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REVIEW

Developing a new agenda for increased food and climate security

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KEYWORDS

Climate resilience, food security, human health, planetary health, regenerative agriculture

HIGHLIGHTS

- The urgent need to address increasing worldwide food and climate insecurity.
- Potential conflicts between these aims.
- Environmental challenges require a revolution in global farming practices.
- Growing concerns over diet-related health problems.
- New plant science to reduce global food insecurity.

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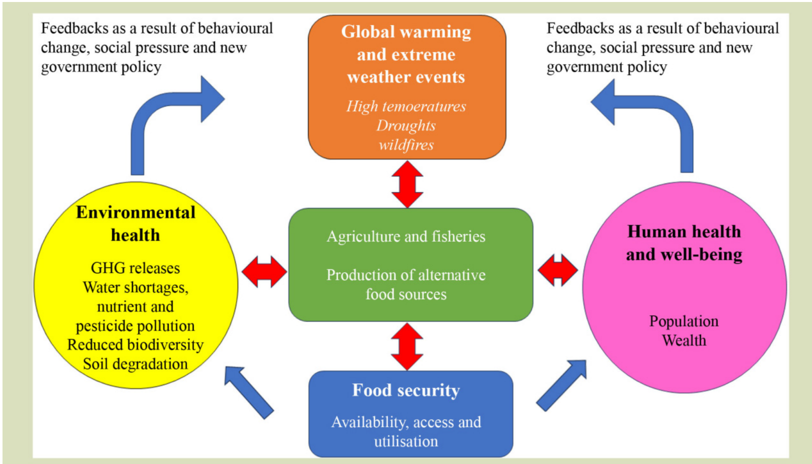
GRAPHICAL ABSTRACT



ABSTRACT

In many countries, political and environmental pressures are currently combining to generate a perfect storm of circumstances that is reducing food availability, increasing food costs and thereby reducing the availability of food to many. The UK is currently considering new national food and land management policies, and attention is also being given to legislation to address diet-related health issues. Many now argue for a revolution in UK farming practices to reduce their impact on the natural environment. The UK is not alone in facing these and other challenges. Both the contribution of agriculture to greenhouse gas (GHG) emissions and the effects of climate change on food production are issues receiving worldwide attention. Regenerative agricultural practices can result in greater C capture, reduced GHG emissions, enhanced soil quality and enhanced biodiversity. However, it is questioned if such farming systems will be productive enough to feed a growing population with the food required for social and health benefits. To fully exploit the impact of new plant science in farmer fields, it is imperative to effectively link science to farming practices and conduct a broader conversation around the food revolution with social scientists and with the general public.

1 Introduction

Nearly 15 years ago, the world was shaken by significant spikes in the price of food on the global market. Many people in many countries, who were already spending a large proportion of their income on food, experienced increased difficulty accessing sufficient nutritious, safe food to enable them to lead active healthy lifestyles. Food price spikes were attributed to increased demand for meat products in rising economies, such as China and India, decreases in agricultural yields and food stocks, futures market speculation, rising energy prices, growing demand for biofuels, depreciation of the US dollar and various trade shocks related to export restrictions, panic purchases, and the rising frequency of occurrence of unfavorable weather[1].

The global response to a rising concern over food security in the early 2000s was multifaceted but prominent among the responses to the food challenge was a surge in interest in increasing global food production, with much attention focused on sustainable intensification of agriculture[2,3]. The necessity to ensure that agricultural intensification is indeed sustainable was highlighted by the threat of what became known as a perfect storm of circumstances affecting global food systems[4]. The UK Chief Scientist at that time (Sir John Beddington) noted that the then current predictions suggested that by 2030, in order to feed a growing population, the world would need to produce 50% more food and energy. This and other global developments would require 30% more available fresh water. At the same time, agriculture would also need to mitigate and adapt to the challenge of climate change. In the years since Beddington’s influential paper, many have noted that while the production of more food can feed more people, it does not necessarily result in increased availability of food to needy individuals and that additional changes in our food system will also be required. We are now nearly half way to Beddington’s reference year of 2030 and it seems appropriate to ask how much progress we have made in turbo-charging our food systems with a food revolution.

In 2023, we are once again hearing much talk of a global food security crisis. Global food prices are increasing, partly because of the reduction of grain and cooking oil exports from both Russia and Ukraine, as a result of conflict in the region. This conflict is also pushing up energy prices, a change which is adversely impacting many, but farmers are particularly badly hit as prices of fuel for farm machinery rise and the cost of fertilizer increases significantly. These changes have caused many farmers in Europe to delay planting or seeding because of uncertainty whether market returns will match the increase in the cost of input resources. Labor is in short supply in many countries, at least partly because of changes in work habits in response to COVID-19. In the UK, Brexit has exacerbated this problem, resulting in an increase in food waste as some crops remain unharvested in the fields.

While a revolution in food and agriculture is central to increasing the availability and the quality of food, there are many interactions in the food system (Fig. 1)[5], such that however sustainable are our efforts to intensify agriculture and improve food systems, there will potentially be some unpredictable and undesirable impacts of such changes. It is therefore important that we adopt a systems approach in our planned food revolution. This is true for increased understanding of global food system perturbations but as we shall see it is also the case when we are looking to intervene with new biology to enhance productivity under a variety of environmental stresses.

One factor of enormous importance, given our rising concerns for the increasingly negative effects of global warming, is that agriculture is a primary driver of global climate change[6]. This is a result of high levels of greenhouse gas emissions from livestock farming in particular, but also from intensive land management for food and field crops[5,7]. While the release of greenhouse gases (GHGs) as a result of a range of farming practices is much discussed, we should also focus on the carbon opportunity cost (COC) imposed by farming. The COC is the carbon dioxide that the land could absorb if it were not used for food production. For soybean, for example, the COC is 17 (kg CO_2)·(kg protein)$^{-1}$ produced whereas for beef it is 1250 (kg CO_2)·(kg protein)$^{-1}$[8]. Other environmental issues generated by intensive food production include excess use of water, pesticides and nutrients, and declining biodiversity and soil quality.

At the time of writing (spring 2023) world leaders were still struggling to agree the measures that are likely to be required to deliver on sufficient climate mitigation to limit global warming, as suggested in the Paris Agreements[9]. Following COP 28 held in Egypt in 2022, despite some recognition of the urgency of action, commitments on restricting emissions are still unlikely to limit global temperature rises to the 1.5 °C recommended by the Paris Accords, a value considered crucial if the world is to avoid the most severe climatic impacts on the ways that we currently lead our lives. In 2019, global carbon emissions from fossil fuels and industry reached a high of 36.4 Gt. Although emissions fell in 2020 (as a result of COVID-19 and the resulting economic crisis), in 2021 emissions grew again by 6% to 36.3 Gt. According to NASA, 2020 tied with 2016 as the

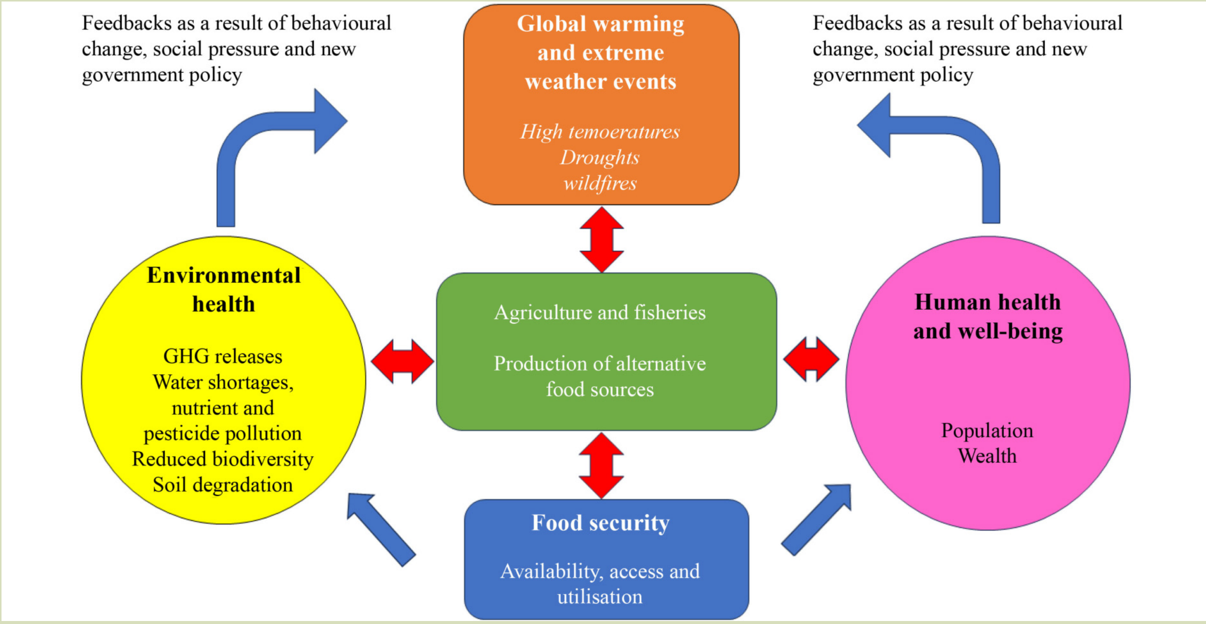


Fig. 1 A food systems approach to understanding the impact of global warming on food and farming, environmental health and human health and welfare.

hottest year on record. Notably, the 2020s temperature level was reached without it being an El Niño year, as it was in 2016. In the UK, the 21 century so far has been warmer than any other period of equivalent length from the last three centuries[10] and we are seeing a rising frequency of extreme weather events in most parts of the world (resulting for example in wildfires in southern Europe and western USA, and flooding in many countries in Asia). These record-shattering weather events have spurred advances in our efforts to understand how climate change is associated with the occurrence of extreme weather events.

2 Some climate, food and agriculture issues for the UK (and for much of the rest of the world)

I discuss below proposals by the UK Government to increase the environmental sustainability of UK food production and supply systems but we should also note that the UK imports food from nearly 200 countries across the globe[11], thereby generating emissions and other pollution, and resource-use issues offshore as a result of both production and transport of food. The UK has committed to achieving net zero by 2050, and this will likely require significant changes to environmental accounting and food systems both at home and abroad[12].

As well as environmental damage caused by the operation of the food system, inappropriate diets and consumption of too little and even too much food contribute to a wide range of human health problems. The EAT Lancet Commission[13] and others have stressed that to address these and other food challenges requires nothing less than a planetary food revolution. A large part of this will inevitably be driven by the 2.5 billion smallholders and their small production units which provide up to 80% of the food supply in Asia and sub-Saharan Africa[14]. Many of these people live in some of the most climatically and socially vulnerable regions in the world, and many changes in food and farming will need to be specifically tailored to these regions (as is discussed in this paper). In more-industrialized agricultural systems, such as in the UK, agricultural productivity is high but changes to the food system combined with interventions based on modern plant and crop science can still help achieve sustainable intensification of food production systems with increased emphasis on issues such as reversing environmental damage caused by current farming systems and increasing the quality of food consumed by many. Ultimately, our aim must be the development of sustainable food systems that are healthy for people and the planet, and fair to those working in these systems[15].

Current global conflicts and a rise in the general cost of living in the UK (and many other countries) mean that more people are struggling to access adequate amounts of good quality food.

Children's health is particularly vulnerable to high fat, sugar and salt content of much relatively cheap, ultra-processed food. Deteriorating public health is a major social challenge in many regions and malnutrition is now a leading cause of early deaths globally. These deaths are not just caused by lack of food. Overeating of poor quality food is a major problem even in the developed world. Over half of the global population is now underweight, overweight or obese[16]. By 2035, two thirds of the UK population may be malnourished. The childhood obesity problem in the UK is particularly acute[17].

As a result of these challenges, making more reasonably-priced, healthy food available to more people is one of a number of high social priorities for the UK and many other countries. Changes in our food system will require an increased focus on where and how food is actually produced. In the UK and in countries that export food to UK, food is produced on farms ranging in size from one person-operations to multinational, often-industrialized organizations. A revolution in agriculture across the board will not be easy to achieve, and various kinds of sustainable production units and the potential requirement for more food that is not sourced from agriculture are discussed below.

Our focus must also be on more reliable and sustainable international trade in food. In the UK, attention must also be given to the prospects of UK-based producers increasing the proportion of food consumed here that is actually produced here. One motivation for such a change would be the comparative fragility of our food supply chains, a fragility recently exposed by the conflict in in Ukraine. No matter how good our agronomy and plant science, producing more food in UK is not necessarily a straightforward option. The recent National Biodiversity Network report on biodiversity in the UK[18] emphasizes the point that loss of soil biodiversity threatens sustainability of ecosystems and that UK retains only half of its natural biodiversity, much of this in the soil. There are about 11 million species of soil organisms and the health or otherwise of this community is one of the major indicators of soil health. Emmett and coworkers[19] found significantly fewer invertebrates in arable habitats than other habitats and there are considerable data showing worldwide decline over recent years in soil health and soil biodiversity[20]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has reported that of all the practices affecting our natural environment, land-use changes have had the greatest overall negative impact on nature since 1970[21].

A critical question (as considered below) is how we can produce more food while concurrently addressing associated environmental challenges, i.e., effectively making room for nature. Will this, for example, necessitate the development of new soilless production units in which crops are grown either in artificial substrates or solution culture? Cusworth and coworkers[22] have promoted the idea of such comparatively low-technology facilities for intensive crop production located close to centers of population as a means of making more healthy homegrown foods (fruit and vegetables) available to increased numbers of people. This potentially very attractive idea has the potential disadvantage of increased buildup of agriplastic pollution in soil with many undesirable environmental and health impacts. A more extreme option for the production of food with a low environmental footprint is the production of laboratory-grown protein as a food source. Culturing animal cells in the laboratory[23] involves harvesting stem cells from a small stock of animals. Cell cultures are then fed with a nutrient-rich solution including blood drawn from bovine fetuses. Cells grow into a meaty pulp which can then be formed into a food item which is acceptable to consumers.

A food-culture option that can be more appealing to many is to use plant cells to create products that can replace meat. A range of companies are now using protein from wheat, soybean, peas and other species as a starting point for culture. Algal protein is another option. In the USA, leghemoglobin is added to cultured protein products to give them a meaty flavor. This is a protein which contains the same heme iron that gives meat its distinctive bloody taste.

Microbial protein[24,25] is another farm-free possibility which could produce significant quantities of food with a much reduced impact on the natural environment[26], although there are costs associated with electricity use during culture. Solar energy is an attractive option for this with energy generation potentially geographically decoupled from CO_2 capture, extraction and conversion into microbial biomass. This theoretically allows for production of microbial biomass anywhere in the world, independently of local climate conditions or land availability as long as there is access to CO_2 and water[26].

The environmental benefits of these new laboratory-made foods are clear, with a claim that production of protein for one commercially-available *alternative* burger involves the use of 96% less land than required to produce a beef burger, 87% less water and emits 89% less greenhouse gas[27].Growing numbers of papers[28,29] are now promoting the benefits of different laboratory-produced foods. A report by the UK Royal Society has predicted that within 10 years, 10% of the global meat industry could be replaced by alternative proteins [30].

3 Increasing future food security while restoring the rural environment

Considering the operation of our current food system, Global Food Security (GFS) UK[15] notes there is a potential conflict in the different policy decisions that might be made to both produce more food and reduce the environmental impact of our food system. Despite some success in recent years in feeding the global population (partly a result of increased production in key locations but also through advances in the effective distribution of food), there is still nearly a billion people needing increased access to more good quality food[29]. Mostly, those concerned with global food insecurity have focused upon food shortages in the developing world but the current conflict in Ukraine and other economic challenges are adversely impacting the supply of food in both the developing and the developed world. For example, in 2023, there is a general increase in the cost of living for all in the UK[30] and we are now faced with a combination of circumstances that can be described as another perfect storm of factors that are threatening both our food and environmental security, meaning that we must redouble our efforts to respond appropriately to this growing range of challenges.

Scenario planning by GFS UK[15] considers different potential impacts of changes in the way we may have to live our lives in order to deliver on two much-lauded, landmark global agreements aimed at delivering greater environmental and food security, namely, the Paris Agreement on climate change[9] and the UN Sustainable Development Goals (SDGs)[31]. Scenarios were developed based around two significant uncertainties that will drive changes to the food systems of different countries. First, it is critical to know what would be the impact on our food systems if they were transformed to deliver either some climate mitigation[32] or to deliver on the broad range of sustainability metrics implicit in SDGs[31]. A second uncertainty for food systems, such as in the UK, is the extent to which the population will increasingly need to depend on locally-produced food or will continue to rely on significant quantities of imported food with all of its growing uncertainties and environmental implications.

The UK produces just over 50% of the food that we eat but only 23% of the fruit and vegetables consumed (which are essential for a healthy diet). In the UK, 70% (c. 17 Mha) of our land area is devoted to agriculture, of which 6 Mha is used to produced cereals, oilseeds, potatoes, salads, fruit and vegetables, with the remaining land used for grazing and raising livestock[11].

There is now no doubt that a changing climate is starting to present enormous challenges for the lives of people on most continents of the world[6] and the UK is no exception to this situation. We know that much current practice in agricultural land management is highly damaging to the environment with for example, high emissions of GHGs from livestock farming and from many soil cultivation techniques. In addition, declining biodiversity and other particularly damaging effects of intensive agriculture are now dominant in many countries (e.g., excessive use of many input resources and reductions in soil health). Our own historical experience of the development of the global food system suggests that a focus only on reducing the effects of agriculture on factors contributing to climate change could undermine key food systems for the planet and for society. Nevertheless, there is much interest in the development of regenerative agriculture[33] and in other restorative forms of agriculture[34] but still many questions remain over whether highly-productive agriculture systems can also be regenerative and sustainable. Another issue in this key discussion is whether we can ensure that people will continue to have access to nutritious food that they actually want to eat. Many global crop improvement programs focus on the four or five major crops while so-called orphan crops (often traditional foods) receive little attention from plant breeders because the returns from these expensive processes are often too small to drive progress.

The GFS UK exercise (described above) has suggested that both greater self-sufficiency in food and multilateral cooperation could to some degree protect the UK food system against future climate change disrupting food supply. Recent political changes following the departure of the UK from the EU are likely to greatly affect food and farming policy and researchers are beginning to consider how a more-localized, communal UK food system might be developed and how it might help deliver benefits to both human and planetary health. Some have championed the development of low-technology, intensive production units for fruit and vegetables close to urban developments. Such facilities can be environmentally sustainable and socially beneficial for local communities (Fig. 2). One area where all commentators agree is the need to reduce food waste[13,24]. In the developed world, the bulk of food wastage occurs in the home and the development of local food production hubs can help address this problem. In developing nations, there is more food waste on-farm, at the market or in transit. There is good understanding that technology (e.g., cooling produce postharvest) can greatly enhance shelf life and reduce food waste. Technology to achieve this, and other storage and transport technologies can be expensive and may therefore be unavailable to many smallholders and small businesses in the food supply chain.

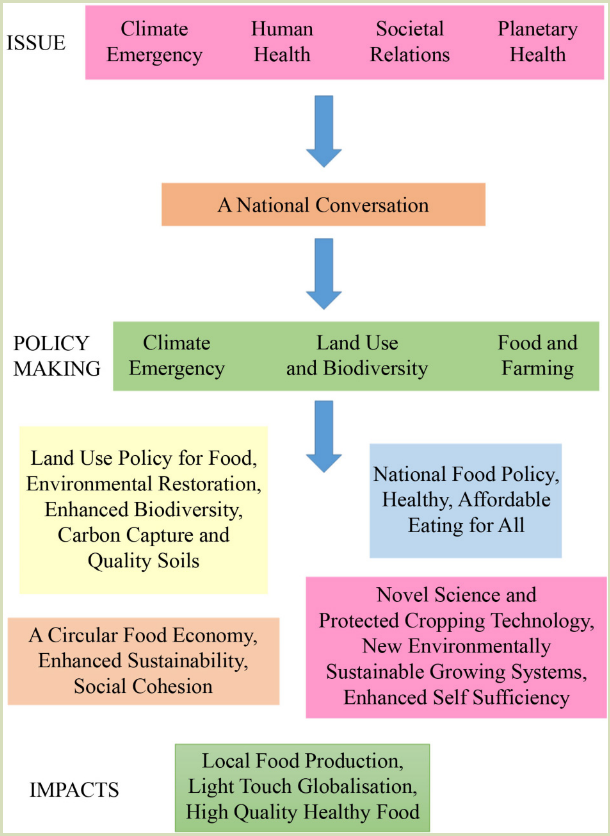


Fig. 2 A localized communal food system in the UK developed in response current environmental and social issues. Impacts are developed within a framework of possibilities. Modified from Cusworth et al.[22] under Creative Commons.

For many years, the EU Common Agricultural Policy (and the policy of many developed and developing countries across the globe) has supported farmers generating higher incomes from increased agricultural productivity. In the opinion of many, this policy has driven the development of an intensive, highly mechanized form of agriculture resulting in damaging impacts on soil health, biodiversity (e.g., reduction in populations of farmland birds[35] and insects[36]), and overuse of water, pesticides and fertilizers[37]. Since the UK left the EU, the UK Government has developed proposals for novel agricultural support packages based on rewarding farmers for good environmental stewardship, rather than for productivity. The UK Government's new environmental land management (ELM) policy has been released and widely discussed, although at the time of writing farmers are still waiting for more detail on implementation of many new proposals (early 2023). The UK Government, faced with growing economic uncertainty and worries about global food supplies, is now reported to be increasingly uncertain about moving away from a focus on industrialized, highly-productive farming. If adopted, new government ELM policy will lead to significant changes in land management, benefiting the natural environment and addressing the challenges of the climate emergency. ELM will pay farmers for taking actions to improve the environment. It has three components, which are intended be launched in full in 2024[38]: (1) the Sustainable Farming Incentive is open to all farmers and will pay them for actions to manage their land in an environmentally sustainable way; (2) Local Nature Recovery will pay for more complex actions that deliver benefits at a local level and aims to encourage collaboration between farmers; and (3) Landscape Recovery will support large-scale projects to deliver landscape and ecosystem restoration.

Notably, the recent publication of the new EU Common Agricultural Policy[39] emphasizes higher green ambitions with enhanced environmental conditionality and support for eco-schemes providing stronger incentives for climate- and environment-friendly farming. Rural activities will be encouraged with at least 35% of funds allocated to measures to support actions on climate, biodiversity, environment and animal welfare. In particular, there will be operational programs in the horticultural sector. Climate and biodiversity schemes will be supported with a general commitment to dedicate 10% of the EU agriculture budget to restoring biodiversity. In the near future, these environmental challenges in land management will provide a distinctly different context for the introduction of farming innovations in many European countries.

In the UK, environmentalists hope that our government will follow through on its Brexit commitment to reform our food system. The introduction of the two new ELMs alongside the existing Sustainable Farming Incentive will mean that around 60% of agricultural land in UK can be under what is considered to be sustainable management by 2030, and up to 300,000 ha of wildlife habitat might be restored by 2042. More details of proposed legislation are needed quickly to ensure farmers can successfully achieve such ELM goals.

Even in the UK farming community, there is general recognition that the UK must give increased attention to addressing the damaging environmental effects of food production[40]. Maintaining and even enhancing biodiversity is key, as well-functioning ecosystems are critical for human existence, economic prosperity and a good quality of life. A healthy, diverse biosphere aids in the provision of food, energy, shelter and medicines. The new government policy proposals are also aimed at sustaining water and soil quality, reducing emissions of GHGs thereby helping to regulate global climate.

The proposed UK Food Strategy[24] makes it clear that the UK currently emits 54.6 Mt CO_2 from agricultural practices with a COC (from soil converted for agriculture) of a further 12.8 Mt CO_2, a total of just over 67 $Mt \cdot yr^{-1}$ CO_2. If we followed all the recommendations made to the Parliament by the UK Climate Change Committee (CCC), the carbon emitted directly by agriculture would fall to 35 Mt CO_2. This ambitious target would be achieved through some intensification, a reduction in meat-eating, and measures to optimize nutrient applications to agricultural land. The UK CCC also recommends an increase in carbon sequestration by 2050 such that net emissions can be negative (–16.6 $Mt \cdot yr^{-1}$ CO_2) (see National Food Strategy evidence pack, pp. 77–78). The proposals say little about biodiversity. The National Farmers Union proposes a plan to almost reach net zero but without providing enough carbon sequestration to offset remaining land emissions[41]. A plan proposed by the Food, Farming and Countryside Commission shows what would happen if UK agriculture shifted entirely to extensive agroecological/regenerative farming[41]. Under this plan, which is strong on biodiversity proposals, emissions would be relatively high, because this plan includes substantial livestock farming.

A recent report by the UK Royal Society on the development of multifunctional landscapes[42] has warned that without careful assessment of synergies and tradeoffs between different land-use functions (food productivity, carbon sequestration and promoting biodiversity) there are risks that the UK land is being over-promised. Future commitment of more land for C capture and biodiversity (as suggested for example by the UK CCC) means that by 2030, 1.4 Mha of additional land might be required to meet current policy targets for net zero and biodiversity (if current agricultural production, diets and food waste remain static) (Fig. 3). The Royal Society paper[42] recommends that the UK countries should develop and coordinate spatially explicit national land-use frameworks, a strategy that almost certainly involves increasing development of multifunctional landscapes, to ensure coherence in development of land-use policy at different scales. This proposal appears to be particularly timely given the current focus on increasing self sufficiency for the UK food system, which is under pressure from global conflicts.

In all proposals for modified land use, future diet is considered but there is no explicit discussion of laboratory-sourced protein consumption as an approach to make land (currently committed to meat and dairy production) available for enhanced C capture and biodiversity. The CCC model proposes lower meat and dairy consumption, whereas the National Farmers Union proposes no change in diet. In line with the proposals made by EAT Lancet[13], the Food, Farming and Countryside Commission proposes a healthy future diet with more fruit, vegetables and nuts than we currently eat as well as reduced consumption of meat and much less sugar. It is to be hoped that discussions of this kind over both environmental and human health will increasingly take place in many countries of the world.

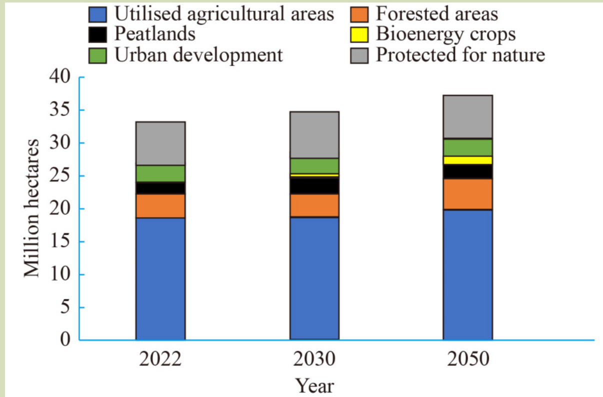


Fig. 3 Potential increase in the UK land area needed by 2030 and 2050 to meet net zero and biodiversity commitments if current agricultural productivity, diets and food waste remain static. Reproduced from The Royal Society[42], with permission from The Royal Society.

4 A new food strategy for the UK and beyond

In 2000, the food entrepreneur Henry Dimbleby was tasked by the UK Government to advise them on the development of a National Food Strategy[24]. The proposals, based on consultations with farming business, the food industry, academia and other stakeholders, sought to connect up different parts of food and farming, to give specific recommendations that would move the UK toward a food system that could address adverse effects on human health of the UK diet and reduce the many environmentally-damaging effects of the UK food supply chain.

For both health and environmental reasons, many commentators have stressed the need for developed societies to eat less food and to reduce the amount of animal protein in their diets[5,13,43]. These proposals apply to many of those who regularly consume what has come to be known as a Western Diet or a Global Standard Diet[44]. We will continue to examine below the environmental benefits of reduced meat production, and agriculture in general, in UK but the case seems clear for a reduction of the impact of intensive agriculture on biodiversity, GHG emissions, and overuse of water and nutrients.

A range of lobby groups and the Dimbleby food strategy report[24] argue that any new UK agricultural and food policy should tackle the UK obesity crisis in a variety of ways. Healthy food must be made more accessible, particularly to children, though, for example, broadening access to free school meals and ensuring the benefits of consuming fruit and vegetables are clear to all. Proposals from a variety of groups have also recommended increased support for the production of climate-friendly nutritious food[45], a change that could be effective in reducing the costs to the consumer for such food . These are strongly-argued components of the Dimbleby report, intended to inform development of new government policy. One other suggestion is increased taxation of high-salt, high-sugar foods and another that future health policy might use financial incentives to encourage UK residents to adopt healthy, environmentally sustainable diets.

In the UK, the debate over the health benefits (or otherwise) of meat consumption has been vigorous[43,46]. It is accepted that meat is a good source of energy as well as a source of a range of essential nutrients, including protein and micronutrients such as iron, zinc and vitamin B12. Other foods can provide good sources of these nutrients if the food sources are sufficiently nutrient dense but if this is not the case then diets low in meat may have negative health impacts[47]. The “Grazed and Confused”? report of the Food Climate Research Network[48] notes that analyses in developed countries seem to show that total mortality rates are somewhat higher in people who have high intakes of both red and processed meat than in those with low meat intakes. There is good evidence for an adverse effect on colorectal cancer of a high intake of processed meat[49]. There is also an apparent association between the amount of processed meat consumed and the relative risk of cardiovascular death[50].

Policymakers are increasingly concerned with the health and environmental consequences of rising meat consumption, but Godfray and coworkers[46] note that “it is not clear the degree to which policymakers have the societal license to intervene to influence meat consumption and if they do, what interventions might be effective.” Despite this uncertainty, Henry Dimbleby’s UK National Food Strategy of 2021 calls for a 30% reduction in meat consumption over the next decade. Dimbleby states, “careful livestock farming can be a boon to the environment, but our current appetite for meat is unsustainable: in UK, 85% of farmland is used to feed livestock. We need some of that land back.” In early 2022, the UK Government’s Committee on Climate Change recommended a 20% cut in the consumption of meat and dairy by 2030, rising to 35% by 2050 for meat only[51].

Ruminants such as cattle and sheep contribute the bulk of the meat and dairy products consumed in the UK. These animals, being ruminants, are able to obtain nutrients from ligno-cellulosic rich plants by fermenting them before they are digested. This is achieved with the aid of microbes in their specialized, four-compartmented stomach. When the intestinal microbes degrade carbohydrates, hydrogen is produced, which is subsequently incorporated into methane that is released to the atmosphere. The fourth stomach of the animal functions much like a monogastric stomach, using enzymes to further digest the food (but contributing less than 10% to total methane emissions).

The particular characteristic of the digestive system of ruminants of significance in this discussion is that these animals are able to digest coarse cellulosic material such as grass, husks and stalks, which cannot be digested by monogastric animals. This capacity to utilize multiple feed sources has been promoted as a positive feature of ruminant grazing (see below) but despite this, methane production and release is still a massive issue for climate warming. Although methane gas released by ruminants turns over quickly in the atmosphere, continuous flow of methane emissions from any source warms the planet. That warming effect will only decline if emissions are reduced, a strong reason for cutting methane emissions by changing agricultural practices and working to change some traditional dietary practices. For this, economic and sociocultural aspirations are relevant, and appropriate conversations with all interested parties will be required, if we are to bring about fundamental changes in lifestyle.

To reduce the risks of the most damaging climate changes, we do not need to eliminate beef or lamb production. However, one of the most effective things that citizens of UK and other developed countries can do to reduce their own climate impact is to significantly reduce their consumption of red meat. Monogastric products (pork, and poultry meat and eggs) might be substituted for beef and lamb since these animals emit much less methane and use far less land per unit of livestock product over their production cycles[5]. Another way of addressing the issue of methane emission is by making ruminant products a little less damaging in environmental terms (e.g., by improving feed crops, animal breeding, optimizing feed formulations and reducing the amount of land that animals use). Although extensive grazing can be compatible with high levels of biodiversity, an extensively-reared ruminant is a problem since its productivity is low in relation to the land that it requires, and the volume of gases it emits per unit of meat or milk output is great.

Much of the UK farming community and other interested parties have reacted with alarm over proposals to limit extensive grazing and legislate to reduce meat consumption (see alternative proposals by the UK National Farmers Union which are described above), suggesting that the environmental argument for reducing grazing of livestock in the UK is oversimplified. Counter proposals include maximizing our efforts to ensure that whatever we eat is more environmentally sustainable in the broadest of terms. Importantly, the international development community places emphasis on the importance of livestock production as a provider of livelihoods, particularly for poor people in low-income countries, but also among rural communities in the affluent West[48]. Some of the most vulnerable people in the world rely on animal husbandry for their living. For many traditional cultures, livestock production is often central to cultural identity[52].

On a worldwide basis, livestock grazing systems contribute a significant proportion of GHG emissions and, as noted above, there is a substantial area within the UK devoted to livestock grazing, which is helping to drive the changes in our climate. It follows, therefore, that a reduction in grazing agriculture and red meat consumption in the UK could benefit the health of the general population as well as aid our progress toward achieving net zero by 2050. Pastoral systems carry a massive carbon opportunity cost (the carbon that could be captured if the land were returned to wild ecosystems). The UK Climate Change Committee has posited, “Transitioning from grassland to forested land would increase the soil carbon stock by 25 $t\cdot ha^{-1}$ C (on average across England) in addition to the large amounts of carbon that would be stored in the biomass of the trees themselves.”

We should not downplay the impact that such changes to farming practices might have on the farming community in the UK. Most people greatly value Britain’s *rural* landscapes and, of course, traditional farming practices are important for sustaining this image of Britain. Mental health is greatly benefitted by urban residents having access to the countryside. This is not to say that rewilding and even regenerative agriculture more generally would be any less beneficial here. In an examination of some of the pros and cons of a UK agricultural revolution, Garnett et al.[48] have reviewed arguments against a substitution of plant protein production systems for extensive animal production system in a developed country such as UK. These include a proposal that grazing systems even help sequester extra carbon in the system and that a move away from grass-based ruminant production could actually make climatic matters worse rather than better. It cannot be denied that a move toward diets rich in grains[13] might involve some increase in plowing of pastures, soil carbon release and biodiversity loss. Nevertheless, we discuss below, some of the components of regenerative/restorative agriculture that could help the UK transition to farming systems that can help the industry contribute significantly to achieving net zero for the country by 2050. At the same time, the farming system can respond to potential government food policies aimed at a healthier UK population

5 The UK Government’s early responses to calls for an agricultural revolution

The four overarching conclusions of the 2021 Dimbleby Food Strategy Report [24] were: (1) Escape the junk food cycle and protect the UK National Health Service; (2) Reduce diet-related inequality; (3) Make the best use of our land; and (4) Create a long-term shift in our food culture

At the time of writing (early 2023), the UK Government had released a response to the Dimbleby Food Strategy Report[24]. Its proposal was for National Food Strategy legislation, trialed in advance and presented as “a groundbreaking plan to tackle the climate and nature emergencies”. However, the Government’s proposals so far have, in the opinion of many, failed to tackle these challenges and there are similar shortcomings in the proposals intended to tackle issues of food quality and health. There are no specific proposals on taxing high salt and sugar in foods. These, often highly processed foods, are generally cheaper than foods generally considered as healthy and it seems likely that the 2022–2023 food price crisis will lead to consumption of more poor quality food which will lead to increased pressure on our health services[53].

Perhaps most disappointingly for many is the absence of any substantive proposals to address the considerable current contribution made by UK agriculture to GHG emissions, for example, by reducing the contribution made by livestock farming across the country. There are also scant details on how the Government plans to implement the ELM proposals first made in 2021. These proposed changes are intended to address worrying declines in soil quality and biodiversity in the UK. While these ELM proposals have been cautiously welcomed, the introduction of more extensive farming systems will raise questions over how the UK can sustain and even increase its food productivity with the introduction of the proposed land management systems. Particularly, given the uncertainty over food security caused by the conflict in Ukraine, this issue is causing some rethinking on policy within the Government. Many land management systems aimed at environmental regeneration are known to enhance ecological resilience but we need additional thinking around new systems for enhanced food productivity[43].

The Food Ethics Council[54] emphasized that “a good food strategy should be shaped by people and empower them to act”. Despite a broad conversation between actors in our food system and many other interested groups, the proposed legislation outlined in late 2022 has not been well received by some in the UK food system. The Food Ethics Council commented that “it has narrowly focused on papering over the cracks of a crumbling industrial food system”, and that “it fails to recognize the power of food to bring communities together, the right that everyone has to be able to access sufficient, nutritious food and the urgency to address climate, biodiversity and obesity emergencies.” One significant criticism, in the view of many is that “the proposals make no effort to make the best use of our land and enhance our diminishing biodiversity”.

I will now consider how future UK agriculture could deliver both ecological regeneration and higher food productivity, and the kind of policy development required to address these urgent global challenges, especially the kind of government actions which are being taken elsewhere in the world[39].

6 Regenerating agriculture in the UK and beyond

6.1 Making space for nature in the UK

A recent National Biodiversity Network report[55] on biodiversity in the UK showed that the UK was in the bottom 10% of all countries globally for retained biodiversity. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services reported that land-use changes globally have had the greatest overall negative impact on nature since 1970 and many other reports have resulted in many countries introducing legislation to address this issue[56]. Where and how food is produced has been one of the biggest drivers of global land-use change[57] and we must intervene to ‘make room for nature’.

Loss of soil biodiversity may be a particularly critical impact of modern farming practices as changes in soil communities and the loss of biodiversity threaten ecosystem multifunctionality and sustainability[58]. A 2019 Environment Agency report indicated that the UK soil invertebrate community has not been fully surveyed since 2007 but results from this survey indicate significantly fewer invertebrates in arable habitats than other habitats[19]. Changing land management practices can have a significant effect on biodiversity of many groups of plants, animals, soil bacteria and fungi. For example, review of a substantial range of studies[59] found that when livestock were removed from land, the diversity and abundance of almost all groups of animals (herbivores, pollinators and predators) increased but this is not the case with all studies[60]. Soil health generally is declining across the globe due to inappropriate land management and along with use of water, nutrients, energy and land, is one of the major resource-use issues for sustainable farming. Changing management practices on previously intensively managed land can impact positively on all of the variables discussed above. Farmers and others in the current food system, while generally supporting the concept of regenerative agriculture, ask how the UK agricultural productivity can be sustained with many of these practices used on reduced land areas available for crop and livestock production.

Giller and coworkers[33] noted that the concept of regenerative agriculture (sometimes termed restorative agriculture) has been promoted strongly by civil society and NGOs as well as by many of the major multinational food companies. Many of the central components of this practice have been promoted in other contexts (e.g., as part of an agroecological approach to farming or as part of the practice of conservation agriculture). They include approaches such as crop residue retention, zero or minimum tillage and cover cropping, and are generally accepted by farmers as effective ways of protecting soil structure, biodiversity and chemistry. Giller[33,34] stresses the importance of considering context for the introduction of changed management as many potential component of regenerative agriculture are unlikely to lead to the benefits claimed in all soils, locations and environments. This issue is discussed in detail below.

Hearteningly for many, in a recent report[61] on a widespread survey of 30 long-term experiments where the impacts of ecological intensification (a form of regenerative agriculture) were assessed, the effects were generally positive. A meta-analysis of data from 30 long-term experiments from Europe and Africa confirmed that ecological intensification practices (specifically, increasing crop diversity and adding fertility crops and organic matter) have generally positive effects on the yield of staple crops. ecological intensification practices substantially increase yield at low N fertilization but had minimal or no effect on yield at high N fertilizer rates. Reducing tillage did not strongly affect yields. The authors conclude that ecological intensification could help return agriculture into a safe operating space for humanity[3].

Many UK farmers already manage their land to minimize and even avoid soil degradation. Increasingly efforts are made to boost soil carbon levels with measures such as contour plowing, reduced tillage, cover crops and buffer strips[62]. Importantly, analyses from cropping with herbicide-resistant genotypes have revealed a net accumulation of atmospheric carbon in soil under no-till crops but a net loss of carbon from soil under tilled crops[63]. Cover cropping can also enhance the soil biodiversity of simplified cropping systems and reduce nitrate leaching[64]. Plant improvement has resulted in a general increase of biomass of grains, stems, leaves and roots, with the vegetative parts of the plant providing more crop residue for the soil, thereby potentially providing substantial carbon input to the soil. Amendment of soil with added sources of organic carbon, such as green manures, biochars and organic fertilizers produced from waste streams increases the content of stored carbon, and has been proposed as an option for climate change mitigation[65].

There is general recognition that a healthy soil microbiome can be key for healthy plant growth and the expectation is that it will be possible to design plant-microbe-soil ecosystems which will address particular environmental challenges and opportunities for particular crops, climates and geographic areas[66,67].

Today, about 40% of land worldwide is committed to agriculture (production of food, fiber and biofuel crops, or livestock)[68]. In the UK, where 70% of our land area is devoted to agriculture, less than one third of this is under cultivation for cereals, oilseeds, potatoes, fruit and vegetables, with the remaining land used for livestock production. These UK statistics suggest that finding more land for extra fruit and vegetable production could be achieved by reducing the production of extensively-reared ruminants (with protein in the diet augmented from laboratory-grown food sources), especially if the production systems for these new crops were intensive operations involving protected, vertical cropping[69], some of which could be located in peri-urban or even urban locations[22].

Rockström et al.[3] have stressed that even if there is land available for further expansion of agriculture, this development could overshoot the safe operating space for agricultural land use well before 2050 (c. 25% of anthropogenic emissions of greenhouse gases are sequestered in terrestrial non-cultivated ecosystems, which importantly includes land managed extensively for grazing). Despite the UK being a highly urbanized country, only 6% to 7% of the land is used in built environments[70] but, in contrast, livestock grazing occupies 51% of the land area[43]. Currently only comparatively small areas are used for crop production[11] and nature reserves. Ecological intensification, regenerative agriculture or some other form of conservation agriculture could help make more room for nature. As discussed above, to effect changes to GHG emissions, C capture and biodiversity (and increase the availability of healthy food) in the UK, we will have to reduce the consumption of meat. This could involve consuming more vegetable protein, the production of which is less demanding of land. The website, Our World in Data[71], shows that to produce 100 g of soybean protein requires just over 2 m^2 of land. Production of the same amount of chicken and pork protein requires less than 10 m^2, beef 163 m^2 and lamb 185 m^2.

As noted above, there was early use of the term, sustainable intensification of agriculture[2], as well as a growing number of terms used to describe land management systems with an environmental focus. There is now a timely and well-documented debate[72,73] on what actually constitutes sustainable intensification of agriculture and the contribution that sustainable intensification could make in addressing global food and climate security[74]. We can consider how to produce more food while reducing its environmental impacts[75] (a productivity-first strategy), or put the emphasis on ecological processes in agroecosystems to enable some progress in increasing agricultural output while reversing environmental degradation[76]. In many developed countries, such as the UK, there is a real interest in following the second of these alternatives. Particularly in agricultural development in developing regions of the world, the productivity-first strategy often prevails.

There are many reasons for country to country variation in the strategies employed. In the UK there are now excellent examples of rewilding of previously productive agricultural land[77] with highly impressive gains in biodiversity, but production of animal protein in these systems is often unacceptably low for commercial operators[43]. This makes wide-scale adoption of this change to extremely environmentally-friendly farming a rather specialist undertaking. For many years in the UK we have debated whether it is better for the environment to farm more intensively on a limited area of improved land (termed land sparing) with consequent, but localized, damage to biodiversity than to farm less intensively to allow *wildlife* to prosper within the farming operation (termed land sharing). The sharing option finds less favor because large numbers of the birds and insects, and other kinds of biota and microbiota do not survive well in most agroecosystems. The exception to this is extensively managed grazing land but the food productivity per unit land area of such systems is generally quite low[43]. Consequently, the generally held view is that agricultural sprawl (sharing) inevitably causes greater loss of biodiversity. The sparing approach is not always a clear benefit for the environment, however, as such landscapes are not easy to manage as large protected areas and they can fail to fulfill their purpose if they are completely isolated without wildlife corridors. There is currently an active discussion in UK about the development of multifunctional landscapes which can deliver on a range of priority areas such as agricultural productivity, C capture and enhanced biodiversity[42]

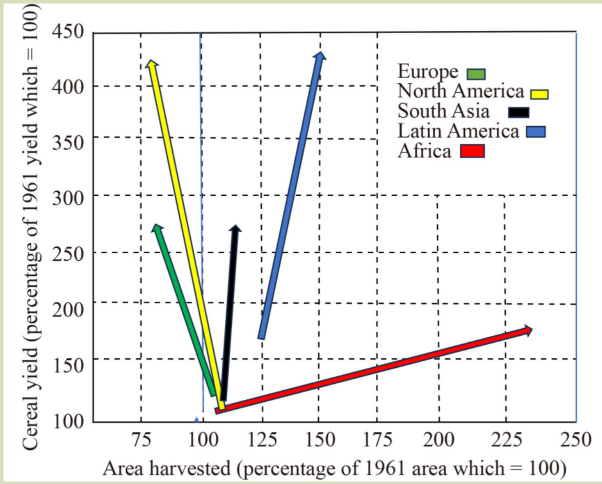


Fig. 4 Past cereal productivity related to area harvested to produce increased yield. Data trends are shown for agricultural systems in different continents. Adapted from Giller et al.[79] under Creative Commons.

6.2 Global perspectives

In addition to the issues discussed above, farming in the UK today is subject to many additional pressures which are also felt in most other parts of the world, including human resource challenges exacerbated by rural depopulation. As we move toward more farming systems that are less dependent on external inputs there is renewed interest in recoupling of crop and livestock production, particularly for the resilience it provides[78].

With over 70% of global food still produced by smallholders, Giller et al.[79] have stressed that for Asia and Africa, as well as in many other contexts, pro-poor policies and investments are needed to stimulate small-scale agriculture as part of a broader focus on rural development to address persistent poverty and hunger. These authors and other recognize that in the absence of alternative livelihood security, for many, smallholdings remain an important source of food and income. However, historical development of yield growth has stagnated in Africa and area expansion has been the dominant pathway to increase production (Fig. 4). The gaps between potential and actual crop yield are substantial in Africa and in non-irrigated agriculture in Asia[80]. Giller and coworkers[79] stress that with limited possibilities for smallholders to establish in these regions, the agricultural engine of growth appears to be broken[80].

I will now discuss the role for new developments in crop science and cropping systems that might provide opportunities for farmers across the globe to rise to the challenge of climate change, and changing economic and policy scenarios, achieving greater livelihood security as well as responding to the continuing challenge of increasing food quality and availability. The novel plant science funded by the Gates Foundation and discussed below is an example of the massive potential opportunity presented by modern developments in plant science. As stated on the RIPE website[81], RIPE (realizing increased photosynthetic efficiency) has pursued the theory that the process of photosynthesis in crops could be engineered to increase productivity. It has already demonstrated three separate plant-engineering approaches to achieve this, each of which showed the potential to deliver more than a 20% increase in productivity. Gates funding has allowed expansion of this work, accelerating progress to deliver royalty-free benefits to smallholder farmers in sub-Saharan Africa and South Asia. The hope is that this and other related projects can recharge the agricultural engine of growth in these regions. It also seems clear that crop improvement of this kind can help to further increase yields in regions where good quality agricultural land is in short supply.

6.3 New plant science and cropping systems to increase climate resilience of food systems across the globe

In the European summer of 2022 there was a period of extremely high temperatures that caused wildfires across the continent and a range of other problems for farmers, such as shortages of irrigation water. In July 2022, UK experienced its hottest temperature on record (40.3 °C). It seems clear that to cope with continuing global warming, it will be necessary to increase the resilience of global farming systems to extreme climatic conditions. A recent initiative from the UK Government is likely to be influential. Following the departure of the UK from the EU, the UK Government will allow gene editing as a means of improving yields, stress resistance and resistance to pests and diseases of food crops. New rules brought forward by the Government in 2022 encourage field trials and other research efforts and a bill introduced in the UK Parliament in May 2022 allows commercial growing of gene-edited crops in in the UK. Such changes are likely to be contentious and we can expect an active public conversation on such developments.

In the years since Beddington's prediction of 2009 that by 2030 the world was likely to need a 50% increase in food availability, there has been a substantial global effort to increase world food production. Given the complexity and long lead time for any revolution in food production methods it is important to try to quantify how much extra food will be needed. Those who are uneasy about high input industrial agriculture often criticize global future-food projections because they believe the narrative is often framed around the assumption that global food insecurity is a function of food supply/scarcity that can largely be fixed by increasing food production through technological innovation. It is well-recognized that food availability is influenced by many factors in addition to food production and we must give attention to these factors, if we are to address the growing challenges of food insecurity.

A recent meta-analysis and literature review[82] concludes that between 2010 and 2050 (taking account of climate change predictions) there could be changes of −1% to 20% in per-person food demand, 30% to 62% in total food demand and −91% to 30% in the population at risk from hunger. These figures reflect global food security outcomes in five different, but plausible, future worlds with respect to sustainability, equality and technological development. For example, in addition to access to improved genetic material, the productivity of many smallholders around the world could be greatly increased by better advice, market and credit access, fair financial returns, and other measures. In many countries there are strenuous efforts to bring about changes in these areas as well as in crop development and management, and given the enduring magnitude of the challenge[82], we will require developments in all of these key aspects of the food system.

While we accept the need for a multidimensional change in the food system to allow us to address predicted changes in food demand, there can be no doubt that the potential increases in food availability offered by advances in food-related science and technology are impossible to ignore. There is now an increasingly broad range of plant biology where we already have a good understanding of potential manipulations that can increase plant productivity and crop stress resilience (if applied in appropriate contexts, particularly when water and/or nutrients are in short supply). That said, annual increases in yield of our major crops are often less than impressive and often well below the needed increases if such changes on their own are expected to feed the still-growing global population[83]. We will need substantive improvements to plant breeding techniques to meet our food supply targets. New plant science approaches to enhancing global crop productivity are now emerging from well-funded international projects targeting both C and N relations of crops. Horton et al.[66] discussed the development of high-yielding, resource-efficient crops to deliver increased agricultural yield. Potentially such developments will free land that is less suited for intensive cropping for land use practices that will further increase C capture and may also themselves contribute to extra C storage[66,84]. Importantly, there is now recognition that systems modeling of the biology of C capture by plants can help identify pinch points in the different stages contributing to biomass accumulation[85]. This is important because many now accept that harvest index of many major crops, a breeding target previously so influential in helping to deliver yield increases, has now been maximized. In the future, increases in potential crop yields will largely be dependent on increases in total biomass. It is now apparent that this can be achieved by increasing photosynthetic efficiency[85,86] and recent improvements have delivered increases in productivity and sustainability in replicated field trials of a range of crops including food crops[87–90]. Similar yield gains have been achieved in field trials of crops engineered to increase the efficiency in mechanisms by which plants can protect themselves from excessive solar radiation. They do this by dissipating excess light energy using non-photochemical quenching[91] and soybeans have now been bioengineered to increase the rapidity with which this process can be switched off when radiation levels decrease. On cloudy days, this can enhance C gain. Field trials of this globally important crop show increases in seed yield of up to 33%. To fully understand the importance and potential for practical application of manipulations of this kind, field trials need to be conducted across a range of different environments and the reasons for this are discussed below.

Potential increases in food supply from such an increase in productivity can be substantial but success in increasing potential crop production will only be possible if more water resources are available to farming or the water productivity of crops can be greatly increased. Will it be possible to meet future demand for food without stressing even further what are already scarce water resources? It is heartening to see that upregulation of only one key gene has been shown to increase crop water use efficiency of field-grown tobacco[92], raising the possibility that modern plant biology can help address the challenge of limited water resources, one of the key issues for farmers in many parts the world. Nevertheless, there have been many false dawns in this field of endeavor, particularly when results of laboratory or greenhouse experiments cannot be replicated in the field. One of the reasons for this has been limited understanding of the importance of considering the interactions between the genetics (G) of the crop, its immediate environment (E) and its field management (M) in determining the impact of any manipulation of the genetics (or management practices) of crops. Yield, plant morphology, water productivity, nutrient productivity and other outcomes are of interest. This G × E × M interaction is also the basis of reservations expressed by some over the universal utility of particular crop management options [34].

One good example of this interaction is the G × E × M interaction in performance of wheat cultivars improved to show high transpiration efficiency (TE) (or water use efficiency) in environments where water availability to the crop differed significantly. Much interest was shown in early work in Australia which reported a significant advantage of related high-TE lines of wheat over low-TE lines in drier locations [93]. Despite the apparent importance of this result, some urged caution as the benefits over a wider range of environmental conditions were less clear, illustrating the importance of an apparent G × E interaction. In later work, a high-TE wheat cultivar, Drysdale, was grown in close proximity to its closely related low-TE parent Hartog (a 60 site-year comparison across the Australian wheat belt)[94]. This study showed a significant yield benefit of greater TE across a broad range of environments ranging in yield from 0.3 to 6 $t \cdot ha^{-1}$. Subsequent work[95] showed that highest yields were not necessarily directly correlated with highest TE but the yield advantage of Drysdale over Hartog was clear and the potential annual cost-benefits of this increased genetic TE trait across the wheat growing areas of Australia were substantial.

In other TE studies, Ryan et al.[96] and Sinclair et al.[97] investigated genotypic diversity in the transpiration response to vapor pressure deficit (vpd) in maize. By limiting transpiration at vpd above a threshold, this ABA-related trait can decrease daily water loss and potentially increase the water available for grain development later in the growing season[97]. The impact of G × E × M interactions with respect to this vpd-sensitivity trait was explored by Messina et al.[98] using a simulation model. These authors demonstrated that the limited-transpiration trait can result in improved maize yield performance across a range of States in the USA. Simulations showed that the largest average yield increase from selecting genotypes with a high stomatal sensitivity to vpd was found in drought prone environments (135 $g \cdot m^{-2}$). A small yield penalty was simulated when the same trait was introduced in environments where water was not limiting (−33 $g \cdot m^{-2}$).

While there has been much interest in increasing the TE of a range of crops, both as a result of genetic manipulation and agronomic management, there are other water-related traits where genetic improvement has yielded significant benefits for the farmer. Researchers have focused on genotypic variation in yield under challenging environmental conditions and analyzed these differences to gain insight into the mechanistic basis of stress resilience (e.g., Thiry et al.[99] and others in this special issue). It seems important to fully understand the basis of the environmental stress experienced by the crop in the field and analysis of this is another starting point for crop improvement programs for different agricultural systems. Kirkegaard and Lilley[100] have recently described a body of work stimulated by the recognition that yield of annual wheat crops in southern Australia depends heavily on water availability at different stages of development from establishment through to grain filling. For example, careful field observations showed that there was often much water remaining in the subsoil at the end of a wheat cropping season. A key question was whether productivity could be enhanced by capturing this water with deeper root systems. While breeding for steeper and deeper root morphology has yielded some benefits for dryland farming systems[101], crop management, in particular early sowing, has also proved to be a key intervention resulting in more effective capture and utilization of stored water. This work is a particularly good example of the importance of understanding the interactions between G × E × M, as illustrated by the observation that the benefit of presumptively-improved root traits is influenced by the pattern of water availability in the environment under consideration[102,103]. A simulation run by Lilley and Kirkegaard[104],has shown that benefits (in terms of grain yield) of deeper roots varied with site and season and interacted strongly with crop management, antecedent soil water content, the seasonal pattern of rainfall and soil type.

In addition to the above benefits of selecting deeper rooted genotypes, a potential adaptation strategy with a similar benefit is to sow earlier and deeper, to take advantage of stored soil water. Such early-sown crops have sufficient time to proliferate roots in the subsoil. However, deeper sowing of modern semi-dwarf wheat varieties (which have short coleoptiles restricting plant vertical development), can reduce seedling emergence from the soil. Novel genotypes with alternative dwarfing genes have longer coleoptiles to facilitate deeper sowing[105]. Zhao et al.[105] predicted that these genotypes, coupled with deep sowing (another example of the exploitation of G × M), would have increased Australian national wheat yields by 18% to 20% under historical climate (1901–2020), with benefits also projected under future warming.

Partly as a response to the changing climate and a move by Australian producers to operate larger farms, early sowing and sowing into a dry seedbed on the expectation of rainfall have become an important agronomic adaptation strategy. In a study of the effects of these and other management options, Kirkegaard and Hunt[106] reported that unless genetic innovations were accompanied by a particular selection of management strategies, then grain yields by presumptively-improved genotypes could even be decreased in comparison with control genotypes.

Many agricultural systems in Asia have evolved to incorporate simple but sophisticated irrigation systems which can substantially increase water productivity of crops[107], intercropping systems with specialized deliverables including enhanced nutrient and water use efficiency[108,109] and the manipulation of soil microbiology[67] to enhance crop growth and resource use efficiency (Fig. 5). These manipulations all involve advances in understanding of crop biology but also require a full appreciation of cropping systems operating in different climates.

Fig. 5 Crops along the Yellow River, China, clearly show the positive effects of crop management (irrigation and intercropping) on the agricultural productivity.

7 Conclusions

Since Beddington first discussed his concept of the perfect storm of issues around the delivery of greater food security for a growing world population[4], there have been many developments in our understanding of the suite of factors than interact to determine food availability to people across the planet[5]. Although our overall aim of feeding more people with better quality food remains unchanged, we are now equally concerned to address the deteriorating health of the planet. The different drivers and feedbacks in our food system[5,110,111] will all impact the availability of food, our access to it and the ways in which it is used.

Thirteen years after Beddington's predictions we are much more aware of the growing problems of climate change for the operation of the global food system as well as the many damaging effects of the food system on our environment. For the UK, and many other countries, to deliver on net zero by 2050, then many food and farming practices will have to change. Current political turbulence complicates our efforts to act on a global scale but there is still the opportunity for the development of interventions at the local, regional and national scale. Britain's attempts at the development of a new National Food Strategy are an example of such an opportunity. Thus far, a national conversation across the disciplines has generated some interesting proposals but there is still a lack of consensus in many areas.

(a) While Britain is in the middle of a national conversation about food, a conversation that has been made even more urgent by increases in the cost of living, there has been little progress on legislation relevant to dietary change particularly for children. Consumption of foods high in salt, fat and sugar must be reduced. Urgent progress is required in this area. In the view of many, lack of action in this area will increase pressure on the UK National Health Service in the years to come.

(b) There is increased recognition of the damaging environmental impact of many farming practices. We need urgent action to reduce GHG emissions from many operations within the UK food system (and beyond). To achieve this and produce more healthy food for the UK population while reducing water, fertilizer and energy use and addressing biodiversity loss, we almost inevitably need to reduce the amount of land committed to animal production.

(c) For both health and environmental reasons, many British people (and people in many other parts of the world) must eat less meat and consume fewer dairy products. Greater emphasis should be placed on plant-based diets, and more fruit and vegetables should be produced and eaten in the UK. Laboratory-produced protein will inevitably be a larger part of the diets of many people.

(d) We need to produce more healthy food in UK, but the question is how. Advances in modern plant biology and the exploitation of novel engineering solutions can provide exciting opportunities for agronomy and horticulture in the UK[110]. Intensive production of fruit and vegetables can take place in low cost controlled environments in peri-urban or even urban locations. Britain's relationship with food and farming and its natural environment must change.

(e) Kirkegaard and Lilley[100] conclude that the body of their work (outlined above) demonstrates that if we are to fully exploit the impact of new plant science in farmer fields, we must effectively link plant scientists with agronomists, breeders and farming systems specialists. Our view is that as we seek to produce more food across the globe using novel genotypes and environmentally-friendly management systems, this conclusion also applies more generally to different disciplines across our food systems.

(f) The UK food system community has an important contribution to make to programs addressing international food challenges in some of the most climatically and socially vulnerable regions of the world. These programs need to be specifically tailored to these regions.

(g) Lobbying for rapid and substantial reductions in GHG emissions (e.g. at the COP meetings in late 2023) could be crucial for future food security. A recent paper[111] points out the possible vulnerability of global food systems to our changing climate, if we underestimate the possibility of synchronized climate-induced harvest failures.

Compliance with ethics guidelines

William J. Davies declares that he has no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by the author.

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