised production of fresh fruit and vegetables. Focusing on the GFS scenarios presented in Chapter 2 and 3, it must be explored how plasticulture fits into each of these future food-system scenarios and how can these low-cost structures be used to meet the criteria of a future food system that prioritises human and planetary health.

5. Investigating emerging and legacy additives in agricultural soils

Whilst microplastic fate, behaviour and impact is better understood, little is known about the concentrations of additives, such as plasticisers, in terrestrial environments. Many plastic additives are not bound to the polymer matrix and therefore leach into the soil where they may bind strongly to sediment. Whilst Chapter 5 explored the presence and accumulation of microplastics over time, there has not been a comparable time-series analysis of additives in agricultural soils or any other environmental matrices. In addition, it is unknown whether the distribution, mobility and persistence of additives is governed by the biophysical soil environment. Likewise, the impacts of additive exposure in agricultural soils have not yet been comprehensively assessed. Further research needs to be conducted to understand whether the behaviour of additives in soil are comparable to microplastic particles, or whether they behave in a unique manner, independent of the original polymer.

6. An assessment of bioplastic and biodegradable plastic degradation products

In response to the recognition that conventional agriplastics are an issue of global concern, bioplastics and biodegradable plastics have emerged as a more sustainable alternative, introducing a new dimension to modern plasticulture. Polymers such as polylactic acid (PLA), polybutylene succinate (PBS) and polybutylene-adipate-co-terephthalate (PBAT) are emerging as safer alternatives to conventional plastics (PP, PE, LDPE, PVC). However, microplastics pollution from bioplastic and biodegradable plastic may have similar agroecosystem impacts as microplastics from conventional plastics. Biodegradable plastics degrade into microplastics at a much higher rate than conventional plastics. Therefore, biodegradable plastics will, in theory, completely degrade. In comparison to conventional plastics, their persistence and impact is short-lived. However, it is unknown how non-biodegradable components of these novel materials behave in agroecosystems and interact with the biological, chemical and physical aspects of the soil environment. Similarly, knowledge of how the biodegradable components contribute to the formation of novel soil contaminants, of unknown quantities and impact, is absent. Research must focus on the long-term implications of these novel polymers (PLA, PBS, PBAT) in agroecosystems. This data is essential to produce comprehensive assessments of these materials, providing crucial information on whether certain bioplastics and biodegradable plastics are appropriate materials for future food systems.

7. Understanding the mutual interaction between microplastics and properties of agroecosystems

There is limited understanding of how microplastics affect properties of agroecosystems (physical, chemical and biological properties of plants and soil), and how these properties, in turn, influence distribution, retention and mobility of microplastics in agricultural soils. Whilst this concept was briefly explored in Chapter 6, it is this mutual interaction in which microplastics and agroecosystems interact with, and exert mutual influences on, each other, which is largely unknown. In particular, understanding how variable vegetation and crop cover, specifically bioturbation from different root structures, affect microplastic distribution and mobility. Additionally, the impact of microplastics on agroecosystem functioning, considering agroecological endpoints such as soil health and fertility, important symbionts (arbuscular mycorrhizal fungi (AMF) and plant-growth-promoting rhizobacteria (PGPR) and crop health, is yet to be assessed.

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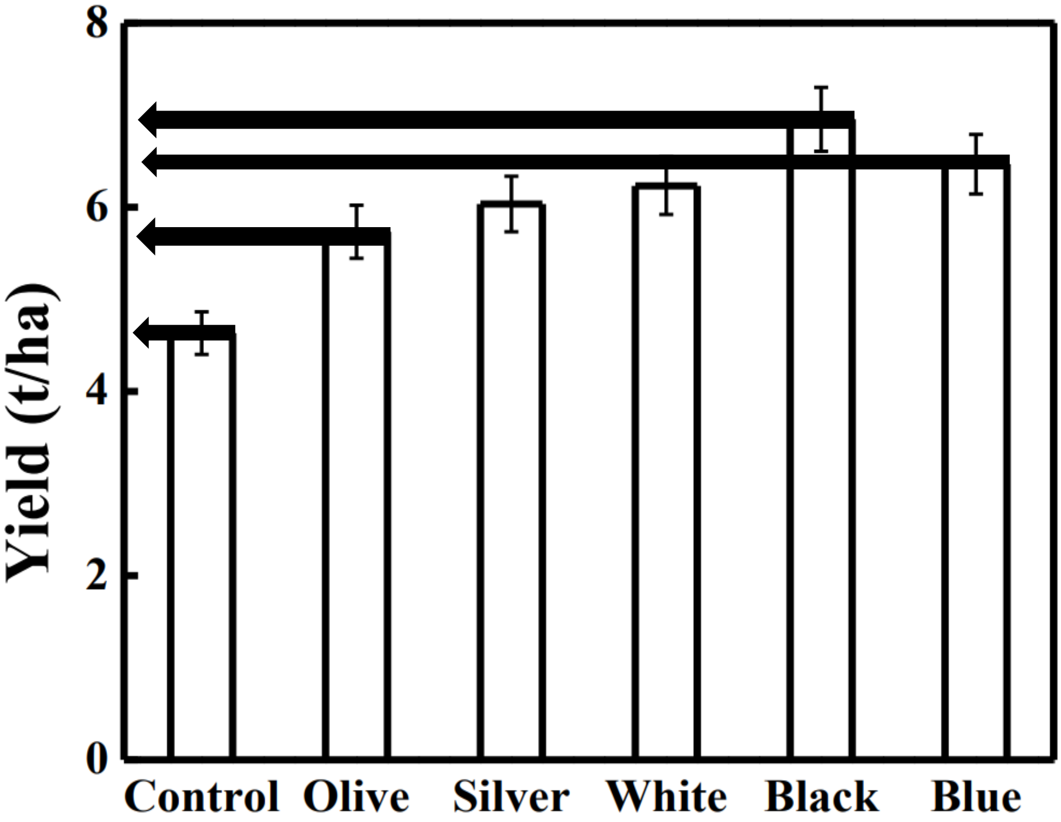
9. Appendix

9.1 Appendix 1: Chapter 3 – Supplementary material



Supplementary Figure 3.1. An example of where data was not presented in an accessible format and was therefore deduced from data points in accompanying figures. For the purposes of interpretation, we use thick lines to extrapolate the data points. A more precise technique was used to collect data used in the meta-analysis. Figure adapted from Sarkar et al., 2018.

Supplementary Table 3.1.

A summary table of all the bias-corrected 95% confidence intervals (CIs) for the categorical variable, crop type.

Crop type	Lower 95% CI	Mean effect size	Upper 95% CI
Carrot	38.57586	48.0788	58.68399
Lettuce	24.322	28.8491	33.7126
Broccoli	43.83496	52.9762	62.92571
Potato	26.39523	28.84442	31.52285
Cauliflower	21.44992	26.91008	32.69073
Strawberry	25.149	27.62491	30.18424
Turnips and Swedes	-1.49029	8.31399	19.34638
Raspberry	25.42179	30.46718	35.58874
Cabbage	37.6115	43.50216	49.52714
Overall	28.8514	30.2972	31.8222

Supplementary Table 3.2.

A summary table of all the bias-corrected 95% confidence intervals (CIs) for the categorical variable, year of study.

Year of study	Lower 95% CI	Mean effect size	Upper 95% CI
<1990	14.437	21.0882	28.7687
1990-1995	49.6046	64.8537	80.2939
1996-2000	24.4377	30.7864	37.8812
2001-2005	24.9471	27.687	30.6004
2006-2010	20.4912	24.383	28.4531
2011-2015	25.4959	28.9684	32.9066
>2015	31.9071	34.2767	36.6878

Supplementary Table 3.3.

A summary table of all the bias-corrected 95% confidence intervals (CIs) for the categorical variable, region of study.

Region of study	Lower 95% CI	Mean effect size	Upper 95% CI
Africa	-15.4422	-6.4477	2.9213
East Asia	24.2259	27.3422	31.3065
Eastern Europe	24.5572	28.106	31.9814
Middle East	34.8111	39.7951	45.0958
North America	28.0484	31.6561	35.3825
Northern Europe	6.603	12.1062	17.7411
South America	22.6207	31.4451	41.4461
South Asia	29.3161	31.7456	34.214
South-East Asia	15.6202	28.2067	40.7122
Southern Europe	28.5968	34.6662	40.7869
Western Europe	29.0225	51.0853	75.8043

Supplementary Table 3.4.

A summary table of all the bias-corrected 95% confidence intervals (CIs) for the categorical variable, type of plastic application used in potato production.

Type of plastic application	Lower 95% CI	Mean effect size	Upper 95% CI
Fleece	6.753	34.512	62.271
Mulch Film	26.085	29.421	32.758
Row Cover	21.9	26.51	31.119
Overall	26.39523	28.84442	31.52285

Supplementary Table 3.5.

A summary table of all the bias-corrected 95% confidence intervals (CIs) for the categorical variable, region of study.

Type of plastic application	Lower 95% CI	Mean effect size	Upper 95% CI
High Tunnel	0.728	12.797	24.867
Low Tunnel	1.593	6.564	11.534
Low and High Tunnel	38.796	45.884	52.971
Mulch Film	18.626	21.564	24.502
Mulch Film and High Tunnel	14.415	37.044	59.673
Mulch Film and Low Tunnel	19.43	23.74	28.051
Overall	25.149	27.62491	30.18424

9.2 Appendix 2: Chapter 5 – Supplementary material

Supplementary Table 5.1. A summary table of microplastic recovery rates. Using a soil sample with a known microplastic concentration (364 particles 100 g^{-1} soil), recovery rates were determined at different dry weights of soil.

Dry weight of soil used for analysis (g)	Microplastic recovery rate (%)
1.5	94.5
5	96.7
25	91.2
50	92.3
100	91.2

Supplementary Table 5.2. A summary table of particles ≤ 10 µm (1.5 g^{-1} soil) in agricultural soil samples collected from the Broadbalk winter wheat experiment from the Rothamsted Sample Archive between 1846 - 2022. Particles ≤ 10 µm were recorded across three treatments a) 2.21 – FYM; farmyard manure at 35 t ha^{-1}, b) 031 – Nil; no soil amendments, c) 081 – N3(P)KMg; 144 kg N ha^{-1}, 35 kg P ha^{-1} triple superphosphate until 2000, 90 kg K ha^{-1} potassium sulphate, 12 kg Mg ha^{-1} Kieserite (35 kg Mg every third year between 1974 -2000).

	Particles ≤ 10 µm (1.5g^{-1} soil)		
	Treatment		
Year	2.21 - FYM	031 - Nil	081 - N3(P)KMg
1846	-	-	39
1856	-	29	-
1865	37	-	-
1881	28	36	38
1893	31	29	36
1914	38	39	44
1936	47	43	45
1944	44	37	40
1966	59	40	49
1987	69	43	60
1992	65	48	58
1997	77	49	57
2000	92	63	61
2005	111	76	79
2010	126	74	89
2015	130	85	115
2020	139	92	128
2022	151	88	153

9.3 Appendix 3: Chapter 6 – Supplementary material

Supplementary Table 6.1. A table of values from the principal component analysis (PCA) of microbial PLFA profiles from unspiked and spiked treatments.

	Component Matrix			
	Unspiked		**Spiked**	
	Component			
	1	2	1	2
NC_A	0.913	0.104	0.886	-0.464
WH_A	0.623	0.728	0.990	-0.142
BB_A	0.608	0.269	0.980	0.198
NC_B	0.885	-0.431	0.767	-0.642
WH_B	0.754	-0.622	0.381	0.925
BB_B	0.900	0.154	0.669	0.743

Supplementary Table 6.2. The influence of crop and soil type on the vertical transport of microplastics. Microplastic concentrations are expressed as particles 100 g^{-1} and presented as mean ± standard error.

		Microplastic concentrations (particles 100 g^{-1})		
		Soil depth (cm)		
Factor	**Treatment**	**5cm**	**15cm**	**30cm**
Crop type	NC	342 ± 28^{a}	266 ± 17^{b}	232 ± 19^{c}
	WH	339 ± 36^{a}	$282 \pm 25^{a,b}$	301 ± 38^{a}
	BB	335 ± 33^{a}	304 ± 21^{a}	260 ± 15^{b}
Soil type	A	333 ± 31^{a}	297 ± 23^{a}	276 ± 45^{a}
	B	344 ± 31^{a}	270 ± 20^{b}	252 ± 25^{a}

Note: Data followed by the same letters within a column indicate no significant difference between treatments at $p > 0.05$.

9.4 Appendix 4: Sustainable Plasticulture in Chinese Agriculture: a Review of Challenges and Routes to Achieving Long-term Food and Ecosecurity

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Alongside the papers presented in this thesis, I was the lead author on the following paper, which was published in *Frontiers of Agricultural Science and Engineering* in July 2023.

(https://doi.org/10.15302/J-FASE-2023508)

Highlights

- Macro-, micro- and nanoplastic pollution in agricultural soils threaten long-term crop production and environmental health in China.

- Resolving the existing issues with plasticulture in China requires holistic solutions that target plastic production, use and waste management.

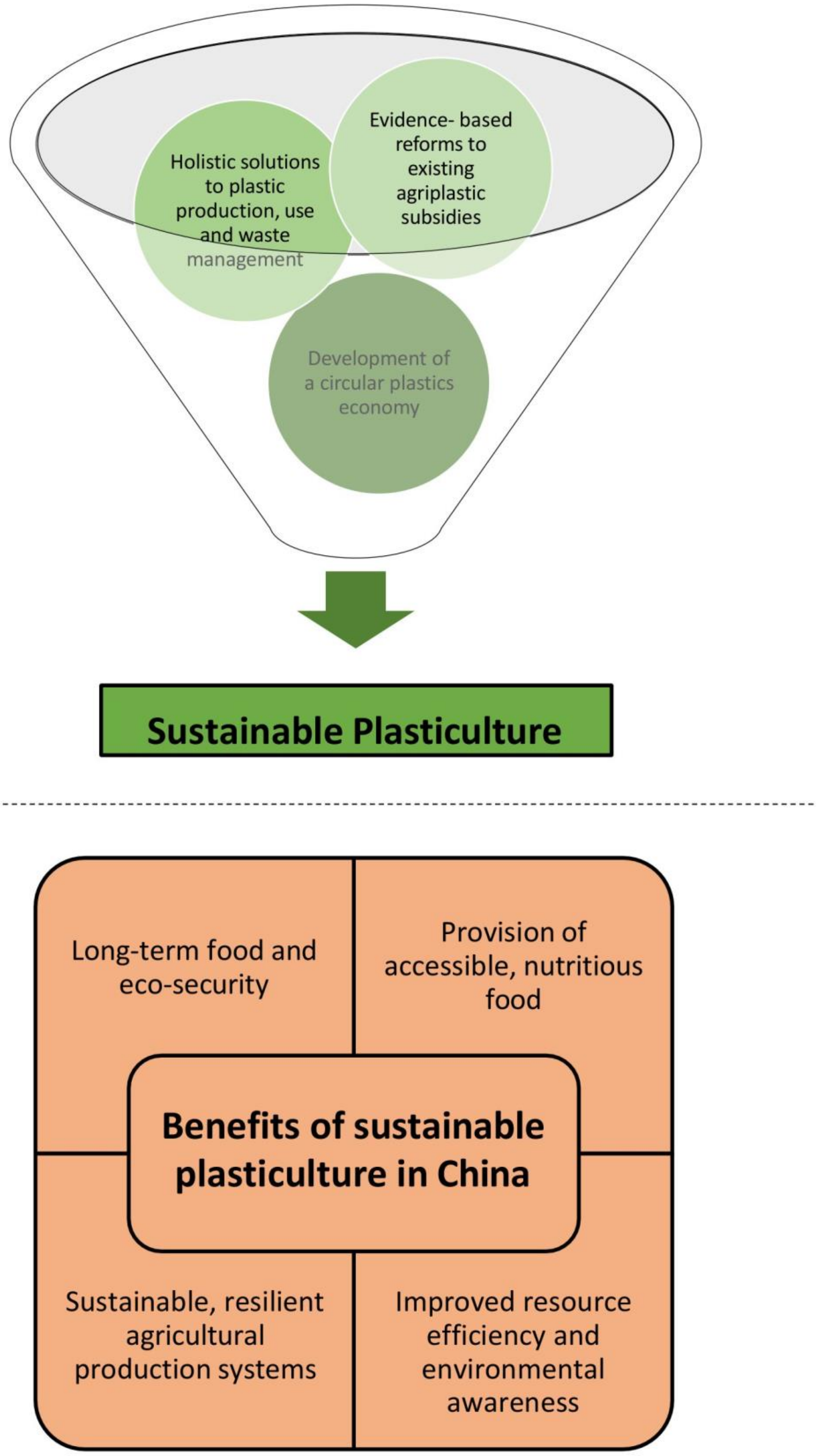
- Mechanisms for change must focus on education, incentivization and the development of infrastructure to positively reinforce the procurement, management and disposal of agriplastics.

- The sustainable intensification of plasticulture in Chinese agricultural production systems is key to achieving long-term food and eco-security in China.

Abstract

Plastic pollution is global concern, affecting most aspects of global food production systems. Plasticulture, a practice used in agriculture to improve crop quality and quantity, among other factors, is a significant source of plastic pollution. This review examines the extent of plasticulture in China, the implications of the practice across decades of use and the legislative instruments used to resolve those issues. It briefly assesses the effectiveness of these policies and proposes possible future innovations to promote increases in long-term food and eco-security, where sustainable plasticulture is a key agent for change. While plasticulture has increased agricultural productivity in growth-limiting conditions, plastic pollution in agricultural soils has become acute in China. Consequently, plastic pollution is having deleterious effects on soil health and in turn, crop productivity in China. Plastic pollution in agriculture is a multifaceted issue and so proposed solutions should be informed by this complexity. Current measures do not reflect a holistic approach to solving this socioecological challenge and adopt a top-down approach, with little or no supportive mechanisms. Future recommendations need to consider the particular set of conditions that influence the production, use and end-of-life management of agriplastics, specific to the environmental, economic and social conditions in each location.

Graphical Abstract



1. Plasticulture: a brief history

Plasticulture, the use of plastic applications in agriculture, has revolutionized agricultural production systems worldwide. Plastics are highly valued in agriculture due to the spectral and material properties, flexibility, low cost and non-toxicity of the material[1,2], although the latter attribute is now widely contested[3,4]. The use of plastics has been crucial to efforts to extend the production of fruit, vegetables and other food crops into periods of the year in which growth conditions are suboptimal[5].

Plastic applications are commonly used, but not exclusive so, in crop production. Greenhouses, polytunnels, irrigation equipment, netting, mulch and silage films are common applications used in global crop production systems. These applications are used for the primary function of increasing the quantity and quality of fresh produce for the consumption by both humans and livestock[6]. Other functions of plasticulture are integral to reduce the overuse of natural resources and agrochemical loads while providing protection against pests, disease and adverse weather conditions[7]. The use of plastics outside of crop production is equally important. The role of plastics in improving the transportation conditions, protection and storage of fresh produce has been fundamental to reduce food waste and increase the supply of good quality food to those who need it[8]. In many regions, the development of plasticulture has come at a critical time when countries are struggling to meet the nutritional and dietary needs of growing populations. Plasticulture is a useful technique to future-proof production systems against increasingly common events such as temperature extremes, droughts, geopolitical instability and supply chain disruption[8,9].

Plasticulture is a global practice, largely concentrated in Asia. By volume, China is the largest producer and user of agricultural plastics, consuming over 7.2 Mt of agriplastics per year[8]. Plastic use is common in many agricultural systems employed in China. Although it is well established that plasticulture has driven an increase in agricultural productivity and food security in China, it is now widely accepted that decades of widespread, and in some cases unavoidable plastic use, have led to unintended environmental effects in both the aquatic and terrestrial environments[4,8,10–12]. Although most plastic residues in aquatic systems originate from the terrestrial sources, little is known about the source, presence, fate and impacts of plastic residues in the terrestrial environment[13].

Emerging research suggests that the accumulation of plastic film residue is negatively impacting crop productivity and soil physiochemistry, jeopardizing the sustainability of future crop production in China[3,14] and in many other parts of the world[15]. Progress toward resolving this issue is being made. Standards for biodegradable mulch film have been developed, prohibiting the production, sale and use of thin mulch film (< 0.01 mm). Regulations have been introduced which encourage the use of high quality, thicker plastic films that can be reused and recycled, as summarized in Table 1.

Table 1. Main policies, strategies and legislative instruments to address plastic pollution in China

Mechanism	Description
Law of the People's Republic of China on Promoting Clean Production, 2002	Agricultural producers are encouraged to use agricultural films in a scientific way to improve agricultural productivity, while preventing agricultural environmental pollution.
Circular Economy Promotion Law of the People's Republic of China, 2009	This law was established to raise resources utilization rate, protect and improve the environment and sustain development.

Soil Pollution Prevention and Control Action Plan, 2016	This action plan strategized improvement of the recycling of abandoned agricultural film, revise standards for agricultural film thickness and test the viability of degradable alternatives to reduce plastic pollution in soil.
Biodegradable Mulching Film for Agricultural Uses (GB/T35795-2017), 2017	Following the promotion of biodegradable mulch films, this standard was created to evaluate the performance, safety and characteristics of biodegradable alternatives. The standard specifies the requirements for production, use and the management of biodegradable mulch films.
Soil Pollution Prevention and Control Action Plan, 2018	This is a development on the previous action plan to make 95 % of polluted arable land safe for use by 2030. By 2020, more than 80 % of all agricultural plastic waste should be recycled. Farmers responsible for plastic pollution in soil must bear the costs of investigating, remediating and managing soil contamination.
National Mulch Film Standard, 2018	This standard requires the thickness of agricultural mulch film to be no less than 0.01 mm, to reduce soil pollution and improve collection rates.

Soil Pollution Prevention and Control Action Plan, 2019	Updated regulations that require the use of thicker, better quality mulch film that remains structurally intact once used. The action plan bans the production, sale and use of mulch film with a thickness less than 0.01 mm. Mulch film should be reused, collected and recycled where possible. Incentives are to be provided to encourage the use of biodegradable mulch.
Notice on making solid progress in the treatment of plastic pollution, 2020	This notice requires that each province should provide a detailed and feasible plan to improve the recycling of waste agricultural film. Provinces should investigate and punish those producing or using agricultural film with a thickness less than 0.01 mm.
China’s National Green Agriculture Development Plan, 2021 (14th Five Year Plan)	The plan aims to strengthen the control of plastic pollution from plastic agricultural films. An increase in the collection rate of agricultural plastic film to 85 % by 2025 is expected. This plan includes the development of pilot projects for agricultural pollution control as well as the supervision and provision of guidance to better manage and control agricultural pollution.

It is increasingly difficult to detach plastic use from agriculture without compromising agricultural productivity. Current food production systems are so reliant on plastic that production systems without plastic in particular parts of the world could potentially show increased susceptibility to climate extremes at particular times of the year and further contribute to global greenhouse gas emissions[6,15]. Instead of recommending the abandonment of plasticulture, we explore the viability of a future food system that promotes food and eco-security, where the sustainable use of plastic is a key component of the food production process.

Here, we explore the condition of the current agricultural system and discuss the legacy of current and past plasticulture practices in China. With knowledge of the positives and negatives associated with plasticulture, we recommend techniques to help farmers manage agriplastic waste and remediate plastic pollution, on farm and in the wider environment without compromising food production. We propose adaptations to an established plastic-intensive production system compatible with Agricultural green development (ADG) techniques to form a more inclusive and sustainable method of future food production in China, reducing the environmental effects of plastic use in agriculture from production to disposal[16-19].

2. Plasticulture: a key contributor to the rise of agricultural productivity in China

There is little doubt that the food production system in China has benefitted enormously from the introduction of plasticulture over the past 40 years. Faced with feeding a growing population from a diminishing area of agriculturally productive land due to widespread development of housing and industry, water scarcity, soil erosion and desertification[20,21], plasticulture has become a widely used technique to deliver high crop productivity per unit area of cropping. Semiarid and arid regions represent 37 % of the total area of China, where two-thirds of the local population is in poverty[21]. An example of which is southern Xinjiang, characterised by limited water resources, a high poverty rate and slow economic development[22]. The use of plastic mulch in China is thought to increase crop yield by 25 % – 42 % in the immediate season, largely as a response to increase in soil temperature and moisture (+ 8 % and + 17 %, respectively)[14]. In China, the development of plasticulture has equipped farmers with a relatively inexpensive means to improve yields, particularly under water-scarce conditions[11].

Nationwide, the use of plastic mulch has translated to a 45.5 % increase in crop yield across 51 crop species[23]. Ridge-furrow mulched systems, where ridges are covered by plastic mulch and the furrows are left bare or laid with straw, have delivered an 84 % increase in crop yield[23]. This increase is of international and domestic importance. As the world's largest producer of potatoes, the use of plastic applications, primarily mulch films, has led to an increase in potato yield exceeding 24 % between 1989 and 2017[24]. Similar rates of increase in crop yield have been observed across a range of grain and cash crops due to the application of plastic mulch films[10,11]. In 2012, the use of plastic film in grain production (maize, rice and wheat) resulted in a 30 Mt increase in production volume[23].

Plastic mulch films are typically laid over the soil before planting or shortly after to induce localized soil warming, conserve moisture, provide weed control and accelerate the germination of crops (Fig. 1). To monitor the crop and apply field amendments these films are briefly removed and re-laid until the crop has matured. At this stage, mulch films are either removed, ploughed into the soil, or left to degrade as the crop grows through. Although it is well established that the use of plastic applications has been successful in improving crop quantity and quality in China, the effectiveness of plastic applications is highly dependent on the environmental, social and economic conditions in the region[15]. In arid regions, greenhouses can provide protection from scorching, heavy rainfall events and dust storms (Fig. 2). However, these structures are not as effective at retaining heat and buffering the diurnal temperature variation compared to more complex structures and are therefore not suitable to grow frost-sensitive crops or for use in colder regions. Novel polymers in more complex systems modify the incoming solar radiation to manipulate the micronutrient content of the crop and improve taste, quality and aesthetics[5], but can also create a favourable environment for fungal development[15].

Fig. 1 Plastic mulch film used for maize cultivation in northwestern China. The mulch film is left to degrade into the soil once the maize crop grows through the film and matures.

Fig. 2 Steel-framed, multilayered polyvinyl chloride covered greenhouses used for the production of fruit and vegetables in spring and autumn. The plastic film is buried in the ground to secure the structure.

The success of plasticulture in Chinese agriculture has driven an increase in the volume of agriplastics and the area of arable land covered by plastic. From 1981 to 2010, the area of arable land covered by plastic in China rose from 4.2 kha to 28 Mha of which 19.8 Mha were covered by plastic mulch films[7,10,25]. The area of arable land covered by plastic mulch films has significantly increased in China, growth rates of 30 % a year have been observed, eclipsing the 5.7 % global annual growth rate[1]. In 2012, the area of land covered by plastic mulch films accounted for 13 % of cropland in China[23]. In 2015, the total amount of agricultural film used in China was above 2.6 Mt, of which the amount of plastic mulch film was 1.45 Mt. At this time, national agricultural film recycling rate was less than 66 %[26]. Models suggest that the use of plastic mulch films in China will increase to 2.28 Mt by 2025, covering 23.4 Mha[4]. The cost of plastic film per mu (~0.07 ha) varies depending on the coverage and thickness of the plastic film. For example, if a plastic film with a thickness of 0.008 mm is used to implement half-film coverage (at least 50 % soil cover), the average amount of plastic film applied is 4.8 kg·mu–1 with an investment cost of 70 yuan, whereas the use of a plastic film with a thickness of 0.012 mm that is used for full-film coverage (complete soil cover), has an average weight of 8.4 kg·mu–1 and an investment cost of 120 yuan[27].

Crop growth in China is widely limited by water stress and plastic mulch helps to minimize water loss from the soil thereby increasing water availability to the crop. In conjunction with a ridge-furrow system, plastic mulch can increase water use efficiency, that is, crop yield produced per unit of water used by the crop, by 106 %[23]. Generally, the greatest economic benefit of using plastic applications in China, particularly mulch film, is due to improved water use efficiency[1]. Farmers anticipated a saving of up to 25 % of their total water budget when plastic mulch film was applied to fields[28]. Not surprisingly, the effect of plastic mulch on water-use efficiency and a corresponding economic saving are more pronounced in regions where annual precipitation is lower[23]. The use of plastic applications does not necessarily translate to higher returns for the farmer. In some cases, the acquisition and removal of the plastic applications can be costly, negating the savings from reduced resource consumption (e.g., water, fungicides, and herbicides)[1]. To reduce the cost of agricultural production, state administered prices for mulch film, compensation for increases in price of mulch film and subsidies for residual film recycling have been provided[29]. Many of these support mechanisms were not statewide and have now ceased or are significantly reduced, which is similar to the heavy subsidy and overuse of fertilizers, pesticides and water, all of which are now recognized to compromise long-term agricultural productivity in China[17,18].

The incompatibility of some crops with plastic mulch film has triggered a shift in cultivation patterns across semiarid and arid regions in China, particularly Gansu, Inner Mongolia, Ningxia and Xinjiang regions. Traditionally, families in this region practice subsistence agriculture to meet their own nutritional needs, primarily wheat cultivation. Due to acute water scarcity in many regions, a government-mandated irrigation quota further restricts the water use of individual farmers[28]. A combination of both has led to a shift from more waterintensive grain production to the cultivation of cash crops suitable for the use of mulch, such as cotton, maize and potatoes. Plastic mulch film is often placed on the soil before planting to warm the soil and create a favourable environment for growth. Crops are then planted through punctures in the mulch film which then germinate, grow through the film, and mature, leaving plastic residues in the soil as the structural integrity of the mulch film is often compromised[10,14]. Semiarid and arid regions such as northern China, rely on the use of plastic applications more than humid regions in southern China. The use of plastic greenhouses has increased since the 1970s, covering an area over 3.3 Mha, accounting for over 90 % of plastic greenhouses worldwide[30]. Plastic greenhouse use is concentrated in semiarid provinces, such as Henan, Hubei, Shaanxi and Shandong, and are critical to maintaining and increasing productivity in regions with diminishing availability of arable land. In this context, where desertification is increasingly prevalent, plastic greenhouses provide a vital role in soil retention, optimizing fertilizer application and provide protection against dust storm events[30]. Plastic greenhouses are relatively inexpensive, easily-erected and require little management, making an ideal method of cultivation for smallholder farmers[31]. The use of both plastic greenhouses and plastic mulch film has been integral to alleviating the degree of poverty in many semiarid and arid regions of China. The income of farmers in Sanyuanzhu, Shouguang County, increased by 68 % annually, coinciding with an increase in the use of plastic greenhouses[30]. Plastic mulch films are often designed to last for a single growing season and then ploughed or left to disintegrate in the field, whereas plastic greenhouses are generally replaced every 3 years and are easier to recover and recycle post-use. If these applications are well-managed in use and as a waste material, the almost immediate benefits of this practice should, in theory, continue to have an effect. However, the continuation of traditional practices in parallel with the unsustainable use and inappropriate waste management of plastic applications has impeded and, in some cases, is beginning to reverse decades of agricultural progress (Table 2).

3. Issues with plasticulture: production, use and waste management

Plastics, throughout their lifespan, represent a relatively unknown environmental, ecotoxicological and human health hazard. The majority of plastics in use are produced from fossil-fuel feedstocks, which inherently contributes to the rising levels of greenhouse gas emissions[33]. Although agriplastics represent only 2 % – 3.5 % of annual global plastic production, the degradation and contamination of these applications in the environment raise significant waste management and pollution concerns[19,34]. Globally, 16 % – 50 % of all agricultural plastic waste (APW) is not managed[8], although it has been suggested that these rates are higher in China[35]. Given that 80 % of all marine plastics are thought to originate from terrestrial sources[36], mismanaged APW can be a significant source of pollution to the marine environment.

By design, many of the plastic applications used in Chinese agriculture do not exceed the duration of the crop cycle or are reused irresponsibly when the structural integrity of the application is clearly compromised[14]. As the thickness of plastic mulch film used within China is typically thin (0.01 mm), relative to that used in Europe and the USA (0.015–0.20 mm), mulch films can degrade shortly after use and it is therefore more difficult, time-consuming and costly to recover this material from the field[10]. Contamination of mulch films limits the amount that can be recycled with up to half the weight of such recovered films consisting of soil debris and inorganic amendments, and such material is often rejected by the operators of recycling facilities. Considering that most films are used in areas of water scarcity, cleaning the plastic application is unlikely to be a viable option. As a result, a significant portion of these films is left on the field and are often incorporated into the soil. As a result, a significant portion

Table 2. Average annual growth rate of agricultural production and plastic use in China

Average annual growth rate (%)	1952–1977	1978–1985	1986–1995	1996–2005	2005–2016
Gross value of agriculture	2.48	6.29	4.22	4.35	4.55
Grain	2.91	3.35	2.16	0.51	2.24
Cotton	5.07	12.21	2.75	2.81	-0.03
Oil seeds	2.13	18.00	4.12	3.36	1.74
Sugar crops	9.34	14.87	2.84	3.27	2.79
Vegetables	*	*	*	8.32	3.23
Fruits	3.88	6.97	14.13	17.96	5.27
Livestock	5.26	10.77	9.38	7.44	3.43
Aquatic products	13.10	9.44	14.82	7.58	5.03
Mechanization	*	8.61	5.64	6.60	3.41
Irrigated land	*	-0.30	1.14	1.11	1.83
Fertilizers	*	10.69	7.32	2.88	2.10
Pesticides	*	*	9.26	3.04	2.04
Plastic greenhouse area	*	*	*	65.0	13.3
Plastic mulch film area	*	*	44.26	12.4	8.33

Note: data extracted from Chang et al. and Yu[30,32].

of these films is left on the field and are often incorporated into the soil. Additionally, the inadequate provision of waste-management facilities and a lack of knowledge on how to appropriately handle end-of-life agriplastics, both in China and worldwide has contributed to the pollution of agricultural soils, water courses and beyond[37,38].

The issue of plastic pollution is particularly acute where plastic mulch film is used. It is well established that this application is the primary source of plastic residues in agricultural soils within China[39]. Although plastics used in greenhouse cultivation can be easily recovered and reused, due to the lack of contamination, films used in this way are still a source of environmental concern. Once the plastic has served its use in the field (a single season for mulch but perhaps two or three seasons for greenhouse film), these films are often buried, burned or discarded on farm, releasing toxic byproducts, posing a threat to air and soil quality[40]. The reasons behind these decisions are well-known and are relevant to agriplastics and other agricultural waste products, that is, a lack of experience and environmental awareness, and often technical guidance available to farmers is minimal. Combined with a lack of economic compensation and the lack of infrastructure to collect, sort and transport plastic applications, farmers have limited options to appropriately handle APW[38]. In recent years, the use of mulch film in the Gansu, Hebei, Shandong and Xinjiang regions has increased. By 2010, 6.96 Mha of arable land in Gansu was covered by mulch film as part of a double-ridge-furrow system, amounting to 100 kt, 80 % of which became agricultural plastic waste within a year[41]. The thickness of domestic agricultural mulch film is only 0.006 – 0.008 mm, much thinner than the 0.02 mm standard in the USA and some European countries[10]. Thinner film is cheaper to produce but has a lower tensile strength and therefore loses its structural integrity more quickly, readily degrades and is harder to recover. As the recovery of waste agricultural film is labour-intensive and the mechanized recovery of waste is poor, the mechanized recovery rate can be less than 15 % in some areas[41]. Although efforts have been made to regulate the thickness of plastic films used in agriculture and enforce the collection and recycling of plastic applications globally, there is little evidence to suggest that the accumulation of plastic residues in agricultural soils worldwide is being reduced.

Once plastic residues are incorporated into the soil, any further degradation is slow as the residue is no longer exposed to the conditions that trigger photodegradation. In such contexts, plastic residues could potentially remain for decades until mechanically, chemically or biologically degraded[1]. Due to a combination of inadequate waste management and the slow degradation rate of plastics in the environment, plastic residues have begun to accumulate in the terrestrial environment, particularly agricultural soils[3,4,8,10,11,42]. The load of plastics in agricultural soils is compounded by other inputs such as plastic-coated fertilizers, farmyard manure, agricultural machinery, slurry and atmospheric deposition from dust storms. The fragmentation of plastic residues, from macroplastics to microplastics, can be accelerated where the soil is subject to high intensity machine tillage[43].

It is well established that the concentration of plastic residues (macro-, micro- and nanoplastics) in agricultural soils across China are of great concern. Due to the lack of standardized analytic procedures, reporting the concentrations of plastic residues in agricultural soils yields a range of results. Metaanalyses have reported that the concentration of plastic residues in agricultural soils across > 700 sites averaged 34 $\mathrm{kg\cdot ha^{-1}}$, in some cases exceeding 380 $\mathrm{kg\cdot ha^{-1}}$ [7,14]. From 25 % to 33 % of plastic mulch film applied each year can remain in the field[44]. This, accompanied with a slow degradation rate, has led to the progressive accumulation of plastic residues in the soil, averaging 51.9 kg $\mathrm{ha^{-1}}$ in cases where plastic mulch film has been used for 20 years or more[14]. Due to the longstanding use of plastic mulch film, the residue load in north-western China and on the North China Plain is the highest recorded in China. Microplastics, defined as plastic particles < 5 mm, have been reported to range between 320 and 42,960 particles $\mathrm{kg^{-1}}$ in farmland soils across China[45–47]. Although macroplastic pollution in China is thought to be acute in comparison to other agricultural environments, published quantities of microplastics in similar environments are comparable. For example, 3500 particles·kg^{-1} was detected in Chile, 500 – 7659 particles kg^{-1} in Valencia and 71,000 – 145,000 particles kg^{-1} in Danish agricultural soils[48].

4. The impact of agriplastic pollution on soil, plant and human health

Quantifying the impact of plastic residues (macro-, micro- and nanoplastics) on environmental, ecological and human health is complex. Due to the difficulty in point-source tracing, it is hard to discern whether an observed impact is the direct result of agriplastic pollution. During the production of agriplastics, a host of additives and plasticizers are integrated into the polymer, depending on the material characteristics required for use. As these chemicals are often loosely bound to the polymer, and can be released into the environment shortly after use and accumulate in the soil[4]. Consequently, it is difficult to separate the effects of the plastic residue and that of the additives that are integrated into the polymer.

The proposed effects of plastic pollution on crop production are multifaceted. The microbial, physical, chemical and structural properties of soil have been observed to change as a function of varying degrees of contamination. In highlycontaminated soils, macroplastics can compromise soil structure. Here, nutrient and water transport is limited, negatively affecting the water holding capacity of the soil, which can lead to soil anoxia[4,10], one of the most damaging of soil conditions for all crop plants. Anoxia will negatively impact seedling emergence and the establishment of a root network. This has been shown to reduce the yield of the cotton crop by 4 % – 19 % [7,10]. Based on a meta-regression, plant height has been shown to decrease at a rate of 2 %, root weight by 5 % and crop yield by 3 % as plastic residues in soil increase by 100 kg·ha^{-1}[14]. Laboratory-based experiments suggest that the impacts of these changes increase markedly as macroplastic load increases[14]. Micro- and nanoplastics can accumulate in plant tissue through sub-micrometre openings in roots[49]. In such contexts, particles and additives have a negative effect on plant physiology. The diffusion of additives, notably diisobutyl phthalate, into mesophyll cells disrupts chlorophyll formation[7,50]. Other studies have observed that germination, height, biomass and root length in cereal and cash crops are negatively impacted by the presence of macroplastics and microplastics[51].

Under both plastic mulch films and greenhouses, soil health and fertility are threatened. Although, plastic covers protect soil from water erosion and weathering, farmers often manage these systems in a similar way to open-field grain crops, often leading to the overuse of fertilizer[10,30,31]. The accumulation of residual salts, particularly NO3 −, has led to soil salinization and acidification in many of these systems[31]. Compared to open-field systems NO3 −, K+ and Ca2+ concentrations were 265 %, 224 % and 139 % higher[31]. Under these conditions, the soil microbial community is reshaped, inhibiting crop growth, production, and quality[52]. In areas which practice flood irrigation or receive isolated heavy rainfall events, the leaching of these residual salts can pollute surface and groundwater systems[53]. The impact of plastic pollution on soil chemistry and nutrient cycling is poorly understood. Evidence has suggested that plastic residues in soil can affect carbon and nitrogen cycles and the consequent release/sequestration of greenhouse gas emissions[51,54]. Meta-analyses have shown that soil available phosphorus and soil organic matter are negatively impacted by plastic residues, decreasing at a rate of 5 % and 0.8 %, respectively, as residue concentrations increase by 100 $\text{kg}\cdot\text{ha}^{-1}$[14]. In some cases, the use of plastic greenhouses has led to an increase in plant-available N, P and K, although, the underlying mechanisms for these changes are unknown[30]. A consensus has not been reached on whether plastic residues in agricultural soils have a direct net positive or negative impact on nutrient cycling.

The presence of microplastics in soils is known to negatively impact the reproduction, survival and weight of soil organisms[51,55]. Earthworms serve a vital role in maintaining soil health and quality. When exposed to microplastics, earthworms have higher mortality and lower growth rate, which is thought to be the result of changes in the gut microbiota[56]. With less available energy due to microplastic ingestion, earthworm activity and density are lower, resulting in less soil mixing and reduced soil fertility and nutrient availability[57]. Changes in the structure and activity of the soil microbial community, and likewise the micro-, meso- and macrofauna, can influence the decomposition of soil organic matter and carbon sequestration, both positively and negatively[58]. In some cases, the presence of microplastics is thought to increase root biomass, soil enzyme activity and the bioavailability of Zn[51,59]. The understanding of the mechanisms responsible for these positive impacts is poor. Effects of plastic pollution are dependent on the concentration, chemical properties, shape, and exposure time to the plastic residue, all of which are magnified in higher trophic levels[60].

Therefore, it is difficult to establish critical limits of plastic residue contamination at which impacts, both positive or negative, are observed. Leaching of additives and plasticizers from plastic residues and the sorption of toxicants, heavy metals and agrochemical inputs poses a threat to aquatic and terrestrial food webs and ultimately human health[3,43]. The use of phthalates as plasticizers, particularly polychlorinated biphenyl, can have deleterious effects on the soil microbial community, directly affecting the endocrine system[61]. The uptake of phthalates in crops has been widely reported, for example, diethylhexyl phthalate (DEHP) has been observed to be taken up by the roots of vegetable and grain crops and translocated to stems and leaves[62]. In 2017, mulch and greenhouse films in China contributed to the release of 42.2 and 24.5 t DEHP, respectively[12]. The severity of this bioaccumulation raises human health concerns, particularly for children. It is thought that human exposure to DEHP is 4–17 times higher from vegetables grown under plastic greenhouses in China, than the EU[63]. Due to the size of smaller residues (micro- and nanoplastics), the bioaccumulation of particles in food, among other things, can expose humans to plastic loads exceeding 100,000 particles per day[49,64]. Microplastics and nanoplastics, due to their size, are able to pass through cell membranes and accumulate within human tissue[65]. An disconcerting amount of evidence has identified the presence of microplastics in human faces, gut tissue, and placenta[66,67]. It is difficult to determine whether these particles have any direct impact on human health. Proposed effects are similar to those caused by nanomaterials and particulate air pollution, including inflammatory and oxidative stress, cytotoxicity, autoimmune response and DNA damage[65,67].

The extent of effects from plastic pollution in agricultural soils, and the accompanying mechanisms, remains largely unknown. However, the known effects already threaten the long-term food security of communities dependent on many agricultural systems, due to potentially irreversible soil degradation and impacts on human health[68]. Considering that plastic pollution is more acute in north-western China, a region that suffers from water scarcity, desertification and a range of other climate change impacts, the impacts of all these pressures can disproportionally affect those in the region who largely depend on production from their own smallholdings.

5. Current solutions to plasticulture

In 1997, China’s Ministry of Ecology and Environment began to focus on the prevention and control for plastic pollution from the agricultural use of mulch films. In response to an increasingly acute problem, a management framework to address plastic pollution was established as part of the Soil Pollution Prevention and Control Action Plan, 2016. Later iterations in 2018 and 2019 aimed to increase the recycling rate of agriplastics to more than 80 % by 2020 and introduce regular soil testing to encourage a shift to less harmful practices, a key mechanism for reducing plastic pollution[69,70]. As a consequence of their nature, plastic films are clearly contributing to a growing plastic pollution crisis. The use of thicker film reduces the time and labour required to retrieve plastic film from the field after use and encourages reuse, if structurally intact. In 2018, only 21 % of plastic mulch film in use met the previous national standard of 0.008 mm and 66 % of all plastic film was not recovered after use. Therefore, in September 2018, the Chinese Government proposed that mulch film for agriculture should be a minimum thickness of 0.010 mm, thought to reduce the amount of residual mulch film by 60 %[70]. This, among other mandatory national standards to improve the production, sale, use, recycling and reuse of agricultural film, were introduced as part of a measure to protect and improve the agricultural environment in China[71] (Table 1).

Much of the production and use of plastic film is decentralized and spread across a vast area of China and it is difficult to regulate and enforce legislative changes with the limited resources available to the state[72]. In such contexts, the local market supervision, agriculture and rural affairs department are responsible for the investigation and enforcement of breaches to the national standards of agricultural film production and use. In 2022, the government of Hebei Province proposed that 3 million mu (~210,000 ha) of thicker mulch film with a higher tensile strength and 500,000 mu (~35,000 ha) of fully biodegradable mulch should be procured and applied to cropland[73]. By 2025, it is expected that the mulch film recovery rate in Hebei will exceed 85 %, and the residual amount of mulch film in farmland will achieve zero growth. Farmers growing crops that are extensively covered by mulch film (cotton, maize and vegetables) will be encouraged to use thicker, reinforced mulch films with a minimum thickness of 0.015 mm to improve the recyclability and recovery rate of agriplastics.

Forming a scientific rationale and standardized guidance for the promotion and use of plastic mulch film alongside clear rights and responsibilities for recycling agriplastics with appropriate governance will be effective at controlling plastic pollution and integrating sustainable plasticulture at a provincial level. These unprecedented approaches to reducing plastic production, use and pollution at a national and provincial level targets a wider range of plastic products at a higher administrative and legal level, promoting research into the development of alternative products over the next 5 years[72]. While other countries have introduced legislative mechanisms with limited range or scope to control agriplastic pollution on a nationwide to individual scale, China's nationwide, provincial and community approach has the potential to create a circular plastics economy and better control domestic and international plastics pollution.

Active research is focused on developing biodegradable, environmentally benign plastic film. Although these films offer a promising alternative to currently-used agriplastics produced from fossil-fuel feedstocks, the short- and long-term effects of these materials are relatively unknown[74]. Following an urgent need to reduce residual mulch pollution in croplands in China, the promotion and application of biodegradable mulch film is a necessary development. In Hebei, the use of biodegradable mulch films which meet the national standard GB/T35795-2017 will be trialed on garlic, peanuts and potatoes to test the feasibility of widespread promotion on suitable crops[73]. Biodegradable mulch films are typically made from polysaccharides (such as starch), cellulose, chitin or polyesters (such as polylactic acid) and polybutylene adipate terephthalate. Most variations of biodegradable films are optimized to undergo photodegradation or microbial degradation and are often prefabricated. Novel biodegradable mulch films can be sprayed onto the soil surface for easier application, faster degradation and this material is less labour-intensive to recover[75]. In theory, once the biodegradable plastic film has fulfilled its purpose, it should undergo complete degradation into biomass, carbon dioxide and water. However, biodegradation takes place in the soil under suboptimal conditions in comparison to optimal, well-defined laboratory conditions[1]. It is not known whether the use of biodegradable mulch films contributes to microplastic and nanoplastic pollution in agricultural soils.

The nationwide implementation of biodegradable plastic film is limited by the high cost of the material and the lack of a commercially feasible production systems[7,76]. Currently-used plastic mulch film can cost 10,000 yuan t^{-1}, whereas biodegradable film could cost between 25,000 and 30,000 yuan t^{-1}[44]. Consequently, there is a call from industry for the government to subsidize the research and development, and to encourage the use of biodegradable mulch film by farmers and enterprises in the plastics industry. Equipped with the knowledge that biodegradable films, in theory, will ensure sustainable agricultural development, farmers are keen to use these in replacement of currently-used mulch films where economically viable[29]. As the majority of farmers in China are smallholders operating on small-profit margins, many continue to use the prohibited, thinner film, due to its low cost and the better perceived quality[14].

Without widespread financial and behavioural measures to support existing policies and legislative instruments, an urgent transformative change in the agriplastics industry has not been achieved and seems unlikely in the foreseeable future. These policies and regulations target singular aspects of the life cycle of plastics. The FAO has recommended that new laws should regulate all aspects of plasticulture, the production, use and end-of-life management to practice sustainable agriculture[8].

6. A role for sustainable plasticulture in AGD

The impact of plasticulture can jeopardize soil health, crop quality, food security and sustainability of agricultural systems in the long term[1]. In recognition of these impacts, there has been a call to significantly restrict or ban the use of plastics in agriculture. China, much like other countries, has become reliant on plasticulture to feed a growing population with accessible, nutritious and sustainable food. Meeting these demands is a growing concern in China given that water scarcity and desertification is projected to increase[20]. The prevalence of diabetes and obesity is rising, each affecting over 10 % of the population[77]. Given that the Chinese administration has prioritized the improvement of the capacity to grow, handle and store fresh produce, and to reduce food waste, it is therefore expected that plastic use in agriculture will continue to increase[77]. It is not a question of whether plastic use should increase or decrease within the Chinese agricultural system, but rather, how can it be better managed.

To better manage plasticulture through production, use and waste management the Chinese agricultural system requires evidence-based solutions. Policies, regulations and subsidies must be both precautionary and practical, requiring collaboration between scientists and policy, to support farmers to enhance ecosystem services, produce sufficient amounts of fresh produce and reduce the detrimental impacts of plastic use[30,77]. Given the diversity of environmental conditions, agricultural practices and social, cultural and economic landscape across China, solutions must be tailored to the province, local government and village to be most effective.

Waste-management infrastructure must be further developed. The historic exportation of highly-contaminated and non-recyclable APW from the EU and USA to China has been problematic. To reduce the environmental concerns of largely unregulated and often illegal APW, China introduced the National Sword policy in January 2018 to better manage and regulate waste imports. The legacy of this relationship still exists as many of agriplastic recycling facilities in China are designed to process agricultural plastic waste imports and not domestically-produced agriplastics. A nationwide assessment of plasticulture must precede the widespread implementation of waste-management infrastructure. Identifying where inappropriate plastic use, waste generation and pollution is most acute will be integral to the strategic distribution of such infrastructure. The process of recovering, sorting and recycling agriplastic waste must not place a financial burden on the farmer or be excessively time consuming. The design and implementation of accessible, simple waste facilities with sufficient economic compensation is key to increasing rates of reuse and recycling[8,29,78].

To remediate plastic pollution from past, current and future use, subsidizing the provision of recovery machinery for both individual farmers and rural communities might be effective in reducing plastic pollution and improving recycling rates[14]. The integration of recovery equipment into ploughing machinery would improve the separation of plastic residues from complex root systems and increase the efficiency and volume of recovered agricultural plastic waste[79]. Plastic recovery machinery must be able to operate effectively on complex terrain and with the wide variety of crops currently grown in China. Where recovery machines cannot be purchased by individual farmers due to financial constraints, these machines could be purchased at the village level as a collective. In the absence of dedicated recovery machines, the manual removal and recycling of plastic residues could be coordinated at the village level, conducted at the end of the growing season.

The recycling practices of farmers in China are largely influenced by informal institutions, more so than formal institutions such as government[80]. The role of village regulations has an important role in dictating farmer behaviour[71,81]. The regulation of plastic film thickness, use and waste management could be an effective mechanism to promote sustainable plasticulture. Where formal institutions lack the capacity to effectively enforce the plastic film standards, rewards and penalties implemented at a village-scale could generate positive change regarding the purchase, use and end-of-life management of agriplastics[71,82]. To encourage sustainable plasticulture, comprehensive policy should be introduced to suit the environmental, economic and social conditions in each area.

A lack of environmental awareness, experience in agriplastic waste management and technical guidance are key barriers to sustainable plasticulture[69]. Education, engagement, and guidance are important mechanisms in driving change. Equipped with the knowledge of how to prepare agriplastics for recycling with minimal contamination, the recovery and recycling rates of agriplastics by individual farmers might greatly increase. Reducing the contamination of agriplastics at source decreases the loss of soil and nutrients from the topsoil and alleviates the financial burden on farmers and recycling facilities to remove impurities from the waste plastic before it is processed. The Chinese government should encourage farmers to use codes of best practice, whereby any plastic used should have no impact on the immediate and wider environment[78]. Targeted campaigns should seek to increase environmental awareness of farmers in areas that are non-compliant to existing regulations or experiencing severe levels of plastic pollution. Campaigns should actively engage young farmers, equipping the next generation of farmers with the expertise and knowledge to better manage agriplastics in use[69].

Evidence suggests that farmers who have expressed environmental conscientiousness, recognize that plastic film has negative implications for soil health and were less likely to use mulch film[69]. Instead of abandoning plastic use, farmers can work to a set of criteria that has benefits for long-term food and eco-security. Providing guidance on how to handle agriplastics sustainably could have corresponding benefits for the sustainable use of fertilizer, pesticide and water. In parallel, providing farmers with more stable property rights could empower individuals to consider the long-term implications of how they use and manage plastics, instead of being driven by the short-term, economic benefits of the material[69]. Giving farmers greater stewardship over their land encourages investment into improving soil health, quality and environmental awareness over the continuation of unsustainable practices[77,83].

All of these solutions require investment and funding to be effective. Enforcing the extended producer responsibility principle on agriplastics producers would assist farmers in procuring agriplastics and managing their agricultural plastic waste, through education, appropriate financial support and provision of waste-management facilities. In such contexts, the responsibility of end-of-life plastics is shared between the producers, distributors and users proved to be effective in parts of Europe[78]. In parallel, investment is required from centralized and decentralized sources, a nationwide to local government approach, reflective of the environmental conditions, agricultural practices and the social, cultural and economic landscape.

Agriculture in China is experiencing a set of multifaceted pressures which threaten to compromise food and eco-security targets. A solution to these issues could rely on the sustainable intensification of agriculture through new ADG programs launched the Chinese government and supporting universities[16,84]. Plasticulture, as a form of intensive agriculture, has been proven to produce more food, using less land and fewer inputs. As discussed, plasticulture can result in a wide range of negative consequences. There is scope to adapt current production systems and introduce mechanisms to mitigate the existing issues with this practice. The solutions we present here rely on a multifaceted, holistic, collaborative approach to remediate the existing issues with plastic pollution and waste management. The removal and recovery of plastic residues from the soil must take priority. Without immediate action, plastic pollution is likely to compromise a range of ecosystem services and long-term agricultural productivity. From an individual farm to a regional scale, mechanisms for change must be complementary, focusing on education, incentivization and infrastructure. Some of the environmental concerns associated with plasticulture could be addressed in the short-term by widespread dissemination and adoption of codes of best practice[78]. A long-term vision of sustainable plasticulture is desirable. Chinese policymakers must urgently consider how plasticulture is likely to shape the future of agricultural systems and consequently the food security and safety of the nation, both positively and negatively.

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8. References

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