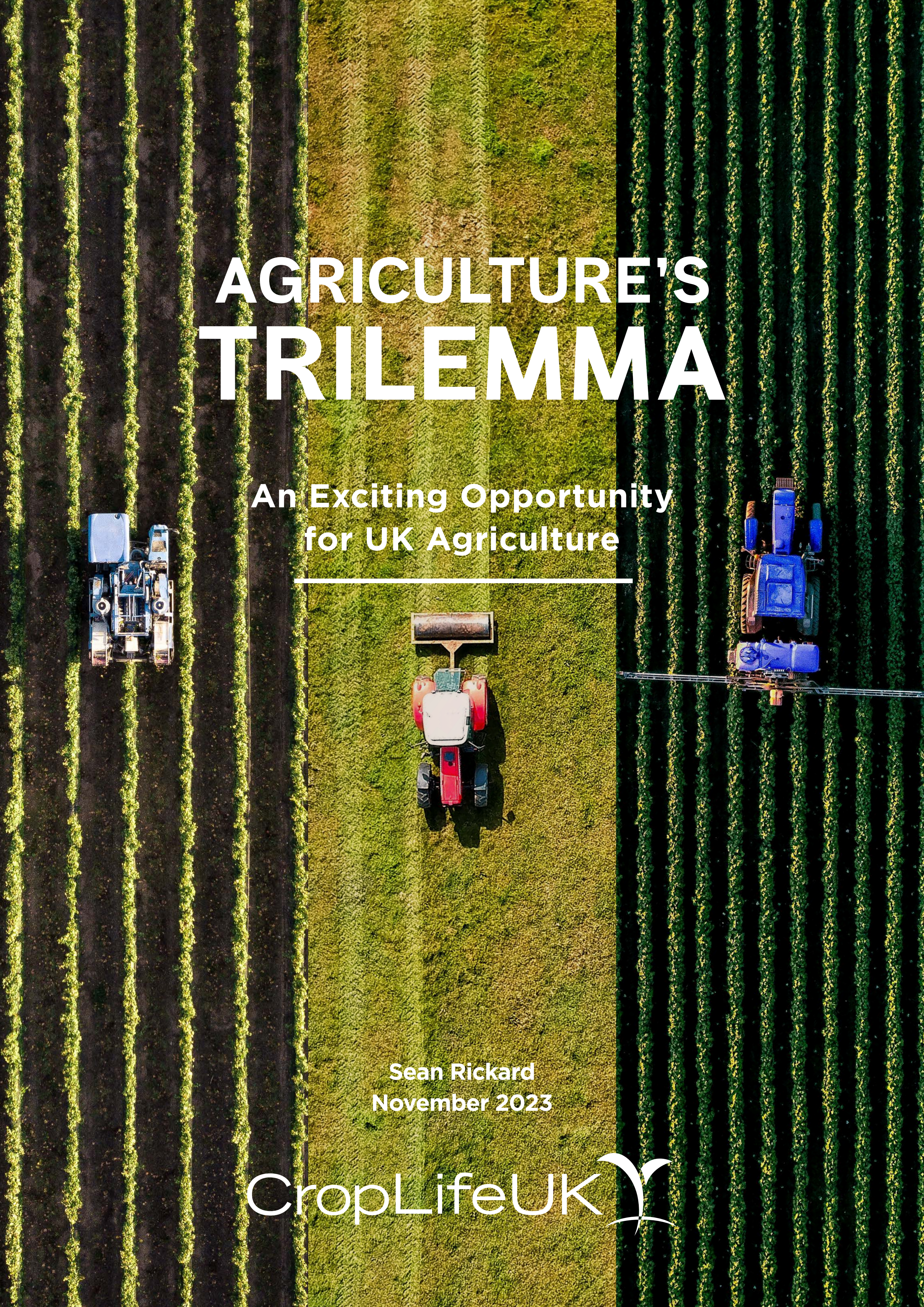

AGRICULTURE'S TRILEMMA

An Exciting Opportunity for UK Agriculture

Sean Rickard
November 2023

CropLifeUK

Executive Summary

The world faces a major challenge in achieving universal food security, that is access at all times to sufficient, affordable, safe, and nutritious food. The global population continues to rise and is growing richer, accelerating the demand not only for a greater volume but also a wider variety and higher quality of food. To match this growth of demand farm outputs must rise, but in order to protect the world's biodiversity this needs to be done without increasing the total area of agricultural land. This places the burden of reducing the risk of food insecurity on yield growth, particularly crop yields. However, if yields are to grow, they must overcome a number of severe biophysical threats including climate disruptions, depleted soil productivity and increasingly limited access to groundwater. Further, agriculture must join other industries in reducing its net greenhouse gas (GHG) emissions if the world is to meet the UN's target of Net-Zero by 2050.

UK agriculture is not immune to these three challenges. The last 15 years have witnessed increasing volatility in global food prices and food security. Food inflation has reached record levels and retailers have experienced supply shortages; outcomes previously considered low risk. Consequently, the issue of food supplies and affordability has moved up the political agenda. At the same time there is growing concern relating to biodiversity loss and declines in ecosystem services. As regards climate change, agriculture is not only vulnerable to its adverse impacts but also responsible for a substantial proportion of UK GHG emissions and committed to meeting a 2050 target for Net Zero.

Agriculture is a science-based industry, never better demonstrated than the 1960s Green Revolution when farmers gained access to new varieties of cereals the higher yields of which depended on synthetic fertilisers and plant protection products (PPPs). Today, science is again called upon to deliver another revolution to meet agriculture's trilemma. A consensus has emerged that meeting future food demand will not only require continued intensification i.e., yield growth, but also that this must not involve further loss of biodiversity and ecosystem services. The need for intensification to be ecological sustainable has given rise to the neologism, sustainable intensification, which involves elevating yields on existing croplands so as to avoid expansion on to non-agricultural land thereby protecting biodiversity and the scope for carbon sequestration. It further involves the adoption of farming practices that minimise the use of inputs to avoid negative impacts on local ecosystems and reduce GHG emissions.

The world faces a major challenge in achieving universal food security, that is access at all times to sufficient, affordable, safe, and nutritious food.

Agriculture is a science-based industry, never better demonstrated than the 1960s Green Revolution.

Crop yields, or more correctly their levels and resilience, are influenced by a number of factors including plant breeding, weather, and soil fertility but also managerial skills and practices. Critical to the success of sustainable intensification is the security that crops receive the appropriate protection necessary for them to achieve their potential. This necessitates not only the economic efficacy of plant protection products and methods but also their constant evolution. Practices associated with the Green Revolution have now progressed such that modern farming systems, where appropriate, adopt integrated pest management (IPM), a broad-based approach that integrates both synthetic and biological forms of protection.

Sustainable intensification came to prominence in the first decade of the 21st century coinciding with advances that enabled the fusing of information and engineering technologies to deliver what has become known as precision agriculture. The use of the Global Positioning System provided agricultural equipment with a much-enhanced ability to gather site-specific information on the regenerative needs of soils and the health of crops in order, using automation, to control, inter alia, the precise application of nutrients and PPPs in the pursuit of optimisation. Inextricably linked in the pursuit of maximising yields, sustainable intensification and precision agriculture provide the rationale and means to restrict the use of variable inputs in order to avoid damage to local ecosystems and minimise GHG emissions.

Agriculture now stands on the cusp of a new scientific and technological revolution, generally referred to as Agriculture 4.0, whereby biological, digital, and engineering technologies are integrated to enhance agricultural processes and products. Information collection is central to computing and Agriculture 4.0 takes this ability to unimaginable vast amounts of pertinent information—'Big Data'—that are necessary to facilitate disruptive technologies such as genome editing, nanoparticles, artificial intelligence (AI) and machine learning. Further, the connectivity permitted by the Internet of Things (IoT) allows devices and machines to autonomously exchange data and commands, creating 'cyber-physical production systems' capable of acting independently of human intervention. In essence, Agriculture 4.0 offers to greatly enhance agricultural productivity, a necessary condition for food affordability.

More broadly, Agriculture 4.0 promises a revolutionary step-change in the ability of precision agriculture to deliver sustainable intensification. The embedding of Agriculture 4.0's technologies in agricultural products and systems will deliver crops that more effectively utilise applied nutrients as well as PPPs with augmented efficacies. It will further enable agriculture to take full advantage of a new generation of crops and PPPs, by bringing heightened levels of sophistication and efficiency to identify and precisely target nutritional and protection needs in soils and plants. Central to this revolution will be higher crop yields and realising their potential will not be possible without synthetic PPPs. Hence, for the foreseeable future the development of synthetic protection products and application methods will remain integral to sustainable intensification, the more so given the pest threat that climate change is projected to have on cropping systems.

The widespread adoption of precision agriculture, incorporating Agriculture 4.0 technologies and agronomic techniques, will also generate potential growth opportunities for the UK agri-food chain. The government's post-Brexit policy of 'Global Britain' has, at its heart, the support and encouragement of free trade, and in this context growth opportunities can only be realised if the UK agri-food chain is internationally competitive. Productivity growth and high standards at the farm level, are necessary conditions for international competitiveness, but they are not sufficient. To succeed in dynamic, global food markets, UK food manufacturers will need more than the boost of Agriculture 4.0 technologies to the timely delivery of quality products at affordable prices. Across the world, burgeoning, urban middle classes are increasingly revealing a broadening demand for distinctive food products whose differentiation extends beyond experience attributes such as taste and convenience to credence attributes such provenance, safety, and ethical production.

The adoption of sustainable intensification, supported by Agriculture 4.0's technologies and agronomic techniques, offers scope to build on the UK's positive credence reputation by improving key aspects of ethical production; namely, food safety, environmentally friendly and carbon neutral production. The evidence suggests that by credibly exploiting credence attributes to differentiate its food products, the UK's agri-food chain is likely to improve its international competitiveness. However, as credence attributes are largely delivered at the farming stage of the food chain this will necessitate providing consumers with greater transparency and traceability along the agri-food chain. In short, based on Agriculture 4.0 technologies, UK agriculture stands on the threshold of a new renaissance in food production capable of providing the UK food-chain with a potential competitive advantage.

The British government has put on record its ambition for the UK to become a world leader in agricultural technology, innovation, and sustainability and this report has set out how the realisation of this ambition promises a solution to the trilemma now facing agriculture as well as creating opportunities for the agri-food chain. The urgency of the situation calls for a speeding up in the pace of the take-up of these technologies, and this requires a wide ranging, joined-up strategy on the part of government including an updated regulatory environment as well as greater incentives for investment and skills training.

Finally, we are well aware that the widespread adoption of the technologies and farming operations set out in this report must command broad based social support. Until recently in the UK the issue of affordability has not been emphasised in public discussions of agriculture. Recent events have served to remind that this, alongside safety and quality, remains the priority for food production. What is required is an open and balanced debate regarding the benefits of a high-tech agricultural industry in solving the trilemma facing agriculture. We hope this report contributes to such a debate.

> The urgency of the situation calls for a speeding up in the pace of the take-up of these technologies, and this requires a wide ranging, joined-up strategy.

CONTENTS

The world's agricultural industries face three production challenges. The first is to significantly increase food production in order to reverse a deteriorating outlook for global food security and meet the rising demand from populations growing steadily in numbers and affluence for access at all times not only to sufficient, safe, affordable, nutritious food but also for greater variety and higher quality.[1]

The second challenge is to achieve this increase in production using methods that are protective of the ecosystem services of agricultural land while maximising non-agricultural areas of natural vegetation and forestry to deliver the highest levels of biodiversity-richness. The third challenge is to reduce agriculture's net GHG emissions and meet the commitment to become a Net Zero industry by 2050.[2,3]

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[1] FAO, (2006), Food Security, Policy Brief, Food and Agricultural Organisation, Rome, No. 2, June

[2] OECD/FAO, (2022), OECD-FAO Agricultural Outlook 2022-2031, OECD Publishing, Paris, available at, https://doi.org/10.1787/f1b0b29c-en.

[3] Falcon, W., et. al., (2022), Rethinking Global Food Demand for 2050, Population and Development Review, Vol. 48, No.4, pp921-957

Introduction

Experts expect the demand for agricultural commodities to rise by more than 50 per cent by 2050, and to avoid further damage to global biodiversity while maximising the land area available for carbon sequestration this must be achieved without an overall expansion of the world's agricultural area. It follows that output per unit of agricultural land will need to steadily increase; that is, yields, and particularly crop yields, must continue to rise a process defined as intensification. This recognition has given rise to the neologism, sustainable intensification, to describe systems of production where agricultural yields are increased without adverse environmental impacts and without the conversion of additional non-agricultural land.[4] It is a system that rests on science and technology in areas such as plant breeding, the efficacy of farm inputs, and the precision of farming operations to deliver ecological sustainable productivity improvements. That is, persistent gains in the efficiency of resource use whereby the total agricultural area may actually decline, and variable inputs are limited to yield-maximising levels thereby avoiding damage to local ecosystems and supporting progresses towards Net Zero GHG emissions by 2050.[5]

UK agriculture is not immune to these challenges. The last 15 years have witnessed increasing volatility in global food prices and food security. Food inflation has reached record levels and consumers have experienced food shortages—outcomes that were previously considered low risk. Consequently, the issue of domestic food production has moved up the political agenda. At the same time there is growing concern relating to biodiversity loss and declines in ecosystem services including river pollution. As regards climate change, agriculture is not only highly vulnerable to its adverse impacts but also responsible for a substantial proportion of UK GHG emissions and therefore under pressure to adopt farming and land management practices that will help the country meet its 2050 target for Net Zero.

This report has as its primary purpose to explain the critical role of crop yields to sustainable intensification as a solution to the trilemma outlined above. It will further argue that for the foreseeable future achieving and sustaining higher yields will only be possible with the support of synthetic plant protection products (PPPs) to control potentially large losses due to weeds, pests, and diseases;[6] a risk that is heightened by increased climate variability.[7] However, its primary purpose is to explain that despite previous harm, going forward there need be no contradiction between reliance on PPPs and the protection of local ecosystems and the world's biodiversity. We will explain that the combination of precision agriculture and advanced technologies promise to unlock a revolutionary step that has the potential to improve agricultural yields while simultaneously fostering a more harmonious connection between intensification and environmental equilibrium.

What follows, is separated into four sections. **Challenges Facing Food Production** provides an overview of the trilemma now facing global agricultural industries; namely, the prevalent expert view that food security must be achieved without further harm to the natural environment and also the mitigation of climate change. It explains that in finding a practical solution, a consensus has formed around sustainable intensification and implicitly the necessity to increase crop yields. **Sustainable Intensification and Plant Protection** explores the nature of sustainable intensification and in particular, why it is the only realistic way that agriculture can simultaneously rise to all three challenges. It explains how the combination of sustainable intensification and precision agriculture will enable PPPs to maintain their critical role in helping yields achieve their potential while becoming more benign with respect to the protection of local ecosystem services and climate change.

Seizing the Opportunities of Agriculture 4.0 introduces what is known as the 4th Agricultural Revolution but now more generally referred to as Agriculture 4.0. After a brief summary of the transformative technologies involved, it discusses how advances in these areas will serve to reinforce the consensus that sustainable intensification is the practical way forward. Recognising that PPPs will remain crucial to a strategy of sustainable intensification, the section will outline the step change the new technologies underpinning Agriculture 4.0 promise in plant breeding and importantly, precision agriculture's ability to simultaneously deliver advances in the areas of yield growth, the protection of biodiversity and local ecosystems as well as climate change mitigation. **The fifth section** provides a brief introduction to the role that Agricultural 4.0 technologies could play in driving the international competitiveness of the UK agri-food chain. It also warns that in the absence of a more joined-up industrial agricultural production strategy the country is in danger of lagging behind its competitors in the take-up of agriculture's 4th revolution.

Experts expect the demand for agricultural commodities to rise by more than 50% by 2050.

The last 15 years have witnessed increasing volatility in global food prices and food security.

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[4] Pretty, J. and Bharucha, Z., (2014), Sustainable Intensification in agricultural systems, Annals of Botany, Vol 114, No.8, pp1,571-1,596

[5] Defra, (2023), The Net Zero Growth Plan and our farming offer, https://defra-farming.blog.gov.uk/2023/04/06/ /

[6] Oerke, E-C., (2006), Crop losses to pests, Journal of Agricultural Science, Vol. 144, No. 1, pp31-43.

[7] Brown, M., et. al., (2015), Climate Change, Global Food Security, and the U.S. Food System, available at http://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf.

Challenges Facing Food Production

Despite many years of impressive advances in the production of food the outlook for the world is one of deteriorating food security; that is, access at all times to sufficient, safe, affordable, nutritious food. Hopes that food security would begin to improve as the world emerged from the Covid-19 pandemic are not being realised; world hunger has continued to rise, and projections are that some 670 million people will still be facing hunger in 2030—8 per cent of the world's population.[8] Although the rate of growth is slowing the latest projections estimate that the world's population will rise by 21 per cent (1.7 billion) to reach 9.7 billion by 2050.[9] Over the same period the demand for agricultural commodities is expected to rise by more than 50 per cent, reflecting in part the likelihood that the use of biofuels will increase in the future,[10] but chiefly population growth and the fact that as people escape relative poverty their diets involve a larger volume and variety of foods. There exists a positive relationship between economic development and demand for diets richer in animal-sourced proteins; thus, the global livestock sector will have to rise to the challenge of producing more meat, milk, and eggs. For example, a recent study estimates that the consumption of poultry meat will rise 130 per cent by 2050.[11]

670mil. people will still be facing hunger in 2030—8% of the world's population.

High yielding livestock production—especially monogastric species such as poultry and pigs—is reliant on cereal crops such as wheat, barley, and maize. It follows that crops, directly and indirectly, underpin all food systems and the fact that in most countries agricultural output has kept pace with rising demand has overwhelmingly been due to persistently rising yields, particularly cereal and rice yields. This success was the outcome of the post war transformative 2nd Agricultural Revolution, more generally known as the 'Green Revolution'. The 'revolution's' significantly increased crop yields, which was achieved by breeding smaller, hardier versions of common crops e.g., dwarf wheat, that could more efficiently utilise fertilisers. However, achieving and sustaining these higher yields was only possible with the support of synthetic PPPs to control potentially large losses due to weeds, pests, and diseases.[12] For example, in the early stages of crop growth, the use of herbicides to control weed infestations is essential for boosting yields and consequentially the desired social and economic benefits.[13]

Figure 2.1 summarises the forces outlined above that determine the balance of supply and demand on global crop markets. As discussed, the demand for crops reflects not only global population growth but also, as

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[8] FAO, (2022), The State of Food Security and Nutrition in the World 2022: Repurposing food and agricultural policies to make healthy diets more affordable, Rome, FAO IFAD, UNICEF, WFP & WHO, https://doi.org/10.4060/cc0639en

[9] UN., (2022), World Population Prospects 2022: Summary of Results, United Nations Department of Economic and Social Affairs, Population Division.

[10] OECD/FAO, (2022), op. cit.

[11] Falcon, W., et. al., (2022), op. cit.

[12] Oerke, E-C., (2006), op. cit.

[13] Kraehmer, H., (2014), Herbicides as Weed Control Agents: State of the Art: I. Weed Control Research and Safener Technology: The Path to Modern Agriculture, Plant Physiology, Vol. 166, No. 3, pp1119-1131.

Figure 2.1: Determinants of Food Security

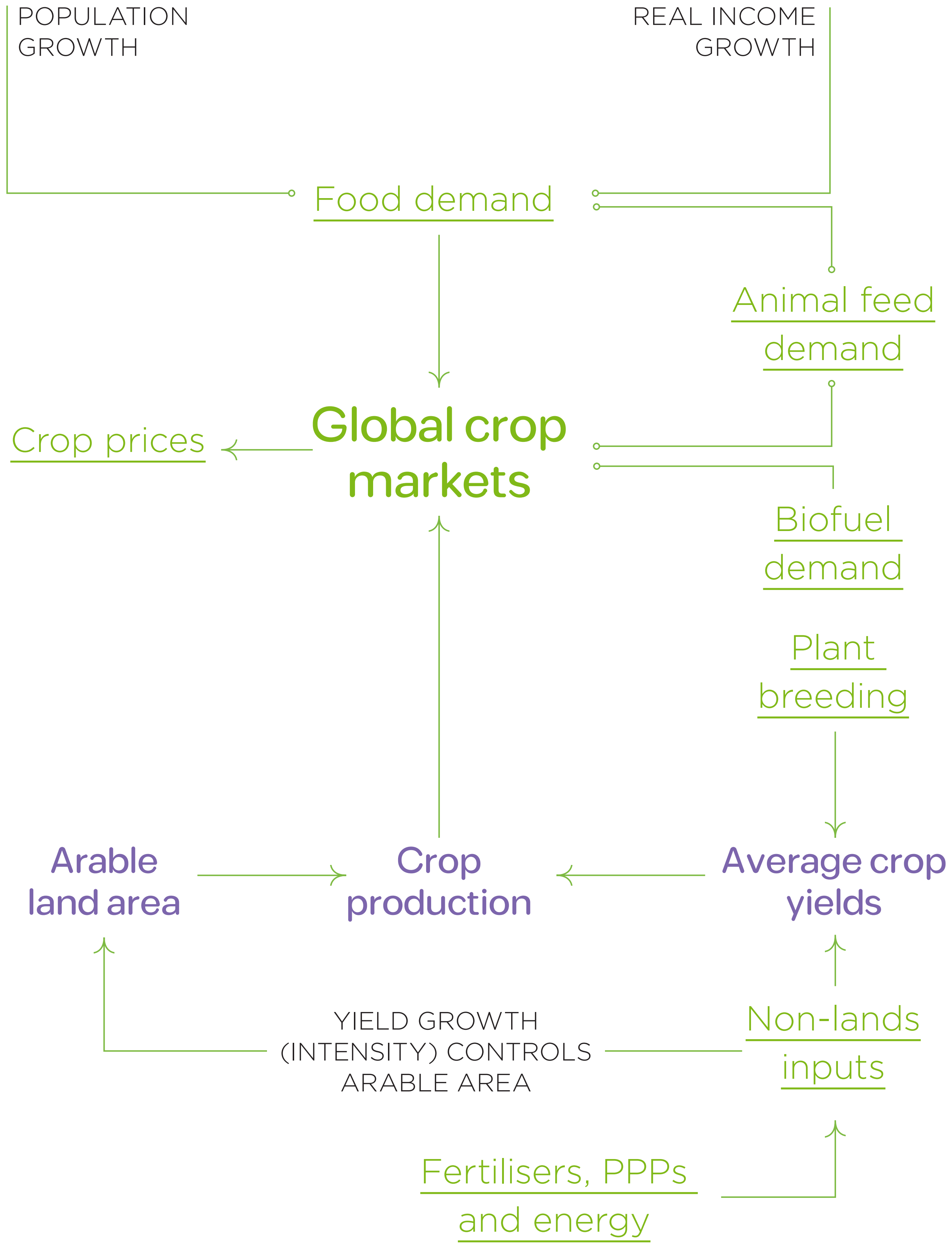
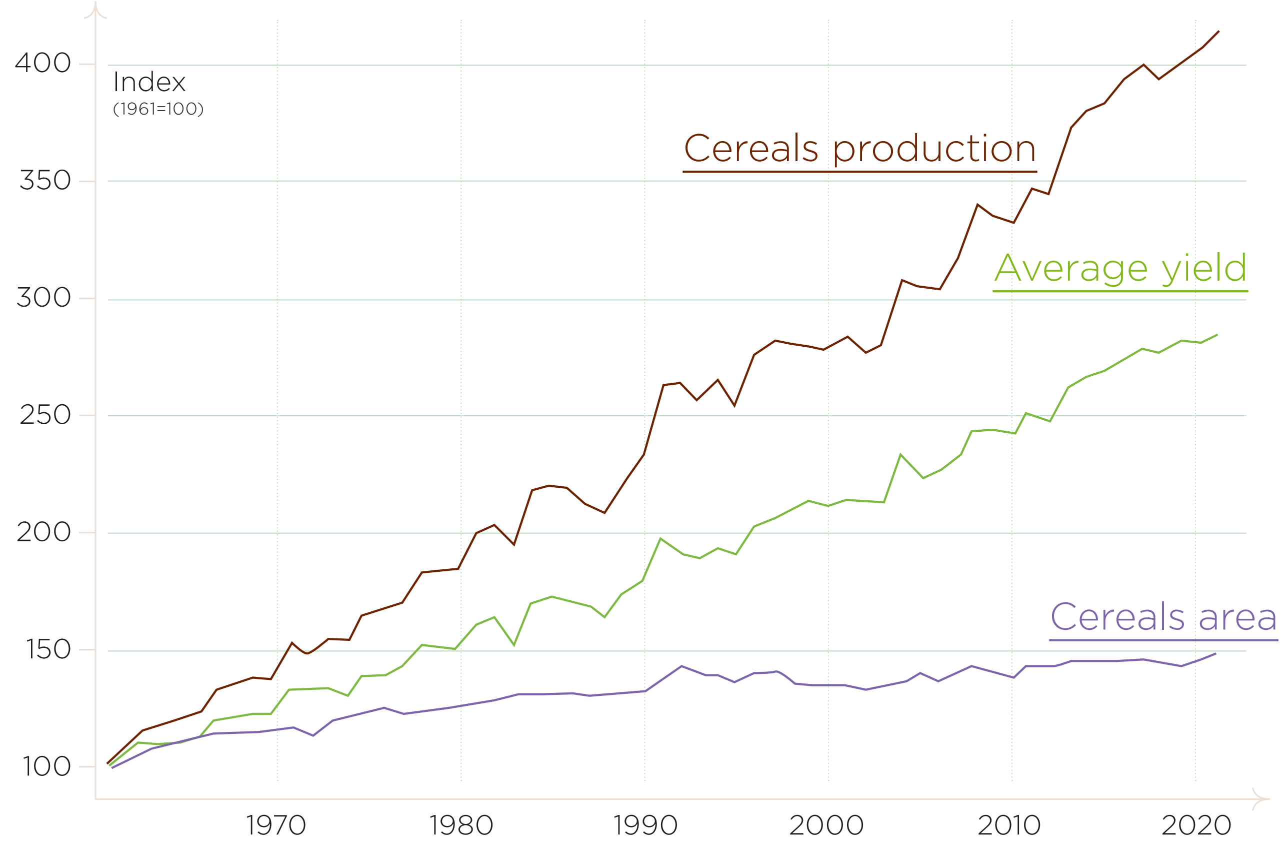


Figure 2.2: Global Cereals Production, Area and Average Yields



Source: World Bank

It is estimated that crop production would need to increase by 100-110% between 2005 and 2050 to meet demand.

real incomes increase, the demand for animal feeds as an increasing number of households broaden their diets to contain more meat and dairy products. The lower third of the figure captures the importance of crop production in achieving food security e.g., a sufficient supply to meet demand at affordable prices. The supply of crops is the product of the area devoted to arable production and the average level of crop yields; the higher the crop yields the smaller the total area that must be devoted to arable crops. Potential yield levels are determined by plant breeding but at the farm level actual yields are controlled by the agronomic skills applied to the use of variable inputs such as fertilisers and PPPs. Productivity is defined as the ratio of output to inputs, including land, and the higher the level of productivity the more affordable crop prices.

The Green Revolution marked a critical turning point for food security and its influence on global cereals production is shown in *Figure 2.2.* Since the early 1960s worldwide food production has tripled[14] providing most of the world's population with access to affordable food. Over the past 60 years, global cereals production has increased by more than 300 per cent, of which more than two-thirds has been contributed by the growth of yields.[15]

Although switching from low yielding to higher yielding crops and land have been an influence, overwhelmingly the growth of average cereal yields shown in *Figure 2.2* represents pure yield growth i.e., output per unit of land. The growth in pure yields reflects the enduring success of science and technology in bringing forth new crop varieties capable of more effectively exploiting fertilisers and advances in the efficacy of PPPs.

Closer inspection of the figure shows that the growth of the area devoted to cereals slowed after the mid-1990s. In 1960 the global cereals area, translated on to a per capita basis, stood at 0.42 hectares, since when it has been steadily declining in response to the burgeoning global population and is projected to fall to 0.18 hectares by 2050.[16] One of the most widely cited, peer reviewed studies of future global food demand, estimated that crop production would need to increase by 100-110 per cent between 2005 and 2050 to meet demand.[17] Subtracting the increase in crop production since 2005 implies a further increase of between 50 and 60 percent will be needed by 2050. As the growth of the cereals area has stalled and, as we will explain below there are good reasons to reduce its size, improving food security and meeting

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[14] Alexandratos, N. & Bruinsma, J., (2012), World agriculture towards 2030/2050: the 2012 revision, ESA Working paper No. 12-03. Rome, FAO.

[15] World Bank, (2023), Data bank, https://data.worldbank.org/indicator/AG.PRD.CREL.MT

[16] Deepak, R., et al., (2013), Yield Trends Are Insufficient to Double Global Crop Production by 2050, PLOS ONE, 8(6) https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0066428.

[17] Tilman, D. et. al., (2011), Global food demand and the sustainable intensification of agriculture, Proceedings of the National Academy of Sciences, Vol, 108, No 50, pp20260-20264.

demands for broad based diets can only be delivered by higher yields and this will require a substantial increase in the world's average rate of yield growth.[18]

The implication of the data set out in *Figure 2.2*, as made clear by a recent UNCTAD study, is that the application of science and technology to crop yields continues to be critical in meeting the ambitions and commitments of the United Nation's Sustainable Development Goals.[19] If the world's farming industries are to meet this challenge, they will need to overcome a myriad of problems including increased competition for land, water, energy, and other inputs. Numerous studies draw attention to the risk that climate change will contribute substantially to food insecurity. There is a wide consensus that higher temperatures, weather extremes and increased climate variability pose an increasing threat to the yields and quality of crops.[20] In part, this threat arises from heightened biotic stress i.e., weeds, pathogens and insects,[21] but also from reductions in the ratio of harvested to planted area caused by abiotic stress e.g., drought, flooding and soil salinity.[22] In the coming years climate change is likely to render some parts of the world unsuitable for agricultural production while in the short-run extreme weather events may cause sudden reductions in agricultural output leading to very large price increases.

For reasons that are unclear the Intergovernmental Panel on Climate Change (IPCC) barely mentions agricultural productivity gains as a mitigating strategy to climate change threats to food security.[23] This might reflect the IPCC's focus on prevention rather than adaption and awareness that in some parts of the world, the impact of temperature changes, altered precipitation patterns, and increased CO2 concentrations on the growth of crop yields may not be adverse. That said, on balance climate change threatens adverse effects on yields via impacts on pests, weeds, and plant diseases.[24] While prevention is a laudable objective, reality suggests that for the foreseeable future adaption as much as mitigation will be a pressing need for the world's agricultural industries. As the resilience of the world's agricultural industries, let alone the ability to adequately respond, is highly varied owing to underlying vulnerabilities such as poverty, extreme climate variability and low productivity,[25] international trade will continue to play a critical role in the achievement of food security.[26]

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[18] Deepak, R., et. al., (2013), Yield Trends Are Insufficient to Double Global Crop Production by 2050, PLOS ONE, 8(6) https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0066428.

[19] UNCTAD, (2017), The role of science, technology and innovation in ensuring food security by 2030, United Nations Conference on Trade and Development, Geneva.

[20] Brown, M. et. al., (2015), op. cit.

[21] Miedaner, T. and Juroszek, P., (2021), Climate change will influence disease resistance breeding in wheat in North Western Europe, Theoretical and Applied Genetics, Vol. 135, pp1771-1785

[22] Min Kim, S. and Mendelsohn, R., (2023), Climate change to increase crop failure in U.S., Environmental Research Letters, Vol. 18, No.1, pp1-9.Physiology, Vol. 166, No. 3, pp1119-1131.

[23] Deepak, R., et. al., (2013), Yield Trends Are Insufficient to Double Global Crop Production by 2050, PLOS ONE, 8(6) https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0066428.

[24] UNCTAD, (2017), The role of science, technology and innovation in ensuring food security by 2030, United Nations Conference on Trade and Development, Geneva.

[25] Brown, M. et. al., (2015), op. cit.

[26] Miedaner, T. and Juroszek, P., (2021), Climate change will influence disease resistance breeding in wheat in North Western Europe, Theoretical and Applied Genetics, Vol. 135, pp1771-1785

Figure 2.3: Solutions to Agriculture's Trilemma

ATTAIN FOOD SECURITY

Yield based production growth sufficient to meet the world's increasing demand for a greater volume and variety of nutritious food at affordable prices

ACHIEVE NET ZERO BY 2050

Production methods and machinery that lowers the industry's net greenhouse gas emissions and increases the scope for land to sequestrate carbon

AVOID HARMING BIODIVERSITY

Production methods that protect the ecosystem services of farmed land as well as the vegetation and forestry of non-agricultural land

Despite the undoubted benefits of the Green Revolution, it is now widely accepted that agricultural intensification i.e., pure yield growth, was accompanied by unintended adverse consequences for global biodiversity and its ecosystem services.[27] These environmental impacts were not caused by the revolution's technologies per se but rather by the understandable single-minded policy focus on production that facilitated excessive i.e., wasteful, use of inputs and the expansion of cultivation areas, often unsuited to crop production e.g., steeply sloping lands, resulting the loss of ecosystem services and habitats.[28] That said, technological limitations required that field areas were treated as homogeneous; inputs were applied at a fixed rate without regard for their many aspects of spatial and temporal variations. The systems failure to vary the use of fertilisers and PPPs according to the micro needs of field areas and/or specific incidents of stress in growing crops, imposed external costs in the form of degraded soils, water pollution and losses of beneficial insects.[29]

To an extent, this environmental damage frequently resulted from poor agronomic skills and practices such as the careless and haphazard usage of PPPs resulting in pathogen and pest resistance, the loss of useful soil microbes and run-off into water courses causing algae blooms and harm to fish and other aquatic species.[30] Context and scale are also considerations. The same practice, undertaken in different places, can have different outcomes due to local variations in environment or climate, and if an area of intensive production is matched by an area of natural vegetation and forestry, any adverse impact on the region as a whole may be slight. To what extent environmental damage was the result of human failings is not for debate here, rather this report agrees with the widely agreed need to limit, and preferably reverse, the harm.

Agriculture is also recognised as a significant source of anthropogenic GHG emissions giving rise to the need for mitigation. Research shows that as regards controlling GHG emissions, the increase in both crop and livestock yields has been superior to the alternative of the expansion of croplands and livestock herds that would otherwise have been necessary to meet global demand.[31] That said, GHG emissions remain a concern and this is encouraging research as to how agriculture might continue to increase output while progressing towards a target of Net Zero emissions. In essence, simultaneously achieving these two outcomes depends on productivity growth and in particular increasing crop yields while minimising applications of fertilisers, PPPs, and energy. More broadly, farming operations will have to become more efficient in their use of inputs and practices such as less tillage and the incorporation of crop residues must become the norm.

If agriculture is to satisfactorily solve its three production challenges; namely, attain global food security, avoid harming global biodiversity and achieve Net Zero by 2050 it must increase production.

It is clear from the foregoing, that if agriculture is to satisfactorily solve its three production challenges; namely, attain global food security, avoid harming global biodiversity and achieve Net Zero by 2050 it must increase production, particularly of crops, in ways that are more land-efficient and input-efficient—see *Figure 2.3.* The message is clear; continued improvement of crop yields is paramount if the threat to remaining natural vegetation, forests and habitats is to be reduced,[32] and avoiding encroachment on to non-agricultural land will augment its ability to provide the service of carbon sequestration and thereby the mitigation of the world's carbon footprint.[33]

Higher yields might be paramount, but the many strands of research demonstrate that any practical solutions to the triple challenges facing food production have to involve improved efficiencies along the entire food chain and in particular, reduced levels of food waste. Waste occurs at all stages of the food chain including post-harvest losses due to damage and pests, contamination during processing and post-consumer poor storage and preparation but realistic reductions in food waste would not be sufficient to secure food security.[34] Solutions downstream of the farm-gate are not for consideration here, but they will necessarily involve changes in both businesses and consumer behaviour. This report is focused on the agricultural stage of the food chain where a consensus has formed around a solution known as sustainable intensification, which having emerged in the 1990s has been given broad support by leading scientists,[35] and is now central to both the UN Sustainable Development Goals and efforts in general to improve global food and nutritional security.[36]

The definition of sustainable intensification has been subject to various nuances in the pursuit of balancing the paradigm's economic, social and environmental aspects, however, for this report an accurate, working definition can be summarised as an evidence-based approach to distinguish a set of agricultural processes or systems in which the ability to grow production is maintained alongside progression towards substantial enhancements of environmental

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[27] Min Kim, S. and Mendelsohn, R., (2023), Climate change to increase crop failure in U.S., Environmental Research Letters, Vol. 18, No.1, pp1-9.Physiology, Vol. 166, No. 3, pp1119-1131.

[28] Pingali, P., (2012), Green Revolution: Impacts, limits, and the path ahead, PNAS, Vol, 109, No. 31, July

[29] Pretty, J., (2018), op. cit.

[30] Gill, H. and Garg, H., (2014), Pesticides: Environmental Impacts and Management Strategies, in Pesticides, ed. Soloneski, S., Open Access Books, ISBN 978-953-51-1217-4.

[31] Burney, J., et. al., (2010), Greenhouse gas mitigation by agricultural intensification, Proceedings of the National Academy of Sciences of the United States of America, Vol 107, No. 26, pp12052-12057

[32] Pretty, J., (2018), Global assessment of agricultural system redesign for sustainable intensification, Nature Sustainability, Vol. 1, August, pp441-446

[33] Burney, J., et.al., (2010), op. cit.

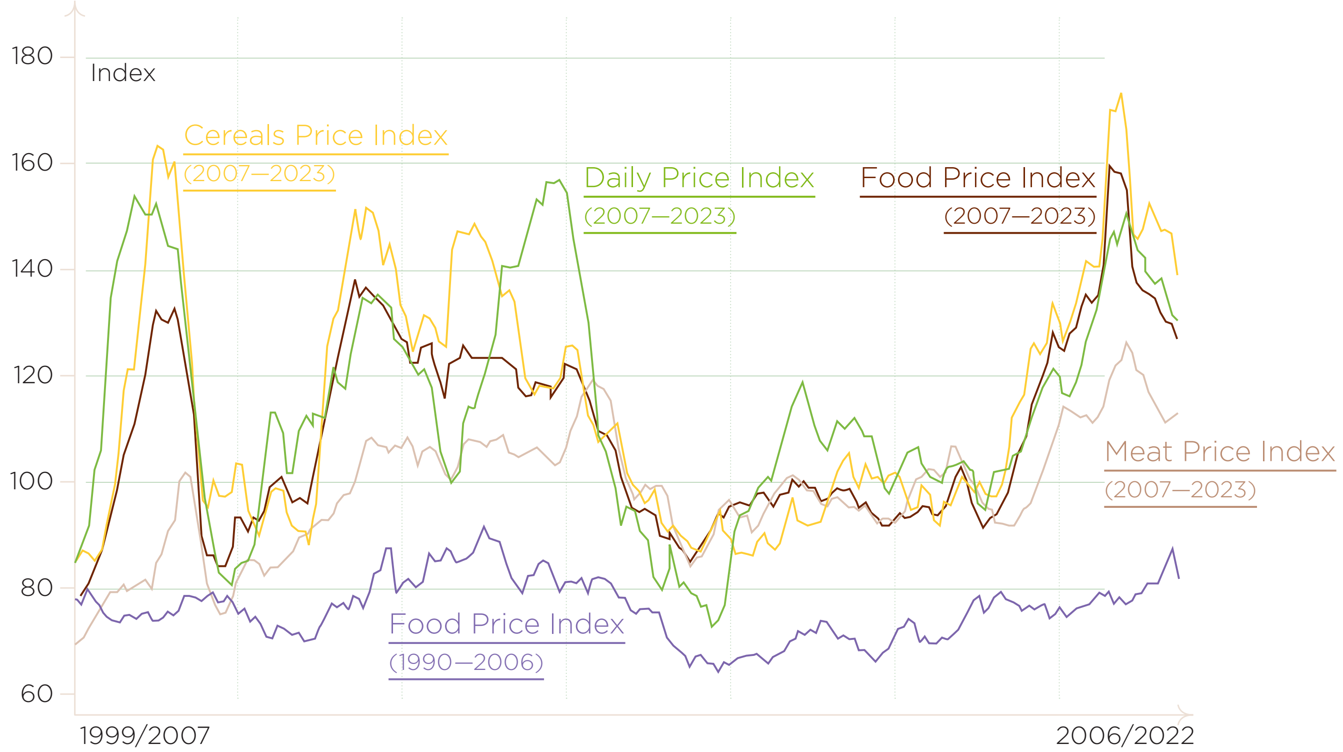
[34] Pretty, J., (2018), op. cit.

[35] Royal Society, (2009), Reaping the benefits: science and the sustainable intensification of global agriculture, Royal Society Policy Document, 11/09, London, October.

[36] Pretty J., (2018), op. cit.

[37] Pretty J., (2018), op. cit.

Figure 2.4: Global Commodity Prices



Source: FAO Indices 2014-2016 = 100

outcomes.[37] In a little more detail, it is a process of producing more output of safe, nutritious food per unit of resource input e.g., land, water and energy, without adding harm to biodiversity and the services provided by ecosystems including food. As with any radically new paradigm, sustainable intensification has attracted debate and criticism[38] but broadly conceived its role in delivering food security is recognised by the world's responsible organisations, such as the Food and Agricultural Organization (FAO),[39] acknowledged by many environmentalists as protective of natural capital[40] and crucial to both the adaption to and mitigation of climate change.[41]

A system known as 'climate smart' agriculture is sometimes presented as an alternative to sustainable intensification. This report takes the view that any differences are a matter of nuance rather than substance. Sustainable intensification and climate smart agriculture are closely interlinked concepts; notably, both are defined as focussed on the role of productivity in achieving food security. The main difference is climate smart agriculture's primary focus on outcomes related to climate change; namely, adapting crops and farming systems to boost resilience, and mitigation by decreasing GHG emissions and developing carbon sinks. That said sustainable intensification also seeks to integrate climate change adaption and mitigation, as well as the protection of biodiversity and its ecosystem services into the planning and implementation of agricultural systems in the pursuit of its productivity priority. In short, all cases of climate smart agriculture invariably turn out to be cases of sustainable intensification.[42]

We will examine sustainable intensification in more detail in following sections and in particular its relationship to scientific and technological advances and the role of PPPs. Here, it is important to point out that central to sustainable intensification is productivity, or more precisely the pursuit of maximum total factor productivity. That is, the amount of output achieved by all the inputs used in its production. Using wheat as an example, yield is output per unit of land and as such is only a partial measure of productivity. To achieve maximum efficiency other inputs used in producing wheat—fertilisers, PPPs, energy, labour—must not be used wastefully. Thus, the use of herbicides on a wheat crop should be limited to the minimum amount necessary to ensure that the yield achieved will be sufficient to generate an economic return. Maximising total factor productivity is a necessary condition for maximising efficiency and

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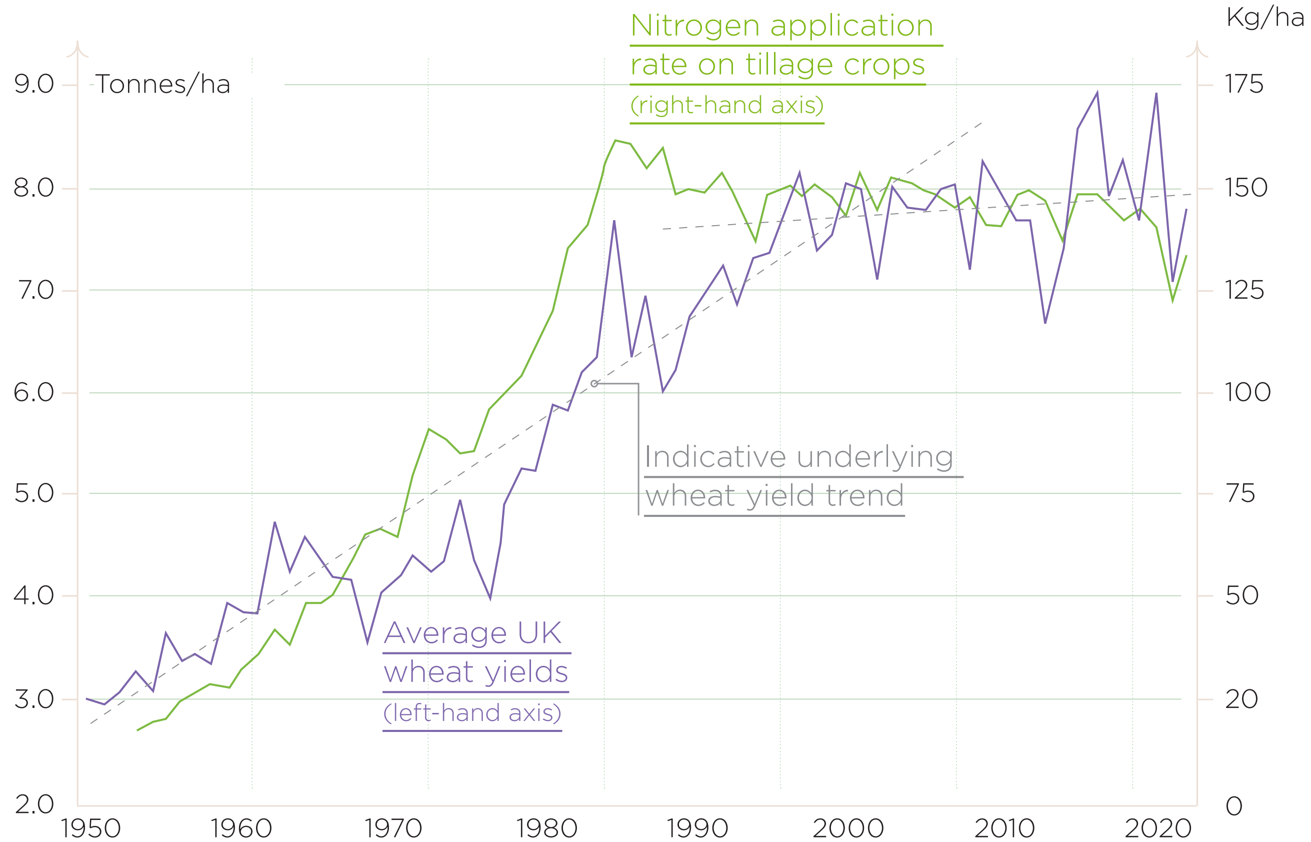
[38] Johan Rockstrom, J. et al., (2017), Sustainable intensification of agriculture for human prosperity and global sustainability, Ambio, Vol. 46, No.1, pp4-17

[39] FAO, (2011), Save and Grow. A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production, Food and Agriculture Organization of the United Nations, Rome.

[40] Pretty, J., (2014), op.cit.

[41] Campbell, B., et al., (2014), Sustainable intensification: What is its role in climate smart agriculture? Current Opinion in Environmental Sustainability, Vol. 8, pp39-43

[42] Campbell, B., et. al., (2014), op. cit.



Source: Defra

Figure 2.5: UK Wheat Yields and Nitrogen Applications

thereby a farm's business income. Put simply, the higher the level of productivity the greater the ability and most likely the willingness of a farmer to go on producing the food we all depend on, let alone in a manner that protects and enhances the natural environment.

UK agriculture is not immune from these challenges and following the harm the 2008 spike in global agricultural commodity prices caused to household budgets and living standards, food inflation and food security moved up the political agenda. In response the government commissioned the Foresight project to report on the Future of Food and Farming,[43] which, in common with a number of contemporary studies, highlighted the role of sustainable intensification. This coincided with, or was followed by, a number of other government initiatives including what is now called the Climate Change Committee (CCC). Founded in 2008, its publications have had a particular focus on the challenges facing land use and farming. In 2012 the Green Food Project—now wound up—was established to study how Britain's food system must change in response to the twin challenges of food security and environmental protection and it took as its starting point sustainable intensification.[44]

These studies were conducted against the background of continued volatility in global prices captured by the FAO's Food Price Index as shown in *Figure 2.4*. The Index is a weighting of the monthly change in the international prices of a basket of five agricultural commodity groups, three of which—cereals, dairy and meat—are also shown in the figure. It is instructive to compare the level and pattern of the Index for the last 16 years with its movement over the previous 16 years which is also illustrated. On average prices have been 45 per cent higher since 2007 though at times the difference was nearer 100 per cent. Between 1990 and 2006 the index was relatively stable: its variance – a measure of how far its values spread out from their average value—was one tenth the index's variance for the period 2007-2023. Experts are forecasting that for the foreseeable future the shortfall of supply will continue to put upward pressure on both the level and volatility of global food prices.[45]

As can be seen from the data set out in *Figure 2.4*, after 2012 global commodity prices started falling back to their 2007 levels in response to rising yields and re-stocking. Reflecting this trend, UK food inflation was more-or-less flat between January 2013 and March 2021. Inevitably, for the

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[42] Campbell, B., et. al., (2014), op. cit.
[43] Foresight, (2011), The future of food and farming, Final Project Report, Government Office for Science, London
[44] Defra, (2012), Green Food Project Conclusions, London, July
[45] OECD/FAO, (2022), op. cit.

British government—if not the FAO and aid agencies—the issue of food security slipped down the political agenda as the rate of food inflation declined. This resulted in a critical report by the Environment, Food and Rural Affairs Select Committee, whose chair warned that 'complacency is a genuine risk to future UK food security' and continued ' if we want our food production and supply systems to be secure, government and food producers must plan to meet the impacts of climate change, population growth and increasing global demand for food.'[46]

The warning has proved to be prophetic. As can be seen from *Figure 2.4*, global commodity prices rose sharply in 2021 reaching a peak in late 2022. Multiple factors contributed to the spike. First as global demand recovered from the Covid-19 pandemic it had to contend with supply disruptions emanating from the same source. This coincided with unfavourable weather patterns e.g., droughts, which reduced production in several parts of the world. Early in 2022 these adverse trends were exacerbated by the outbreak of the Russian invasion of Ukraine. Global food markets were impacted indirectly by the soaring price of fertilisers and directly by the disruption to exports of cereals and oilseeds; all commodities in which Russia and Ukraine are key players. In normal times, so the free-market economic logic goes, 'the cure for high prices is high prices' as this spurs producers to increase supply. This implies a complacent attitude towards volatility in the prices of what is a basic necessity but, more to the point, these are not normal times for agricultural industries with a range of factors e.g., climate change and land lost to agriculture, reducing their ability to aggressively expand production in the short run.

Reflecting in large measure global price trends, the UK is currently suffering record increases in the price of food and shortages for some products. The prices of all staple foods e.g. meat, milk, eggs and cereal based products, rose steadily during 2022 and in March 2023 the Office for National Statistics (ONS) recorded that the price index for food and non-alcoholic drinks in the UK had risen by a record 19.1 per cent to a 45-year high over the previous twelve months.[47] In an earlier release the ONS noted that the impact of food inflation falls most heavily on those with the lowest incomes with 61 per cent of households in the most deprived areas buying less food compared with 44 per cent in the least deprived areas.[48] In April the BBC reported that the UK's largest food bank provider was handing out record numbers of food parcels. Food price volatility is a major concern for all governments seeking to ensure their populations have access to affordable, healthy diets not only because rapid rises in global food prices increase economic risks across food systems but also, they can spark political unrest. Not surprisingly, following recent levels of food price inflation, agriculture and food systems are once again receiving unprecedented news coverage as well as government and academic attention. Here in Britain and across the world, populations are grappling anew with the food security issues that surfaced with vengeance 15 years ago. High food prices and shortages have again risen to the top of political agendas as governments seek actions across the food system that can moderate price levels and dampen price volatility.

Arguably since the Environment, Food and Rural Affairs select committee warned that complacency was a genuine risk to UK food security, climate concerns have taken on greater urgency as the adverse effects of extreme weather events and global warming on food production have become more pressing and better understood. The IPCC has forewarned that continued GHG emissions are putting upward pressure on global warming and has now concluded that the average global temperature is more likely than not to rise 1.5°C above its 1850-1900 baseline in the near term.[49] In an earlier report the IPCC stated that this would put enormous pressure on food production systems. It noted that intense extreme weather events such as heatwaves, droughts and floods were becoming more frequent and that food systems had already been pushed beyond their ability to adapt to these changes, causing irreversible damage to food security.[50]

The IPCC's warnings align with an earlier CCC report predicting the increasing risk to UK harvests and crop yields from extreme weather events; directly from droughts and heavy rainfall but also from the indirect effects of disease outbreaks, insect attacks and weed infestations, resulting in greater production and price volatility as well as substantially higher average food prices.[51] *Figure 2.5* shows the growth of wheat yields in the UK since 1950. The most striking feature of the trend shown is the sudden slowing in the growth rate in the late 1990s. Closer inspection also suggests that yield volatility has increased in recent years. For example, the average wheat yield in 2020 was the lowest since 1990.

Cereal crops underpin the UK's food system—

61% of households in the most deprived areas buying less food compared with 44% in the least deprived areas.

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[46] Guardian, (2014), UK future food security threatened by complacency, MPs warn, London, July

[47] ONS, (2023), Cost of living insights: Food, Office for National Statistics, London, April

[48] ONS, (2022), Rising cost of pasta, bread and other everyday foods leaves most vulnerable the worst off, Office for National Statistics, London, December

[49] IPCC, (2023), Summary for Policymakers, in: Climate Change 2023: Synthesis Report, Geneva, Switzerland

[50] IPCC, (2022), Summary for Policymakers, in Climate Change 2022, Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

[51] CCC, (2019), Resilient Food Supply Chains, Climate Change Committee, https://www.theccc.org.uk/wp-content/uploads/2019/07/Outcomes-Supply-chain-case-study.pdf

Cereal crops underpin the UK's food system—more than half of UK cereals production is used for animal feed—and wheat accounts for almost two-thirds of cereals production.

more than half of UK cereals production is used for animal feed[52]—and wheat accounts for almost two-thirds of cereals production. As noted, crop yields are influenced by a number of factors including breeding, weather, and soil fertility but also by managerial skills and practices, most prominently the efficient use of fertilisers and PPPs subject to regulations. *Figure 2.5* shows how nitrogen applications and wheat yields have moved since the 1960s. The data on fertilisers is drawn from the Department for Environment, Food and Rural Affairs (Defra)'s annual survey of fertiliser practice and although it refers to all tillage crops in England and Wales it represents a very good guide to usage on wheat. Given that optimal applications are subject to variations in the relative prices of crops and fertilisers, the figure suggests that other factors such as climate change and policy are an increasing influence.

Figure 2.5 is again testimony to the success of science based agricultural systems. Plant breeders have brought forth a continuous supply of improved cultivars that, with the aid of inorganic fertilisers, synthetic PPPs and technologically advancing farm operating systems, delivered steady yield growth for 50 years until 2000. Cursory examination of the data set out in the figure would appear to suggest that contemporary wheat varieties have reached their potential. This however would be wrong. We noted above that the Green Revolution has raised problematic side effects for the natural environment and to mitigate these effects, starting in the 1990s, European Union (EU) agricultural policy introduced regulations and incentives to reduce applications of external inputs e.g., Nitrate Vulnerable Zones. To what extent policies and regulations have constrained the growth of yields is not for debate here, the more so as the reasons for the levelling-off since the millennium are not fully understood[53] but climate change is identified as a probable influence.[54]

What is beyond dispute is that the plateauing of yields shown in *Figure 2.5* is not the result of intensive farming reaching its potential. A large-scale study spanning five decades of wheat breeding progress in western Europe, demonstrated that breeding for high performance actually enhances cultivar performance. New cultivars incrementally accumulate genetic variants conferring favourable effects on key yield parameters, disease resistance, nutrient use efficiency, photosynthetic efficiency, and grain quality.[55] The study revealed that even after more than 100 years of breeding, the genetic potential of wheat yields has not been exhausted. It follows that if the nutrient use efficiency of wheat and the precision of applications including PPPs is improved i.e., less waste, the outcome would be higher yields.[56] We will return to this issue in the following sections.

The data shown in *Figure 2.5* also reveals the effect of extreme weather events e.g., the 1976 drought, and very apparent is the increase in volatility in recent years. This volatility is greater than might be expected by seasonal metrics of temperature and precipitation and reflects years with compound weather extremes across growth stages e.g., frost and heavy rainfall, pushing UK wheat production outside of the climatic envelope previously experienced.[57] For example, the yield reduction in 2020 was due to unusually poor weather conditions at critical points of the crop production cycle: very wet weather for preparing the soil and sowing, too dry in the spring when the crops should have established, and bad weather for harvesting. Extreme weather events lower crop yields, but rapid climate shifts also seriously adversely influence starch, fibre, protein, amino acids, and essential nutrients i.e., quality.[58] The quality of a crop affects its processing properties, its aroma, colour, and flavour but also its nutritional value and therefore consequences for the dietary health of people.

This report is primarily concerned with examining how British agriculture can rise to the three challenges summarised in *Figure 2.3* and in particular the contribution of PPPs to the solution. The outlook is now more challenging than at any time since the threat of widespread famine prior to the Green Revolution. In the following sections we will explain in some detail that, at the industry level, sustainable intensification is the best way forward as it is capable of overcoming yield stagnation and building greater resilience to climate induced volatility without causing harm to the natural environment. We will describe how the level of yields in the UK can be raised by the general application of advances in science, technology, and management skills to better exploit the synergies between improved plant genotypes and agronomy. We will further explain how this can be reconciled with the avoidance of further environmental degradation including the loss of unfarmed habitats as well as the enhancement of ecosystems e.g., improving soil productivity and water quality, increasing beneficial insect populations, and the reduction of anthropogenic GHG emissions. In short, UK agriculture must take full advantage of sustainable intensification and it is to this issue that we now turn.

UK agriculture must take full advantage of sustainable intensification.

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[52] Defra, (2021), United Kingdom Food Security Report 2021: Theme 2: UK Food Supply Sources, December, London.

[53] Knight, S., et.al., (2012), Desk study to evaluate contributory causes of the current 'yield plateau' in wheat and oilseed rape, AHDB, Project No. 502

[54] Slater, L., et. al., (2022), Resilience of UK crop yields to compound climate change, Earth System Dynamics, Vol.13, pp1377-1396

[55] Voss-Fels, K., et. al., (2019), Breeding improves wheat productivity under contrasting agrochemical input levels, Nature Plants, Vol. 5, July, pp706-714

[56] OECD, (2001), Adoption of Technologies for Sustainable Farming Systems, Wageningen Workshop Proceedings, Paris.

[57] Slater, L., et al., (2022), Resilience of UK crop yields to compound climate change, Earth System Dynamics, Vol. 13, No.3, pp1377-1396

[58] Zahra, N., et al., (2022), Impact of climate change on wheat grain composition and quality, Journal of the Science of food and Agriculture, Vol. 103, No. 6, pp2745-2751

Sustainable Intensification and Plant Protection

The previous section identified sustainable intensification as the mainstream approach to solving the trilemma now facing British farmers; indeed farmers across the world. The clarity of this solution has been somewhat confused by the suggestion that there are two competing versions of sustainable intensification: 'land sparing,' whereby the area of conservation land is maximised for natural habitats and other environmental services by separating it from high-yielding agricultural land; and 'land sharing,' which involves integrating biodiversity conservation and food production on the same land at the cost of lower yields.[59]

At a local level, choosing between these alternatives will vary according to circumstances and within regions the two systems can, to a degree, co-exist. However, a number of studies have questioned the viability of the land sharing version at a national, let alone global, level as many wild species cannot survive in even the most wildlife-friendly farming systems.[60] Given that world demand for food is growing strongly, our view is that the over-riding priority for national policy makers should be to ensure that their populations have access at all times to a plentiful supply and variety of good quality, nutrient rich food at affordable prices.

This means that overall, agricultural output must increase, but if this is achieved by the large scale conversion of natural vegetation and forests into arable land, the outcome would cause significant damage to the Earth's biodiversity and Net Zero prospects;[61] indeed, over the past 50 years, the biggest driver of habitat loss has been the conversion of natural ecosystems for crop production or pasture.[62] Avoiding the large-scale expansion of cropping areas to 'spare land for nature' will require significant increases in crop yields and from this perspective, the land sparing version of sustainable intensification dominates, the more so as under this version the achievement of higher yields is subject to the constraint that environmental damage and GHG emissions on agricultural land are minimised.

The land sharing version of sustainable intensification seeks to avoid the expansion of cropping land by eschewing the need to produce more food. Proponents assume that diets should and can be changed to include much less meat and dairy products. As this would, in principle, reduce the growth of demand for food—so the logic goes—production growth need not be a primary objective. This report emphatically rejects land sharing sustainable intensification as a general solution to agriculture's trilemma.

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[59] Benton, T. and Harwatt, H., (2022), Sustainable agriculture and food systems: comparing, contrasting and contested versions, Chatam House.
[60] Phalan, B., et.al., (2011), Minimising the harm to biodiversity of producing more food globally, Food Policy, Vol.36., ppS62-S71
[61] Pretty, J., et. al., (2018), op. cit.
[62] Benton, T., et. al., (2021), Food system impacts on biodiversity loss, Chatham House Research Paper, February

This rejection is based on three considerations. Firstly, the FAO is one of many sources pointing out that meat, eggs and milk offer crucial sources of much-needed nutrients which cannot easily be obtained from plant-based foods and should therefore form part of a healthy diet.[63] Secondly, whereas the FAO has a particular concern for improving the diets of populations in the world's poorer nations, the notion that overwhelmingly western populations will willingly drastically reduce or abandon meat and dairy products is at best a fanciful conjecture.[64] In addition to providing rich sources of high-quality protein and important nutrients vital for optimal health,[65] the consumption of meat and dairy products in a variety of forms contributes to what is generally regarded as a higher quality of life.

Seeking to provide the world's population—particularly the poor—with access to affordable livestock-based proteins and nutrients is a moral endeavour. As people rise out of poverty almost invariably their first choice in utilising the growing purchasing power of their incomes is to increase expenditure on meat.[66] In short, dietary change of the scale required by the land sharing, sustainable intensification version, is very unlikely to occur solely through consumer choice implying that actions would have to be taken to significantly raise the price of meat and dairy products e.g., food taxes. Excessive consumption of any food is unhealthy but deliberately raising the price of meat and livestock products—which for a typical family in the UK accounts for almost 40 per cent of expenditure on food eaten within the home[67]—would unnecessarily penalises sensible consumption while cruelly discriminating against the poor whose purchasing power would be most affected.

If the assumption that the world's population can be persuaded or forced to dramatically curtail its demand for meat and dairy products is judged infeasible, then the land sharing option cannot be presented as either a credible or sustainable way forward. Meeting the need for a 50 per cent expansion in agricultural production by 2050[68] would necessitate the widespread depletion of natural habitats. Moreover, in addition to being a major driver of biodiversity loss and land degradation, land conversion from natural ecosystems to agriculture has historically been the largest cause of GHG emissions, linked to loss of biomass and carbon in biomass above and below ground.[69]

A third consideration—surprisingly rarely

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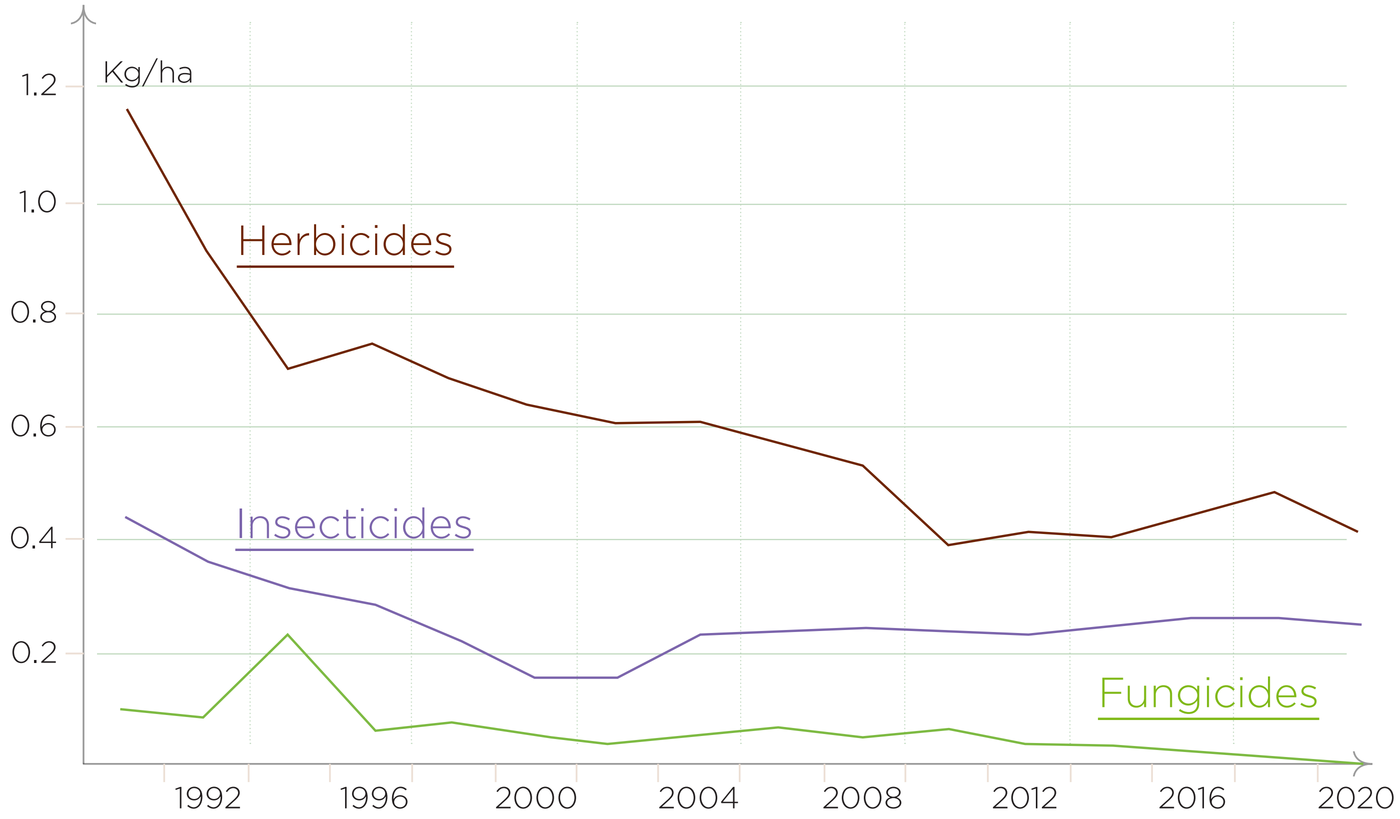
[63] FAO, (2023), Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes: An evidence and policy overview on the state of knowledge and gaps, Food and Agriculture Organization of the United Nations, Rome
[64] Gillison, F., et. al., (2021), A rapid review of the evidence on the factors underpinning the consumption of meat and dairy among the general public, University of Bath, https://researchportal.bath.ac.uk/en/publications/
[65] Wyness, L., (2016), The role of red meat in the diet: nutrition and health benefits, Proceedings of the Nutrition Society, Vol. 75, No. 3, pp227-232
[66] Ritchie, H ., et. al., (2017), Meat and Dairy Production, https://ourworldindata.org/meat-production
[67] ONS, (2023), Components of Household Expenditure, UK, Financial Year ending 2021, Family Spending in the UK, Office for National Statistics, Newport, South Wales.
[68] OECD/FAO, (2022), op. cit.
[69] FAO, (2020), Land use in agriculture by the numbers, https://www.fao.org/sustainability/news/detail/en/c/1274219/

considered in public debate—concerns the suppression of growth opportunities for the UK agri-food chain inherent in land sharing sustainable intensification and possibly increased food imports from countries whose production systems remain harmful to the environment and climate change mitigation. The agri-food chain is defined here as comprising the suppliers of agricultural inputs and investment goods, farm businesses, food processors and manufacturers, wholesalers, and distributors. Its Gross Value Added—broadly the difference between the value of output and the cost of all inputs used (land, labour, and manufactured inputs)—is estimated at almost £50bn and the total number of people engaged is more than a million.[70] This is a large industrial grouping and its expansion, based on rising agricultural output, would make a meaningful contribution the UK economic growth. Only land sparing sustainable intensification is capable of supporting the higher productivity necessary if the UK agri-food chain is to achieve the competitiveness necessary for growth. Global competitiveness is the best way to increase self-sufficiency and food security at affordable prices but also it has the added advantage that UK food production exports not only contribute positively to the country's trade balance but also the wellbeing of consumers in other countries, particularly emerging economies.[71] We will return to these matters in the final section of this report.

Productivity growth is the basis of higher living standards i.e., higher quality products at affordable prices, and this applies as much to food production as to any other industrial activity. The quintessence of sustainable intensification—from now on unless stated otherwise assumed to be land sparing—is responsible, total factor productivity growth where rising yields are achieved within farming systems that avoid harm to the natural environment in part by minimising the total volume of productive resources applied per hectare. At the farm level, high and growing yields depend on a range of factors starting with crop breeding, land quality and climate, but critical is the precision, timing and quantities of fertilisers and PPPs applied. As a modern, efficient industry, UK agriculture's future contribution and sustainability (in all senses) depends on scientific advances and new technologies to maximise productivity. To be more precise agriculture's total factor productivity growth and competitiveness, as is the case generally, rests on the diffusion across the industry of new scientific and technological knowledge to drive innovation in crops, variable and fixed inputs as well as

Figure 3.1. Applications of PPP to cereal crops in the UK, kg/ha



Source: Fera biannual survey, data refers to active substance per treatment not total per hectare

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[70] Hasnain, S., et. al., (2020), Mapping the UK Food System – a report for the UKRI Transforming UK Food Systems Programme, Environmental Change Institute, University of Oxford, Oxford

[71] Mitscherlich, C., et. al., (2021), Balancing international trade and local production for food and nutrition security: animal-sourced foods' contribution to human welfare,Animal Frontiers, Vol. 11, No. 5., pp40-51.

What the growth of IPM demonstrates is that plant protection strategies are dynamic, evolving with advances in science and technology.

operational and management systems.

Critical to sustaining, let alone increasing crop yields is, inter alia, a continued reliance on the economic efficacy of synthetic PPPs which in turn means utilising scientific and technological advances to deliver innovations in products and application systems. Erich-Christian Oerke and his colleagues at the University of Bonn are considered the primary reference regarding crop losses due to biotic factors. Their extensive research has shown that crop yields would be significantly lower than current levels without the protection of synthetic PPPs and that the higher a crop's yield potential the greater its vulnerability to biotic factors and hence, the more valuable PPPs.[72] However, it would be incorrect to assume modern farming relies solely on synthetic PPPs. Integrated pest management (IPM), a broad-based approach that integrates both chemical and non-chemical methods to generate synergies, is increasingly the norm. Progressively, plant protection will augment synthetic PPPs with biological controls via the use of natural predators and pathogens, the adoption of managerial practices to reduce pest establishment and mechanical processes to directly block pests e.g., mulches for weed management. Thus, under IPM systems, plant protection methods are selected and applied in ways that minimises their possible harm to nontarget organisms.

What the growth of IPM demonstrates is that plant protection strategies are dynamic, evolving with advances in science and technology, as well as changes in the policy and regulatory environments. The development of resistance by pathogens and pests means new products and modes of operation have constantly to be sought and improved efficacy and safety are incessant concerns for PPPs scientists and producers. Over recent years the development of PPPs has focused on products that are effective at extremely low dosage and readily degradable.[73] Although the usage of PPPs varies from year to year depending on growing conditions, particularly the weather, the longer-term outcome of these advances has been a marked decrease in the volume of active ingredients used.[74] *Figure 3.1* shows the trend for the three main types of PPPs applied to cereals in the UK since 1992 though the trends also reflect the impact of regulations.

Weeds are the dominant pest group in wheat production worldwide and *Figure 3.1* confirms that this is the case in the UK. Long term studies show that the yield difference between plots untreated and treated with herbicides is significant for cereals.[75] The figure also appears to suggest that insect pests are becoming insignificant for cereal farmers in the UK but this must be set against the growth of IPM and studies showing that climate change is likely to significantly increase the vulnerability of crop yields to insects.[76] The incidence and effects of weeds, pathogens and insects are all driven to a large extent by weather conditions and the threat of a warming climate to yields is now a major area of research including, to a lesser extent, the potential benefits in PPPs that may emerge with climate change.[77]

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[72] Oerke, E-C., (2006), op.cit.

[73] Umetsu, N. and Shirai, Y., (2020), Development of novel pesticides in the 21st century, Journal of Pesticide Science, Vol. 45, No. 2, pp54-74.

[74] Umetsu, N. and Shirai, Y., (2020), op. cit.

[75] Mayerová, M. et. al., (2018), Effect of chemical weed control on crop yields in different crop rotations in a long-term field trial, Crop Protection, Vol. 114, pp215-222

Precision agriculture ushered in higher productivity, reduced operating costs and increased crop revenues but also, and importantly, it supported the environmentally friendly management of crop production inputs such as PPPs.

We previously explained that sustainable intensification came to prominence in the first decade of the 21st century with, inter alia, the 2009 report by the Royal Society.[78] This coincided with a significant development in the industrialisation of agriculture, popularly known as Agriculture 3.0, which brought together information technology and advances in engineering to deliver production systems collectively given the neologism, precision agriculture. The application of automation to agricultural processes had been gaining momentum throughout the 20th century but with the arrival of precision farming systems, it underwent a step-change, becoming more efficient and powerful in monitoring and achieving desired outcomes. Precision agriculture ushered in higher productivity, reduced operating costs and increased crop revenues but also, and importantly, it supported the environmentally friendly management of crop production inputs such as PPPs.[79]

Precision agriculture and 'smart farming' are often used interchangeably but there is a subtle difference. Both can be described broadly as digital farming, both substitute information and knowledge for physical inputs and both have the objective of improving efficiency by helping farmers make better informed, data-driven decisions. Traditionally farmers relied on knowledge passed down through generations and both precision agriculture and smart farming speed up the learning process and enhance its effectiveness with the help of Agritech tools e.g., information and communication technologies, to capture and interpret vital data. The key difference is precision agriculture's focus on a higher level of analysis and sophistication in order to deliver highly controlled and accurate farming operations in the pursuit of optimisation. Precision agriculture, or rather the technologies underpinning it, can be divided into three categories: recording technologies which include spatial mapping

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[76] Deutsch, C., et. al., (2018), Increase in crop losses to insect pests in a warming climate, Science, Vol. 361, No. 6405, pp916-919.

[77] Juroszek, P. and von Tiedemann, A., (2013), Plant pathogens, insect pests and weeds in a changing global climate: a review of approaches, challenges, research gaps, key studies and concepts, Journal of Agricultural Science, Vol. 151, No. 2, pp163-188.

[78] Royal Society, op. cit.

[79] Bongiovanni, R. and Lowenberg-Deboer, J., (2004), Precision Agriculture and Sustainability, Precision Agriculture, Vol. 5, pp359-387.

and sensors; reacting technologies capable of varying the quantities and placement of inputs in field areas; and guidance technologies enabling automatic steering/guidance for tractors and self-propelled machinery.[80]

Recording technologies include a diverse range of remote and proximal sensors e.g., cameras and spectroradiometers, to gather large quantities of information on the topological and physicochemical properties of individual fields as well as post-planting crop health i.e., the monitoring of weeds, plant pathogens and insect pests. Embedded or remote information systems analyse this information to identify targets and local needs for applying nutrients and PPPs which is then stored in an accessible form. Reacting technologies are electronic control techniques, such as variable rate application systems, and these access the recorded information to automatically adjust movements and flow rates to apply the optimal quantity and mix of inputs required by the soil or crop e.g., fertilisers and PPPs. Both recording and reacting systems require the use of the Global Positioning System (GPS) for optimal guidance of field traversing machines as well as determining exact spatial positions within fields. The combination of these three technologies within precision agriculture enables much improved efficiency in the timing and controlled application of inputs. For example, not only are quantities finely applied but also field operations are automatically plotted to minimise distance and avoid overlapping.

By the efficient targeting of micro-localised areas/conditions, precision agriculture ensures that the quantities applied do not exceed the optimal rate for the diagnosed pest or nutrient deficiency thereby reducing, if not eradicating, the risk of damage to ecosystems from excess waste and run-offs. It is the replacement of indiscriminate uniform application rates with discriminating precision in the units of inputs used in the pursuit of maximising yields that justifies the claim that precision agriculture is the logical counterpart to sustainable intensification. In addition to the ability to protect and enhance ecosystems, precision agriculture also contributes to mitigating climate change, principally because of its ability to reduce agricultural inputs, per unit of output, by better targeted, site-specific applications to spatial and temporal needs. A particular benefit is the reduction in fuel usage due to reduced traffic flows when machines guided by the GPS avoid overlapping. The combination of minimal traffic and zero or minimum tillage, potentially reduces GHG emissions by more than 20 per cent compared to conventional tillage.[81] Further, overtime these efficiencies increase the soil's biomass including its organic matter, hydraulic properties and biodiversity,[82] thereby enhancing carbon sequestration.[83] Yet another benefit is that to the extent that intensification avoids, and even reduces, the total area of land devoted to agriculture, so it protects or enlarges the carbon sink areas of natural vegetation and afforestation to mitigate climate change.[84] Land not needed for agricultural production would also be available for other societal benefits such as recreation, rewilding, and solar farming.

Looking specifically at how precision agriculture increases the net positive effects of PPPs within a sustainable intensification strategy, we return to the ability of digital and engineering technologies to finely control farming operations. Combined these technologies afford levels of analysis and precision for the application of PPPs that simultaneously improves their efficacy in protecting higher yields and raises productivity by lowering the quantities used. This not only facilitates large cost savings in the use of PPPs,[85] but also has significant environmental benefits; a direct consequence of the ability to carry out site specific, targeted applications of PPPs.[86] Targeting applications only at those field areas where weeds, pests or pathogens threaten biotic stress lowers the risk of environmental contamination and damage to biodiversity.[87] As regards reductions in GHG emissions the literature suggests that the precision applications of synthetic PPPs is slight, as only emissions from their production are mitigated,[88] though the energy used in their manufacture represents about 9 per cent of the energy used in arable crops.[89]

The foregoing has unambiguously focussed on the role of PPPs in supporting efficient crop production, despite the fact that animal-source proteins will continue to account for a large proportion of diets. Although the usage of PPPs on grasslands in the UK is very similar to that on cereals,[90] it is the case that crops underpin most food systems as high yielding livestock production—especially monogastric species such as pigs and poultry—is reliant on cereals such as wheat, barley, and maize for feeds. That said, livestock productivity growth i.e., decreasing the number of livestock required per unit product, is also key to ecological sustainability. For example, in the UK dairy cow yields have steadily improved; had they remained at their 1970 levels by 2021 the quantity of milk produced would have

[80] Schwarz, J., et al., (2017) Typology of PF Technologies; FP7 Project Future Farm, http://www.futurefarm.eu/.

[81] Umetsu, N. and Shirai, Y., (2020), Development of novel pesticides in the 21st century, Journal of Pesticide Science, Vol. 45, No. 2, pp54-74.

[82] Oliver, M., et. al., (2013), Precision Agriculture for Sustainability and Environmental Protection, Earthscan, Routledge, Oxon.

[83] Finger, R., et. al., (2019), Precision Farming at the Nexus of Agricultural Production and the Environment, Annual Review of Resource Economics, https://doi.org/10.1146/annurev-resource-100518-093929

[84] Burney, J., et al., (2009), Greenhouse gas mitigation by agricultural intensification, PNAS, Vol. 107, June

[85] Jense, H., et. al., (2012), op. cit.

[86] Balafoutis, A., et. al., (2017), op. cit.

[87] Rajmis, S., et al., (2022), Economic potential of site-specific pesticide application scenarios with direct injection and automatic application assistant in northern Germany, Precision Agriculture, Vol. 23, No. 6, pp2063-2088

[88] Balafoutis, A., et. al., (2017), op. cit.

[89] Audsley, E., et. al., (2009), Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use, Cranfield University Report.

[90] Fera, (2023), Pesticide survey, Fera Science Limited, www.fera.co.uk

required a dairy herd more than double its size in that year. This yield growth, the product of improved breeding, feeding systems and health interventions, has not only avoided the need to expand grasslands into areas of natural vegetation and forestry but also constrained the growth of GHG emissions.[91]

At the start of this section we emphatically argued that land sharing sustainable intensification could not provide a practical solution the agriculture's trilemma. This should not be taken as a wholesale rejection of the farming practices associated with the land sharing version. Reality will be more nuanced and land sharing practices focused on increasing soil organic matter, avoiding erosion, and reducing disturbance to the soil e.g., regenerative practices, are compatible with land sparing sustainable intensification and precision agriculture. Regenerative farming shares with sustainable intensification and precision agriculture the aim of optimising productivity while at the same time protecting and improving the condition of the land. Both systems advocate the precise placement of inputs such as seeds, fertilisers, and PPPs, and both seek to minimise mechanical disturbance of the soil to retain organic residues. Regenerative farming practices for cereal areas include undersowing to prevent fallow immediately after harvest and for grasslands the planting of a mixed array of grazeable species, including legumes and herbs. As noted, precision agriculture guidance systems and controlled field operations increase the efficiency of zero or minimum tillage,[92] thereby contributing to the improvement of soil quality.[93]

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[91] Gill, M., et. al., (2010), Mitigating climate change: the role of domestic livestock, Animal, Vol. 4, No. 3, pp323-333

[92] Finger, R., et. al., (2019), Precision Farming at the Nexus of Agricultural Production and the Environment, Annual Review of Resource Economics, https://doi.org/10.1146/annurev-resource-100518-093929

[93] Oliver, M., et. al., (2013), Precision Agriculture for Sustainability and Environmental Protection, Earthscan, Routledge, Oxon

Seizing the Opportunities of Agriculture 4.0

UK agriculture prides itself as being at the forefront of the science and technology embedded in the 3rd Agricultural revolution. The previous section explained why sustainable intensification is the only practical response to agriculture's trilemma given the over-riding priority to ensure populations have access to a wide variety of high quality, affordable food. It further pointed out that the successful adoption of sustainable intensification will continue to rely on the full range of PPPs and increasingly on the use of precision agriculture to control their usage and avoid waste. Agriculture now stands on the cusp of the 4th Agricultural revolution and in this section, we will explore how the science and technologies associated with this revolution will reinforce the primacy of sustainable intensification by delivering step-changes in the efficacy of PPPs and their contribution to total factor productivity growth alongside significant benefits for the natural environment and climate change mitigation.

All agricultural revolutions have been driven by general advances in science and technology. In 2016 Klaus Schwab, Founder and Executive Chairman of the World Economic Forum observed that the world was on the brink of a technological revolution whose scale, scope, and complexity will result in a transformation unlike anything humankind has experienced before and that will fundamentally alter the way people live, work, and relate to one another. Schwab adopted the neologism of the Fourth Industrial Revolution for this transformation—usually expressed as Industry 4.0 or 4IR—to capture the merging of extraordinary advances in the fields of biological, digital, and engineering technologies. Focusing on the supply side, 4IR builds on the 3rd Industrial Revolution—often shortened to the digital revolution—which unfolded from the 1960s and used advances in electronics, information technology and connectivity to automate production. Industry 4.0 advances these technologies to enable the collection, interpretation, and velocity of vast and varied amounts of information—so called 'Big Data'—required by complex, foundational, disruptive technologies such as genome editing, nanoparticles, artificial intelligence (AI), and machine learning. Fusing these technologies via the Internet of Things (IoT)—the ability for devices and machines to autonomously exchange data and commands—will create, inter alia, 'cyber-physical production systems.' That is, smart factories capable of acting independently of human intervention to acquire and analyse vast amounts of information from their surroundings and then collaboratively use the learning to achieve specific goals.[94]

The adoption of Industry 4.0 technologies by agriculture will increasingly transform farm businesses, and their agri-food chain partners, into knowledge based 'smart enterprises' which, unsurprisingly is defined as Agriculture 4.0. Agriculture,[95] or more precisely, sustainable intensification, is in a prime position to gain from Agriculture 4.0 as biological, digital, and engineering technologies are all currently contributing, in varying stages, to modern farming. What Agriculture 4.0 offers is a step change in the efficient working of farming operations resulting from the ability to integrate and apply incredibly disruptive technological advances via highly sophisticated communication networks i.e., the IoT. Advances in biotechnology will deliver, inter alia, crops that more effectively utilise applied nutrients and increase the efficacy of PPPs. The rapid progression of digitalisation will allow the capture and analysis of vast, complex data sets enabling highly accurate, spatial, and timely actions. Engineering innovations will facilitate the autonomous collection of data e.g., drones, sensors, and its use to control automated field interventions. In essence, Agriculture 4.0 will speed-up and deepen the automation, flexibility, and productivity of precision agriculture; it will not only support increased output and minimise waste, but also it will significantly boost the contribution of sustainable intensification to avoiding ecosystem degradation and mitigating GHG emissions. In short, the scope Agriculture 4.0 offers to intrinsically mesh productive excellence with sustainability is a game-changer that can truly lay claim to represent the beginning of a new era in agriculture.

It is beyond the scope of this report to speculate and discuss in detail the enormous potential advantages likely to emerge as the fusion of biological, digital, and engineering technologies gathers momentum. Our focus is the role and likely development of PPPs in Agriculture 4.0 but even here we can only offer a broad outline. In part because the opportunities and potential benefits are very wide but also because the disruptive technologies underpinning the new revolution are only at the start of their life cycles. For comparison consider the status of information technology when in the 1970s, it was at the same stage in its life cycle as Agriculture 4.0 is now. Back then few saw how ubiquitous and transformative the technology would become, not only for production systems but also for the way it has influenced society behaviour

[94] Vaidya, S., et.al., (2018), Industry 4.0 – A Glimpse, Procedia Manufacturing, Vol. 20, pp233–238

[95] De Clercq, M., et. al., (2018), Agriculture 4.0, The Future of Farming Technology, World Government Summit, Dubai. https://www.worldgovernmentsummit.org

in general. Similarly, in discussing the potential impact of Agriculture 4.0 it is very likely that over the next 25 years the new technologies will deliver productive and environmental benefits significantly beyond those now envisaged.

The place to start in considering the role of PPPs in Agriculture 4.0's is plant breeding. We explained in Section 2 how the science underpinning the 'Green Revolution' greatly increased potential crop yields, the realisation of which at the farm level was in large measure dependent on parallel scientific advances in synthetic PPPs to enable the higher yielding crops to effectively resist biotic and abiotic stresses to which they were more vulnerable. Now biotechnological innovations have ushered in a 'Gene Revolution' which includes the introduction of recombinant DNA technology and applications of genome editing techniques. In the science of crop breeding, nanotechnology—the industrial use of matter at or near atomic scales—has emerged to create new transgenic and nontransgenic techniques which promise not only improved yields, quality, and resilience towards biotic and abiotic stresses, but also fewer inputs thereby mitigating the shortcomings of the green revolution outlined previously.[96] From the perspective of crop protection, in prospect are plants that will use biosensors to report regularly on their nutritional and health status.

Higher crop yields, critical to food security, cannot be achieved or sustained without synthetic PPPs, hence, for the foreseeable future they will remain integral to IPM strategies,[97] the more so given the pest threat that climate change is projected to have on cropping systems. We noted previously that PPPs are under constant development and Agriculture 4.0 will directly and indirectly enhance this process.An area of considerable promise for the development of novel PPPs is the interdisciplinary field of nanotechnology. Nanoinformatics—an area of nanotechnology involving the development of software tools for understanding nanoparticles—will be employed in the design and development of nanopesticides. Academic research in this field is gathering momentum generating considerable confidence that nanopesticide-based formulations will enable the development of safer and more effective synthetic PPPs.[98] That said, these advances are still at an early stage, and it may be some years before they are introduced, the more so as their revolutionary nature will ensure strong scrutiny by safety regulators.

Turning to the indirect benefits. Agriculture 4.0's fusion of digital and engineering advances will enable precision agriculture to record, interpret and act upon very large volumes of autonomously collected digital information. Utilising this digital information and advances in machine learning algorithms, AI is developing machines that are able to perceive, reason, learn, adapt, and make autonomous decisions to achieve specific objectives very efficiently. Again, these fields are too wide for a detailed discussion of the potential opportunities and benefits likely to be brought to precision agriculture, even if confined to the application of PPPs. What can be said with confidence is that both AI and machine learning are developing at pace and likely in the short-term to reach levels of maturity that, together with the IoT, will enable precision agriculture in real time to intelligently map instances of pests, determine the appropriate treatment and with pinpoint accuracy apply PPPs to pre- and post-harvest operations. Below, we set out, using the previously identified three precision agriculture technology categories—recording, reacting and guidance—a brief overview of likely Agriculture 4.0 developments that will help synthetic PPPs deliver markedly superior levels of efficacy and environmental benefits.

Remote sensing and proximal sensors already facilitate the collection and recording of data relating to soil conditions and crop management but as Agriculture 4.0 gathers pace these systems will be augmented by robots and other artifacts to deliver to farm businesses, from a variety of diverse sources e.g., climate, nutrients and pests, an exponential increase in the quantity and detail of data to support timely and accurate decision making. Under Agriculture 4.0 the recording capabilities of camaras and sensors will rise to new levels of refinement and machine learning algorithms will process the recorded information to identify in real time specific biotic and abiotic stresses e.g., weed species, as well as the boundaries of crop areas affected. This ability will become routine, and the processed information would be immediately accessible by the next stage, reacting.

The purpose of precision agriculture reacting technologies is to automatically deliver prescribed interventions, and this capability will be much enhanced by the IoT, AI and machine learning. Varying the mix, quantities, and placement of inputs in field areas can be separated into two stages: the processing/analysis of the recorded information to calculate the appropriate response; and the

Higher crop yields, critical to food security, cannot be achieved or sustained without synthetic PPPs, hence, for the foreseeable future they will remain integral to IPM strategies.

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[96] Hamdan, M., et al., (2022), Green Revolution to Gene Revolution: Technological Advances in Agriculture to Feed the World, Plants, Vol 11, No. 10,

[97] Keulemans, W., et. al., (2019), Farming without plant protection products. Can we grow without using herbicides, fungicides and insecticides? Scientific Foresight Unit, Brussels, March

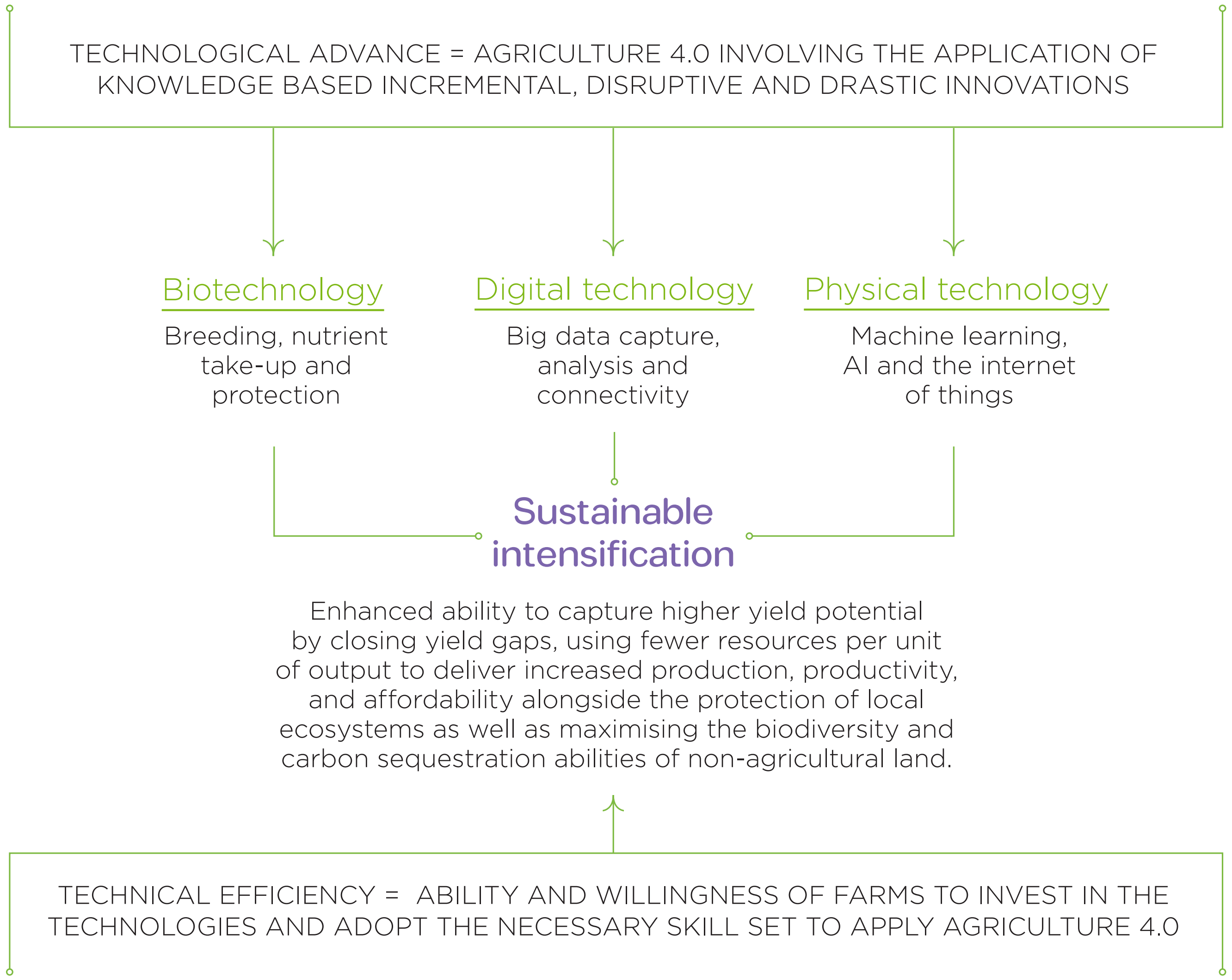
[98] Athanassiou, C., et. al., (2018), Nanoparticles for pest control: current status and future perspectives, Journal of Pesticide Science, Vol. 91,pp1-15.

action taken to apply the response. The ability of AI and machine learning to identify even elusive patterns in large datasets—the larger the dataset the more powerful the machine learning model—will not only enable more accurate predictions of future outcomes, but also more accurately determine the most effective action. Having determined the need and nature of an intervention the information will be sent to AI-machines i.e., smart and automated, capable of autonomously undertaking the necessary actions. For example, if the threat identified was a particular weed the technology could select and dispense the appropriate herbicide without human intervention. It follows that the capacity to systematically analyse vast amounts of data, make choices, and send commands to machines and devices will greatly increase the effectiveness of precision agriculture operations.

The second stage of reacting is facilitated by guidance technologies where spatial resolution developments will make it increasingly possible for variable rate application systems to treat small areas very precisely, thereby significantly reducing the quantities of active ingredients applied without any loss of efficacy. Further, autonomous mobile robots utilising the IoT, AI and machine learning will apply PPPs without human intervention, allowing individual farms to do more in the area of crop protection with fewer people. Continuing the example of weed treatment, the combination of a nanoherbicide and highly sophisticated variable rate application systems technology greatly diminishes the likelihood of excess being left in the soil and therefore little or no impact on ecosystems. The ability to apply target-specific, minimal quantities of PPPs promises a step change in the efficiency of farming operations to exceptional levels of sophistication; not only will superior efficacy become the norm but also, by approaching the ultimate goal of zero waste, they will involve less harm to the environment.[99]

The scientific and technological advances summarised above represent not only a major contribution to the efficiency of UK farm businesses but also a huge opportunity for agriculture and its supply chain partners. However, in order for the industry to take full advantage it must tackle the perennial issue of 'yield gaps'. Agriculture 4.0 offers the prospect of significantly higher crop yields but in practice, actual yields always fall short of their potential. In part this is due to biotic and/or abiotic factors e.g., inclement weather, but managerial shortcomings are also a factor. This may reflect a lack of knowledge,

Figure 4.1: Reaping the Benefit of Agriculture 4.0



TECHNOLOGICAL ADVANCE = AGRICULTURE 4.0 INVOLVING THE APPLICATION OF KNOWLEDGE BASED INCREMENTAL, DISRUPTIVE AND DRASTIC INNOVATIONS

Enhanced ability to capture higher yield potential by closing yield gaps, using fewer resources per unit of output to deliver increased production, productivity, and affordability alongside the protection of local ecosystems as well as maximising the biodiversity and carbon sequestration abilities of non-agricultural land.

TECHNICAL EFFICIENCY = ABILITY AND WILLINGNESS OF FARMS TO INVEST IN THE TECHNOLOGIES AND ADOPT THE NECESSARY SKILL SET TO APPLY AGRICULTURE 4.0

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[99] Shaikh, T., et. al., (2022), Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming, Computers and Electronics in Agriculture, Vol. 198, July

poor agronomic skills, mistakes, or cognitive limitations relating to the perceived costs and benefits of fertiliser and PPPs applications and/or an unwillingness to experiment with higher-yielding techniques. Some farmers may deliberately choose less productive systems to pursue non-economic objectives others may be subject to irrational biases.[100] In the UK the cereal yield gap is large: potential cereal yields are calculated to be between 14 and 19 tonnes per hectare compared to current averages of between 7 and 9 tonnes per hectare.[101] Sustainable intensification, utilising knowledge based Agricultural 4.0 technologies makes narrowing this gap a realistic prospect. That said, ultimately the take-up of these technologies and techniques depends on the willingness and ability of farmers to invest in the technologies and the learning inherent in adopting the necessary skill set. *Figure 4.1* attempts to summarise the importance of recognising that maximising the benefits of Agriculture 4.0 technologies for sustainable intensification will necessitate the parallel development of appropriate skills and mind set by farm level decision takers.

The foregoing has outlined how embedding Agriculture 4.0 technologies in precision agriculture will deliver total factor productivity growth by enabling farm businesses to use fewer resources per unit of output, including a reduced need for people to undertake repetitive, manual tasks. This has obvious benefits for the production of affordable, higher quality food as well as farm profits. However, if the UK is to benefit there will need to be public acceptance of Agriculture 4.0 technologies. Cases of limited acceptance of agricultural technologies are not uncommon e.g., resistance to genetic modification, so it is important that the contribution of advanced technologies to mitigating the twin costs of food security and food inflation—concerns that are now prominent in public and political debate—is widely understood. In obtaining public support it is also important to stress that Agriculture 4.0 is a responsible direction of travel that will contribute positively to the natural environment and the mitigation of climate change.

We explained in the previous section that precision agriculture is the operational counterpart to sustainable intensification as it more efficiently enables site-specific applications of inputs. In the case of PPPs, the outcome is a reduction in the volume of active ingredients applied, and the greater the reduction the lower the risks to a farm's biodiversity.[102] In this section we have stressed that embedding Agriculture 4.0 technologies in precision agriculture will make it increasingly possible to precisely confine applications to ever smaller areas of fields where the density of weeds, pests or pathogens are causing actual biotic stress, and as a result floral resources and habitats will be largely sheltered with beneficial outcomes for a farm's biodiversity and its ecosystem services.[103]

Turning to a region or nation's biodiversity, a benefit, arguably the greatest benefit for sustainable intensification arising from the integration of Agriculture 4.0's technologies in precision agriculture, is the considerable potential it offers taking advantage of potential yield growth in part by narrowing yield gaps. In introducing sustainable intensification, we explained that there exists a significant empirical literature underpinning the thesis that both biodiversity and its ecosystem services, including the provision of public goods, are maximised by separating land for nature from land for agriculture.[104] That is, increasing production from a given area is preferable to increasing the agricultural land area as it preserves the ecosystem services of natural vegetation and forestry land not in agricultural production. Hence, the faster yield gaps are narrowed as potential yields continue to rise the greater the scope to scale-back crop areas,[105] creating significant gains for the natural environment, more scope for carbon sequestration and wider opportunities for recreation.

Yet a further societal benefit furnished by precision agriculture's adoption of Agriculture 4.0 technologies, is climate change mitigation. In part this will be realised by reductions in the volumes of agricultural inputs used in production; principally, energy, fertilisers, and PPPs. In addition to cumulative improvements in the efficient management of inputs, precision agriculture, or more precisely its ability to optimise field traffic movements, will beneficially augment mini- or zero-tillage. As noted in the previous section, combining zero-till farming with minimising the movements of farm machinery mitigates climate change i.e., it delivers fossil fuel savings and it enhances carbon sequestration thereby preventing the release of GHG emissions.[106] Zero-till is also described as regenerative tillage as it leaves crop residues in the field, protecting the soil from wind and water erosion and builds climate resilience by enhancing soil health. Healthy soil has a higher water-holding capacity i.e., it can better absorb and hold water during periods of heavy precipitation and drought, making farms more resilient to extreme weather.

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[100] Mueller, N. and Binder, S., (2023), Closing Yield Gaps: Consequences for the Global Food Supply, Environmental Quality & Food Security, Journal of American Academy of Arts & Sciences, Vol.144, No. 4, pp45-56.
[101] Farmers Weekly, (2022), Reporting ADAS, Yield Enhancement Network, 6th September.
[102] Bongiovanni, R. and Lowenberg-Deboer, J., (2004), op. cit.
[103] Balafoutis, A., et. al., (2017), op. cit.
[104] Benton, T. and Harwatt, H., (2022), op. cit.
[105] Folberth, C., et. al., (2020), The global cropland-sparing potential of high-yield farming, Nature Sustainability, Vol. 3, April, pp281-289
[106] Jensen, H., (2012), op.cit.

As explained hitherto, we have focused on cereal crops because they underpin the food system, particularly in the northern hemisphere. That said, horticultural crops and grasslands are also dependent on PPPs, where applications are very similar to those for cereals.[107] It is the case that all we have said about Agricultural 4.0 technologies is applicable to all agricultural sectors, particularly with regard to improving the productivity, capacity, welfare, and management of livestock. For example, sensors will monitor their health in real time, providing data-driven insights to support producers rapidly making meaningful management decisions. As ruminants grazing livestock contribute significantly to GHG emissions and again Agriculture 4.0's technologies hold out the promise of advances in breeding genetics and feed nutrition that will aid mitigation as will higher yields i.e., increasing the output of meat/milk per hectare reduces the numbers of ruminants and thereby the industry's Net Zero target.

No doubt many who will view the foregoing as evidence of agriculture's high-tech future with concern, even regret, as it represents further industrialisation and a threat to third world producers who are seriously lagging in the take-up of agricultural technologies.

While we do not resile from our belief that the role of science and technology in boosting productivity continues to be critical to delivering food security including affordability, we are mindful that change, particularly radical change brings with it social costs as well as benefits. For example, Agricultural 4.0 technologies will reduce the need for manual labour, a benefit in advanced nations where agricultural labour shortages are a perennial problem but a concern in developing countries where alternative opportunities may be limited. What is required is an open and balanced debate on Agriculture 4.0 technologies, within the context of agriculture's trilemma, where the promised benefits are considered alongside potential social and ethical impacts.

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[107] Fera, (2023), op. cit.

End Piece

Agriculture 4.0's technological advances promise significant total factor productivity growth while protecting the diversity and functioning of ecosystems.

The foregoing has sought to make the case that only a food production strategy based on sustainable intensification utilising Agriculture 4.0 technologies, in which PPPs will continue to play a critical role, is capable of adequately addressing the three key challenges set out in Section 2. Our case has drawn heavily on academic studies that reveal a consensus that Agriculture 4.0's technological advances promise significant total factor productivity growth while protecting the diversity and functioning of ecosystems as well as reductions in GHG emissions and other contributions to Net Zero. In 2018 Defra declared that taking advantage of the next generation of food and farming technology, adopting the latest agronomic techniques, reducing the impact of pests and diseases, investing in skills and equipment, and collaborating with other farmers and processors promised a huge opportunity for UK agriculture to improve its international competitiveness.[108]

We agree. In the previous sections we have added flesh to Defra's declaration by arguing that that not only would the widespread adoption of precision agriculture, incorporating Agriculture 4.0 technologies and agronomic techniques, reinforce the benefits of sustainable intensification but also it would generate potential growth opportunities for the UK agri-food chain. The government's post-Brexit policy of 'Global Britain' has at its heart the encouragement and support of free trade,[109] but within this context growth opportunities for the UK agri-food chain can only be realised if it is internationally competitive. The UK currently produces about 76 per cent of its demand for indigenous type food,[110] and its current trade deficit of £25.6bn in food and drink,[111] is in danger of worsening as more post-Brexit trade agreements are ratified with countries where agricultural production costs are low. Productivity growth and high standards at the farm level, are necessary conditions for international competitiveness, but they are not sufficient. Agricultural productivity growth is the guarantee of affordable food prices, but to succeed in dynamic, global food markets, UK food manufacturers will need more than the boost of Industry 4.0 technologies to the timely delivery of quality products at affordable prices.

Across the world, burgeoning, urban, middle classes are increasingly revealing a broadening demand for distinctive, differentiated food products that, extend beyond experience attributes such as taste and convenience to credence attributes such provenance, safety and ethical production.[112] The adoption of

EXPERIENCE ATTRIBUTES

1. Quality and taste
2. Value for money
3. Brand reputation
4. Supply chain visibility

CREDENCE ATTRIBUTES

1. Provence and safety
2. High standards
3. Environmental protection
4. Climate change mitigation

Figure 5.1: Food Products: International Competitiveness Attributes

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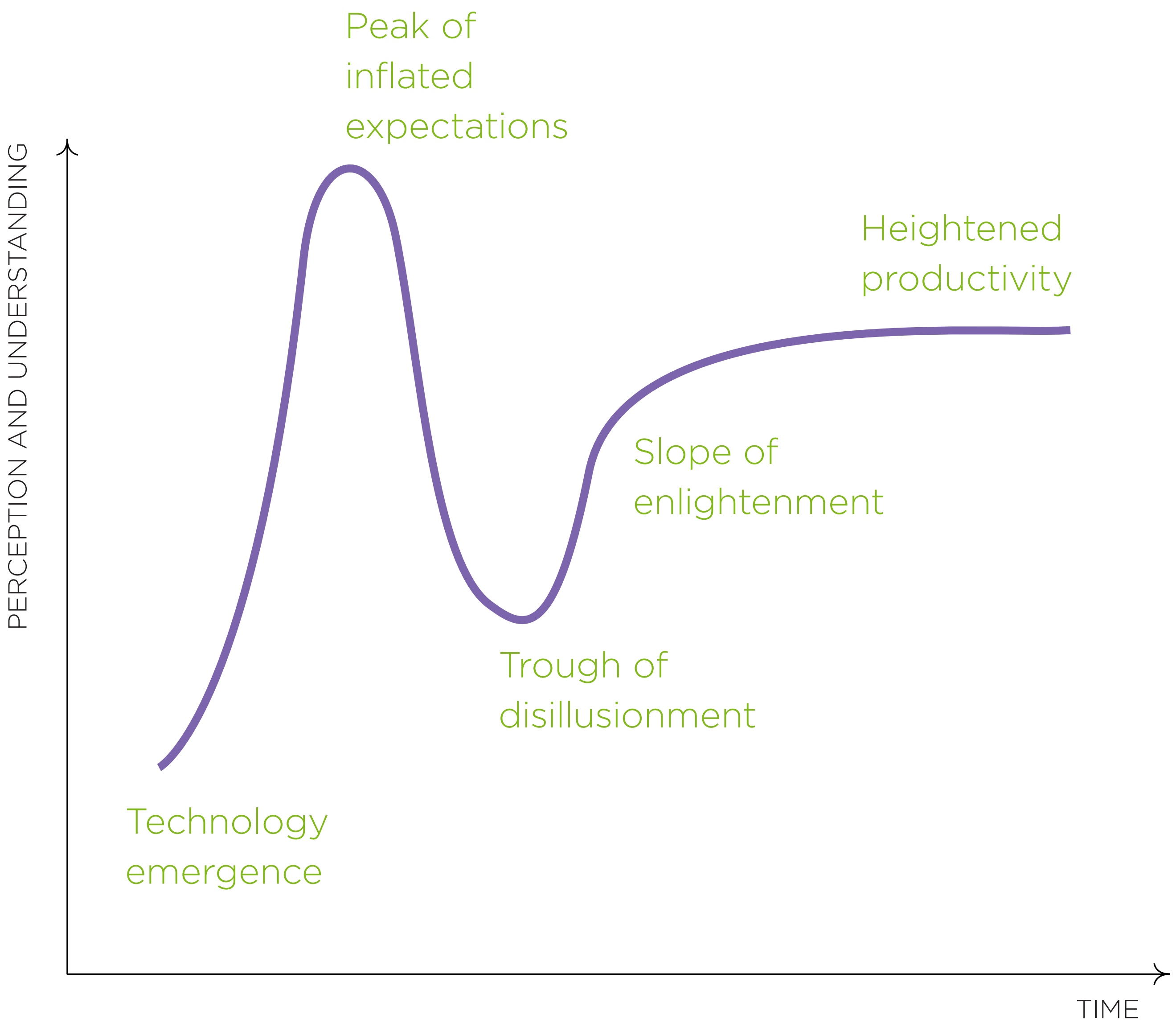
[108] Defra, (2018), Health and Harmony: the future for food, farming and the environment in a Green Brexit, London, February.
[109] Prime Minister speech at Greenwich, 3rd February 2020
[110] Defra, (2021), United Kingdom Food Security Report 2021: Theme 2: UK Food Supply Sources, London
[111] Defra, (2023), Chapter 13, Agriculture in the UK, London, October
[112] Umberger, W., (2015), Demographic Trends: Implications for Future Food Demand, Agricultural Symposium, Federal Reserve Bank of Kansas City, July

Agriculture 4.0's technologies and agronomic techniques offer scope to build on the UK's positive credence reputation by improving key aspects of ethical production; namely, food safety, environmentally friendly and carbon neutral production. n essence, the UK's agri-food chain is likely to improve its international competitiveness by credibly exploiting credence attributes in differentiating its food products. As credence attributes are largely delivered at the farming stage this will necessitate transparency and traceability in the agri-food chain to overcome information asymmetries relating to the production of agricultural commodities.[113] *Figure 5.1* summarises the experience and credence attributes that promise to boost the international competitiveness for UK food products. The implication is that for UK producers, international competitiveness for food products must be supply chain based so that farm sector credence attributes are given the prominence they need to contribute critically to distinctive, value-added food products.

The agri-food chain is a large industrial grouping and its growth, based on the expansion of agricultural output, would make a significant contribution to the UK's economic growth and trade balance. A larger agri-food chain would increase self-sufficiency and food security as well as helping to keep food prices at affordable levels, all issues now high on social and political agendas. Exploiting these opportunities will depend, inter alia, on the robust and widespread adoption of a strategy of sustainable intensification founded on precision agriculture in which Agriculture 4.0 technologies are embedded. As home to universities and research institutes regarded as world leaders in areas ranging from crop and animal science to AI and machine learning, the UK is potentially well placed to take advantage of this new agricultural era including the breeding of higher yielding, more resilient crops as well as the development of new and improved PPPs and agronomic advances in the efficiency of their application. That said, maintaining a leading position will require significant investment from the public and private sectors.

The world's agricultural industries stand on the threshold of a renaissance for food production based on new and exciting scientific and technological advances, ranging from nanoscale up to integrated farming systems. In 2013 the government launched the UK Strategy for Agricultural Technologies tasked with the ambition for the UK to become a world leader in agricultural technology, innovation, and

Figure 5.2: Five Stages of Technology Take-up



Source: Adapted from Fenn and Linden, see footnote

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[113] Schrobback, P., et.al., (2023), Food Credence Attributes: A Conceptual Framework of Supply Chain Stakeholders, Their Motives, and Mechanisms to Address Information Asymmetry, Foods, Vol. 12, January

sustainability. Funding of £90mn over five years was made available to establish a number of Centres for Agricultural Innovation to support advances in sustainable intensification. This initiative has been superseded by Defra's Farming Equipment and Technology Fund, but it might fairly be questioned whether the size of the grants on offer are sufficient to propel UK agriculture to the forefront of the Agriculture 4.0 revolution. Precision agriculture has been gaining momentum for some years but despite the paucity of statistics, there is a consensus that the pace of adoption in the UK is slow, and certainly slower than comparable competitors,[114] raising the fear that the UK, despite its many advantages in the area of agri-science and technology, is in danger of lagging behind other countries. Many Agriculture 4.0 technologies involve high investment costs and we have questioned whether current funding is sufficient. At the farm level additional hurdles have been identified including inter alia farm scale and the age of farmers.[115]

Agriculture 4.0 is only at the start of its lifecycle, and we might expect that the pace of adoption will be confronted by a number of obstacles. One approach to understanding the pace of adoption for a new technology is the 'Gartner Hype-Cycle' set out in Figure 5.2, which shows how, at the industry level, perceptions and understanding change over time to encourage take-up.[116] The emergence of a new technology is often accompanied by unrealistic hype and inflated levels of expectations—a position this report has sought to avoid. This is followed by the practicalities of adoption e.g., costs and skills gaps, resulting in a level of initial disillusionment. The next stage, advanced by commercial developments and frequently government support, engenders growing appreciation (enlightenment) of the technology's real benefits. The pace of take-up then increases which eventually delivers the expected higher levels of industry productivity, the final height of which varies according to whether the technology is broadly applicable or niche.

The embedding of Agriculture 4.0 technologies in precision agriculture offers the promise of solving agriculture's trilemma, is accepted this impels that speeding up the pace and widespread take-up of these technologies should be a priority.

If this report's central thesis, that the embedding of Agriculture 4.0 technologies in precision agriculture offers the promise of solving agriculture's trilemma, is accepted this impels that speeding up the pace and widespread take-up of these technologies should be a priority—the more so as it opens realistic opportunities for the UK's agri-food chain. This, we suggest, will necessitate a wide ranging, joined-up strategy on the part of government. According to one study, take-up is frustrated by the lack of interoperability i.e., technologies made by different companies do not always talk to one another, the lack of infrastructure e.g., access to reliable broadband as well as the ease of use and lack of skills at the farm level.[117]

Existing high standards of PPP regulation should be maintained but regulating innovation should be pragmatic and evidence-led.

Agriculture 4.0 also requires an updated regulatory environment not only relating to autonomous machines and robots,[118] but also PPPs. Existing high standards of PPP regulation should be maintained but regulating innovation should be pragmatic and evidence led, to provide the right foundations for the necessary economic incentives, whilst also meeting the food security and environmental challenges outlined in this report. Many of the current regulatory approaches inherited from the EU are based on an overly restrictive and often disproportionate interpretation of the precautionary principle. In the area of crop protection and the environment, the recommendations of the Government's policy paper should be embraced by applying regulation proportionately and considering new innovation holistically in terms of consumer benefit, food productivity and security, and delivery of climate and biodiversity goals.[119]

Finally, we are well aware that the widespread adoption of the technologies and farming operations set out in this report require economic incentives, but also political and social support. Although referred to in a Defra discussion document,[120] the details of a more comprehensive production strategy for agriculture involving increased output growth, are lacking as are the elements to encourage much deeper integration e.g., partnerships, between the various stages in the agri-food chain. Trusting, collaborative relationships between supply chain partners and also research institutes have a number of benefits. They would help scientists and technologists to understand the needs and constraints of farm businesses more accurately and also to ensure that advances are relevant to market needs. Government support is pivotal to ensuring that farmers have access to the levels of skills and finance required. As regards social support. Until recently in the UK the issue of affordability has not been emphasised in public discussions of agriculture. Recent events have served to remind that this, alongside safety and quality, is the priority for food production. This only serves to reinforce our earlier plea that what is required is an open and balanced debate where the opportunities that advanced technology offers for not only solving agriculture's trilemma but also for advancing the economic contribution of the UK's agri-food chain are set against potential social and ethical impacts. We hope this report contributes to such a debate.

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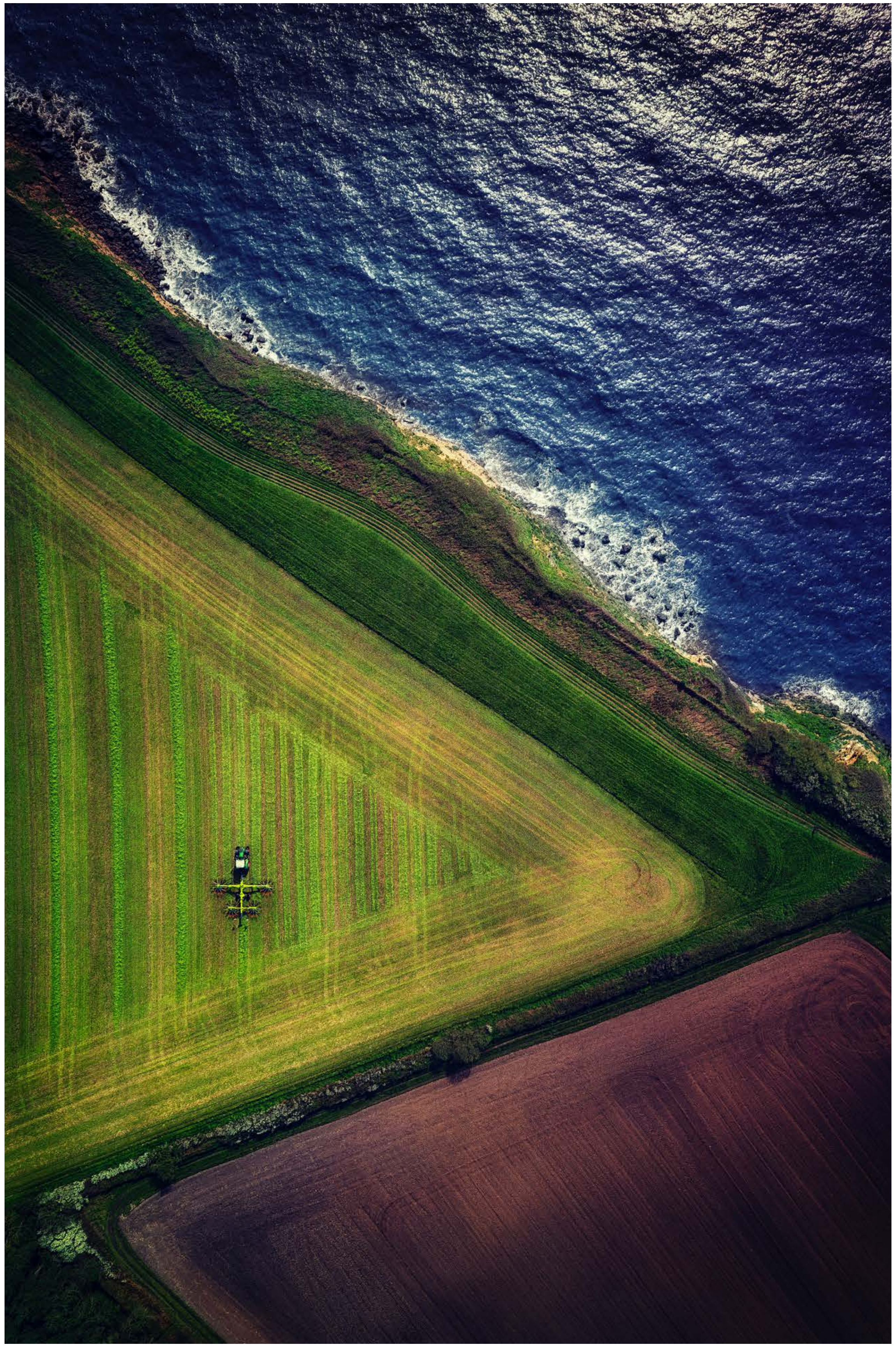
A report prepared by
Sean Rickard

Sean Rickard is a graduate of the London School of Economics specialising in the economics of industry, and post-graduate graduate of Birkbeck College, London. He spent 20 years as a professional economist culminating in serving as Chief Economist and Head of the Economics at the National Farmers Union; during this time, he advised the highest levels of government and the European Commission.

In 1995 Sean joined the Economics Group of the Cranfield School of Management as senior lecturer and later director of MBA programme and director of MBA admissions. During this time Sean acted as a government academic advisor providing strategic advice to a series of governments and the private companies, largely in the field of food and farming. Since 2011 Sean has worked as an independent economic consultant providing economic analysis related to agriculture.

In 2019 Sean produced with CropLife UK, 'Plant Protection Products: The value of their contribution to lowering UK household expenditure on food and drink' examining the impact of Plant Protection Products on UK household bills.



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