Can crop science really help us to produce more better--quality food while reducing the world-wide environmental footprint of agriculture?

Running title: Crop science for a diet for the planet~~if there is the running title, please write down~~.

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Abstract

This paper reviews recent developments in crop science that can be the basis of a revolution in the global food system but it is also emphasised that such a revolution requires more than changes in food production and supply. We must more effectively feed a growing global population with a healthy diet while also defining and delivering the kinds of sustainable food systems that will minimise damage to our planet. There are exciting new developments in crop production biology but much existing crop science can be exploited to increase yields with the aid of a knowledge exchange framework requiring the use of new technology now available to most people across the globe. We discuss novel approaches at both the plant and the crop level that will enhance nutrient and water productivity and we also outline ways in which energy use and GHG emissions can be reduced and labour shortages combatted. Exploitation of new biology and new engineering opportunities will require development of public-private partnerships and collaborations across the disciplines to allow us to move effectively from discovery science to practical application. It is also important that consumers contribute to the debate over proposed changes to food and farming and so effective knowledge exchange mechanisms are required between all relevant communities.

Keywords: Food Security, Environmental Sustainability, Crop Water Use Efficiency, Crop Science, Diet and Health

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1 Introduction

In 2008, significant spikes in the price of food on the world markets almost immediately caused a crisis in food availability for large numbers of people around the world. These were people who were already spending a high proportion of their income on food and who could ill-afford to spend more. While there is still some uncertainty over the causes of these food price spikes, they came at a time when there was already increasing concern about a changing climate and the seemingly inexorable rise in world population and therefore in the demand for food. This demand is further increased as people in many developing parts of the world seek to eat more and to increase the variety of food in their diet. Another concern was and still is, the over-use in many parts of the world of many of the input resources for food production, particularly water and mineral fertilisers. For a variety of reasons, the availability of skilled labour for agriculture is also increasingly limited. In the developing world, this is often because higher salaries in the major conurbations are driving rural de-population. In Europe, political changes make the traditionally-attractive agricultural labour market in the west much less attractive to potential migrant workers who come largely from the east. In the UK, the Agricultural Act of 1947 stressed the importance of production of affordable food and adequate remuneration for farmers. The first part has been achieved with higher yielding crops, intensification, reduction in farm numbers, cost cutting and the end of the traditional farm-village community. Successive UK

Governments have cut out advisory bodies, eliminated market support, reduced research support and given open market access to imported foods. At the same time people's diversity of consumption has moved away from primary UK foods to many imported foodstuffs, much of which food is sold processed. The implications of all of this change are now impacting more and more people. What is now apparent is the destructive effects of many of these changes on our environment and the natural world. In 2009, the UK's then Chief Scientist, Sir John Beddington encapsulated our concerns about future food security by coining the term 'the perfect storm' [1] and in the years since then, much attention has been given to addressing this multi-faceted challenge which now is recognised as one of the 'grand challenges' faced by our society[2].

One way in which we can quantify our progress in addressing the challenge of feeding more people with better, more nutritious healthy food without further damaging the planet is with reference to the 'Development Goals' first formulated by the United Nations in the year 2000[3]. When formulated, these Millenium Development Goals (MDGs) highlighted the need for global collaboration in efforts to address some of the world's most challenging economic and social problems. There is a general view in most parts of the world that the eight Millennium Development Goals (and their framework of accountability) have served the world well. For many countries, they have provided a much-needed sense of direction to national plans and stimulated international co-operations. Crucially, they have also delivered results that can be quantified. This success of the collaborative concept exemplified by MDGs has now led to worldwide agreement on a range of 'Sustainable Development Goals' (or SDGs) for the planet[3]. The SDGs include targets for progress specifically on hunger but also include commitments to action on poverty, health, education, empowerment of women, water quality, climate action and sustainability. There are also other targets but increased global food security has relevance to all of our aspirations here. Under the Millennium Development programme, society managed to go some way towards feeding more people on the planet but there are still many additional food-related targets that require urgent attention.

Referring back to Beddington's Perfect Storm predictions, we are now more concerned than ever that global demand for food is still on the increase. World population is continuing to rise and it is unlikely that the population will peak until it is higher than 10 or perhaps even 11 billion[4]. In addition to this challenge, apparent climate change or the 'Climate Emergency' as it is now termed, is never out of the headlines for long. In the last few years, food production in many parts of the world has increasingly been disrupted by extreme weather events (e.g. too little or too much rain and extreme heat), just as predicted by climatologists.

One very significant development in the climate change field in the period since the first considerations of the threat of 'The Perfect Storm' has been the United Nations Climate Change Conference, or COP 21, held in Paris at the end of 2015[5]. The conference negotiated the Paris Agreement, a global agreement on the limitation of the extent of climate change. The consensus view of the delegates was that, if we are to avoid the very undesirable consequences of a 'hot-house world', global temperature increase should be held to 1.5 degrees centigrade. Despite the considerable achievement of the Paris Accords, pledges to reduce carbon emissions are still only enough to hold temperature increases at around 3.3 degrees and since the agreement, some have stepped back from delivering on their commitments made in Paris and many countries continue to support high-carbon industry. Business as usual will result in temperature increases of more than 4 degrees, with significant consequences for many. Predictions of future climate are still somewhat uncertain but whatever our success in limiting greenhouse gas (GHG) emissions, feeding the world in the future will certainly not get any easier![6]. We discuss below how plant and crop science can help to make the food production chain more resilient to a changing climate. This can involve the production of new crop germplasm using modern genetics and plant breeding. New farming systems and modified agronomy (e.g. involving climate-smart agriculture) [7] are playing and will continue to play a significant part in the development of more resilient food production systems.

A recent report of the Intergovernmental Panel on Climate Change (IPCC) which deals with climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems[8] has concluded with medium confidence that Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2, 44% of methane (CH_4), and 82% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, representing 23% (12.0 +/-3.0 $GtCO_2e\ yr^{-1}$) of total net anthropogenic emissions of GHGs. These statistics highlight the importance of modifying current food production and farming methods in order to restrict the further development of the climate emergency.

The current paper will report on advances in crop science that are key to the production of more food. Equally important is science that will allow increased production with reduced consumption of water and fertilisers. This will be key both because these resources are already in short supply in many regions of the world but also because over-use of water and chemicals in agriculture can be highly damaging to the natural environment and these are impacts that must be reduced to limit the environmental footprint of agriculture

While there is still considerable focus on how we can feed more people with more food, policy makers are increasingly concerned about increasing numbers of people who are over-eating poor quality food of low nutritional value[9] . Recent studies suggest that as a result of too many people eating too much of the wrong food, we are now in a global health crisis that grows worse by the year. Currently, the UK has some of the worst obesity rates in Europe[10]. The World Health Organization has warned that if current trends continue, by the year 2030, almost half the world's population will be overweight or obese[11]. An inappropriate and poorly nutritious diet can be highly damaging for the development and growth of children but there has been a tenfold increase in numbers of overweight children in the last four decades. Depressingly, statistics tell us that increasing numbers of people around the world aspire to eat a so-called western diet, which is not necessarily very good for them, or for the planet. Science has an important role to play here also and in this paper we will highlight some of the opportunities available to society.

It should already be clear that addressing individual problems in the global food system will not be an issue for science alone. There are many social and economic challenges also and most now recognise the importance of adopting a systems view as we strive to increase peoples' access to more good quality, safe food[12] ~~(Fig.1)~~. This is not to say that the importance of scientific intervention has decreased. New technologies and understanding of the science behind key crop responses mean that the opportunities for exploitation of advances in crop production and in water and nutrient productivity are bigger than they have ever been.

2 A diet for the planet and a framework for addressing global food insecurity

In early 2019, the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems produced its first report[4]. The Commission report addressed our need to 'effectively feed a growing global population with a healthy diet while also defining the kinds of sustainable food systems that will minimise damage to our planet'. While the COP21 agreement, discussed above, involved 195 countries reaching agreement on clear scientifically-based targets for GHG emissions, no scientific targets exist for the global food system. The Eat-Lancet Commission report stresses the importance of developing and accepting targets as an aid to policy makers and businesses which are looking for guidance on achieving both SDG and COP21 goals. The approach adopted by Willett et al[4]is based on a concept of a safe operating space for food systems, a concept based on a planetary boundaries framework. The safe operating space proposed for food systems by Willett et al.[4] encompasses human health and environmental sustainability. Scientific targets for different food groups are set to deliver good human health and planetary boundaries are set to ensure a stable earth system.

Although there is much uncertainty associated with the reference diet suggested by the Lancet Commission, their proposals are based on available scientific evidence and the healthy dietary pattern proposed includes ranges of intakes for food groups (e.g. meat, dairy, eggs, starchy vegetables, fruit, nuts, fish and legumes thereby allowing for flexible global application of criteria with foods and amounts tailored to preferences and cultures of different populations. The Willett[4] paper shows country-specific diets relative to the reference diet and the key areas where dietary changes in different regions are required to reduce the impact of regional agricultural practices and where these changes can be made with benefits to health. The Commission argues that in the developed world and beyond, a reduction in the consumption of meat, eggs and dairy would have a beneficial effect on health, while in Sub Saharan Africa (SSA) in particular (but also elsewhere), increase in the consumption of many food categories can be beneficial for human health. In this comparison, a shift in consumption habits towards the reference diet improves the intake of most nutrients. The group then used three different methods to analyse the effects of proposed dietary changes on diet-related disease mortality. Results of these analyses showed generally positive effects of these changes expressed in terms of predicted diet-related deaths per year, although there has been some controversy in the literature since the publication of these proposals[13] .

The need to develop and use sustainable food production practices that safeguard earth system processes, on which food production and human wellbeing depend, has become widely recognised both by the general public and by food producers and suppliers. Farming practices are being developed that reduce high levels of environmental damage that have accrued in some parts of the world from e.g. inappropriate pest control practices, over-use of water and nutrients and soil degradation. These practices can be integral to many evolving agricultural systems aimed at enhanced sustainability, such as conservation agriculture[14] , sustainable intensification [15] , climate-smart agriculture[16] , agro-ecology and precision and organic agriculture. Increasingly, farmers work hard to improve levels of soil carbon and reduce excess use of nutrients, diffuse and point source chemical pollution and excessive use of water. In some parts of the world[17] , landscape management can be an effective way of reducing pesticide use and enhancing biodiversity. Methods used to reduce the environmental impact of agriculture are often very region-specific but importantly, Willett et al.[4] suggest that a universal definition of sustainable food production should use a system-wide assessment of environmental effects of a comprehensive set of environmental parameters at various scales. This means that a consideration of sustainable production requires e.g. a quantification of land and water use, GHG emissions, N and P application, biodiversity loss and pollution from use of agrochemicals (mainly herbicides, fungicides and pesticides). The paper shows the effect of various remediation methods on these key environmental variables relative to the planetary boundaries of each variable. It is clear that a combination of remediation strategies will be required for an effective level of sustainability in future farming.

Focussing on the six main environmental systems affected by food production, there is good scientific data in each of these areas, which has enabled the group to provide proposals for quantified scientific targets–._The paper explains the underlying scientific rationale for decisions taken and assumptions made for each of the boundaries underlying a comprehensive definition of sustainable food production. However, there is a recognition that because of scientific uncertainty, natural variability, and interdependencies of processes, it is difficult to set the points where individual processes cause irreversible and deleterious changes in the Earth system. Nevertheless, we can be confident that particular issues are key to further development of e.g. a policy framework and thus we will discuss below the particular challenges provided by the need to reduce over-use of land, water and fertilisers in agriculture and the means of doing this. A 'half earth strategy'[18] is adopted by the commission for estimating effects of different agricultural practices on biodiversity and given the assumptions implicit in this strategy, here we briefly review the potential impacts of the proposed plan.

The commission report provides scientific targets for the planetary boundaries for food production. These global scientific targets provide an integrated definition of sustainable food production, which can be translated to science-based targets for different scales (regions and nations) and sectors. Thinking of this kind is required to provide information to the general public and to policy makers to enable assessments of how food and farming and land use must change if we are to address environmental and dietary challenges.

The commission summarises studies addressing environmental effects of overall dietary patterns. Most studies find that adoption of more vegetable-based diets are associated with the greatest potential reductions in greenhouse-gas emissions. Production of major broadfield crops, like rice and wheat, may have to be reduced to reduce land use and use of water and fertiliser[19] . We will review below some of the increasing numbers of reports that new crops and cropping systems can decrease environmental effects of agriculture, eg, by increasing yields and improving water and fertiliser management. Scaling up data from the analysis summarised above and applying a global food system modelling framework show that it is possible to feed a global population of nearly 10 billion people with a healthy diet within planetary food production boundaries by 2050. Importantly, the business-as-usual scenario suggests that food production could increase greenhouse-gas emissions, cropland use, freshwater use, and nitrogen and phosphorus application by 50–90% from 2010 to 2050 in the absence of dedicated mitigation measures. This increase would push key biophysical processes that regulate the state of the Earth system beyond the boundaries and safe operating space for food production. The analysis shows that to stay within the safe operating space for food systems, a combination of dietary changes and production and management-related measures are required along with strong government commitment.

While it is clear that our current food and farming practices threaten both human and planetary health, the Commission concludes 'that Global Food Systems can provide win-win diets to everyone by 2050 and beyond. However, this will require nothing less than a 'Great Food Transformation'. Despite a growing realisation of the magnitude of the challenges that are a part of such transformations, in most societies, progress is slow. Plant science has much to contribute to enable better diet quality, increase crop productivity, enhance environmental sustainability and create new products and manufacturing processes[20] but cannot alone bring about all of the required transformations. For the required changes in government policies and in human behaviour, we must be able to convince people of both the nature and magnitude of the growing threats to human and planetary health as well as convince all sectors of society to adopt for the future, targets such as the UN Sustainability Goals. We will now discuss development of some of the knowledge exchange mechanisms that are essential if we are to transform food and farming practices and people's eating habits as suggested by the EAT Lancet Commission and others.

3 Potential actions to achieve food sustainability goals

To achieve food sustainability goals, a range of actions is required from both organisations and individuals working at all scales and the EAT Lancet commission highlights five strategies that will be required for any transformation. The strategies are:

Strategy one: seek international and national commitment to shift towards healthy diets

Strategy two: reorient agricultural priorities from producing large quantities of food to producing healthy food

Strategy three: sustainably intensify food production, generating high-quality output

Strategy four: strong and coordinated governance of land and oceans

Strategy five: at least halve food loss and waste, in line with global SDGs

Detailed consideration of the effects and the nature of these strategies is key to making progress for people and planet. We now discuss the kinds of knowledge exchange (KE) developments that will aid in the delivery on strategies, one, four and five and we will then discuss the production systems for greater amounts of healthy food, using methods that can help us to reduce the environmental footprint of agriculture (strategies two and three). The Commission stresses the urgent need to waste less food (strategy five) and it is clear that more effective production can also help here.

4 Transforming food production systems and peoples' diets: Knowledge Exchange

Effective KE mechanisms between scientists and food producers are recognised as being key to delivery of the many changes in practice required within the framework defined above. Effective transfer of information on possible beneficial interventions must also be communicated to policy makers. In resource-intensive farming, new genotypes and changes to farming systems are common and often readily accepted by practitioners but it is still important to debate these issues and opportunities with a range of constituencies including the general public. A wide range of publications means that new information is available to all, but farmers and interested parties generally cannot be expected to scan all of the scientific literature and so even here, readily accessible KE tools can have beneficial effects on general understanding of the issues and also on food availability and quality.

An example of good practice in KE in food production and supply in the UK has been led by a major food retailer, Waitrose and Partners. A range of stakeholders (the market, suppliers and producers of food, agri-researchers and KE specialists from a range of providers) were brought together to initiate some of the changes in practice proposed by a wide range of influential publications[2] (Fig. 21). The project was driven by a group of the above stakeholders, known as ' The Waitrose Agronomy Group'. The magnitude of the sustainability challenge across the supply chain for fresh produce was assessed by a Farm Assessment Programme and deficiencies in understanding across the supply chain were addressed by an on-line training programme. The Agronomy Group was able to raise support for a collaborative research programme (CRP) involving several research providers and funded by UK BBSRC. The results of this and other relevant research programmes are communicated to the stakeholders (and other interested parties) via an open access web site[21] , an international MOOC (Massive Online Open Course)[22], face to face science communication events with practitioners, and a bespoke postgraduate training programme [23]. While developments to date have focussed on fresh produce, we anticipate expansion into the meat and dairy and fish sectors, with a consolidated focus on a sustainability agenda.

Most food in the world is still produced by smallholders and effective examples at scale of KE between science and this community are less common in this sector. In China, as is the case in much of the rest of the world, there is an urgent need to address issues of food access and availability, food quality and safety and the environmental impact of agriculture. Novel methods of KE are being introduced here[24] to help farmers address developing green government policies. As part of China's successful green revolution over the last 50 years, enormous increases in food production have been achieved as a result of advances in both plant breeding and agronomy[25]. Very large increases in the usage of fertiliser, agrochemicals and particularly of water have increased productivity but all of this has been very damaging to the environment in many regions. Commonly, both quality and safety of food are significant issues in China due to both contamination with agrochemicals and as a result of food fraud. Nevertheless some positive changes are underway in the food system with increased consumption of fruit and organic vegetables in Chinese diets but even here extra water use is often required for production[26] and this is certainly the case also as a result of increasing consumption of meat in the diets of increasing numbers of people. Excess water consumption has reduced water tables in many regions of China (and other important food production regions around the world[27]. Desertification is a major challenge in the north west of China with real threats to natural vegetation, soil quality and capacity for sustained production by farmers. Worrying climate predictions for the north China plain[28] , one of the main food growing regions of the country, add to the need for the introduction of water saving agriculture. Excess fertiliser use has resulted in many high profile pollution problems in surface waters, which are culturally and environmentally valuable.

The introduction by scientists at China Agriculture University of 'Science and Technology Backyards' (STBs)[24] is one very innovative approach to helping smallholders in China transform agriculture to respond to the challenge of greater 'Ecological Civilization', as defined in recent years by the Chinese Government. Using such an approach to exploit recent advances in plant and crop science is very much in tune with the agenda of EAT-Lancet Commission. In increasing numbers of communities across China, agricultural scientists live in villages among farmers to achieve yield, economic gains and increased sustainably. The aims of this knowledge exchange programme are to advance participatory innovation and technology transfer and garner public and private support for these innovations. The approach has identified multifaceted yield-limiting factors involving agronomic, infrastructural, and socioeconomic conditions and interventions at the personal and community level are transforming peoples' lives. Significant networks of extension workers have been assembled (Fig. 32)[29]. The science and technology backyard (STB) model could provide an effective approach to realize the green development of agriculture, as it aims to close yield gaps in China by empowering smallholder farmers through integrating efforts of researchers, farmers, the government, and agro-enterprises.

Success at scale in improving sustainable resource use and increasing grain production in China will enhance the country's food security while decreasing poverty and the environmental footprint of food production, thereby contributing to the global goal of sustainable development. To meet new demands of Chinese agriculture in a new era, as well as for promoting further implementation of United Nations (UN) Sustainable Development Goals (SDGs), the National Academy of Agriculture Green Development and the International School of Agriculture Green Development were launched by China Agricultural University in July, 2018. Importantly, a national strategy of Agricultural Green Development has been issued by the central Chinese Government.

Although the STB concept is an interesting one and the figure above shows how information can be delivered at scale, China is a very big country and clearly the messages are also relevant across the globe. There is now much interest in making information available on-line to those working in the food chain and the evidence with MOOCs (massive open on-line courses) is that these messages can reach large numbers of people. Stevens et al. [22]report that one MOOC focussing on Food Security was viewed by 19,000 'students' over a three year period. These viewers were drawn from 187 different countries. Given the wide availability of mobile phones in the developing world, this is a statistic which shows the potential for making relevant information available to the public, a key factor if civil society is to be convinced of the need to transform both eating habits and methods of food production.

A recent CCAFS AgClim letter from Loboguerrero and Campbell[30] stresses the importance of effective local networking by farmers so that they can share, learn and innovate. Of particular note is the success of 'Wefarm'[31], a farmer-to-farmer digital network with more than a million users across Kenya and Uganda. This is a successful case of effective networking that has been translated into concrete benefits for farmers. Loboguerrero and Campbell[30] suggest that farmer organizations need to reflect on, and improve, their effectiveness. They note that to help with this, public and private sector actors can invest in developing creative and innovative networking mechanisms such as digital platforms that can mobilize and connect farmers. There is a growing body of information available on line to those who are interested in recent developments in fields related to food security[32] and platforms which interpret this information for the benefit of farmers and other practitioners are increasingly influential.

5 Engineering novel crops for increased yields and production efficiencies for greater crop resilience

The United Nations and others have suggested that if we are to provide more good quality food to more people and keep up with the increase in the global demand for food, then the availability of food to the global population must be increased by 50% or more in the next 30 years[33]. While some of this extra food can be made available by wasting less and distributing what food we have more effectively, it seems inevitable that as suggested by EAT- Lancet and others [15], we must work to significantly and sustainably increase food production. Production of new crop genotypes for modern agriculture can be a lengthy process, not least because of registration and approval practices. Even with modern phenotyping techniques, selection of new varieties via traditional plant breeding can take many years. Much of the breeding for increased yield has focussed on increasing yield potential and despite the best efforts of breeders of the four major world crops, annual increases in yield are lagging well behind what is required if we are to avoid significant increases in global food insecurity.

Highlighted below are three of a significant number of ambitious international projects started since Beddington and others called attention to the global requirement for more food. The technology in use promises relative swift and significant advances. While the focus in these projects has been increasing crop yield, we are now more aware than ever that this increase in yield must be achieved with reduced use of input resources. While much food will continue to be produced in regions that are well supplied with water and other requirements for plant growth, increasingly, water and nutrients are in very short supply and inevitably, therefore, as well as trying to increase potential yield, we must focus on bridging the yield gap. Genetics will help in this regard but a rather different focus for crop breeding will be required. Of course, agronomy will also be important here. In many parts of the world the use of deficit irrigation is now the norm rather than the exception and if we are to maximise water productivity, for example, then agronomy and genetics must be made to work together. We will see below good examples of this strategy in practice.

Modern genetics is now offering new opportunities to both speed up and enhance the effectiveness of plant breeding[20] . The three examples highlighted are ambitious international collaborations funded by the Bill and Melinda Gates Foundation across 35 institutions in several countries that illustrate the broad scope of what is possible. These collaborative projects use engineering principles and systems modelling of crops and cropping alongside genetic and genomic tools with the aim of significantly increased yields and resource use efficiencies to enable us to meet some of the targets for sustainable agriculture that are discussed above. The following three questions are the focus of these projects:

RIPE: How can photosynthesis be made more efficient and provide the basis of significantly increased crop yields? The RIPE Project[34]

ENSA: Can wheat be engineered to take nitrogen out of the atmosphere, thereby reducing the use of mineral fertilisers?[35]

C4 Rice: Can rice be re-designed to grow in hotter and drier climates with fewer input resources?[7]

These challenges will only be fully answered over decades but are examples of the kind of ambitious, visionary crop science that is required to feed increasing global populations without further damaging the planet. We are already seeing dramatic progress in some areas.

5.1 RIPE

Realizing Increased Photosynthetic Efficiency (RIPE) is an international research project that is engineering crops to be more productive by improving photosynthesis, the natural process of carbon fixation that all plants use to convert the energy in sunlight into chemical energy and crop yields. The goal of RIPE is to help deliver increased global food security by equipping farmers worldwide with higher-yielding crops to increase their income and well-being**.** A foundation to this project is provided by systems modelling which is facilitated by the increase in high-performance computing capability. Photosynthesis is simulated in dynamic models in which each of the multiple coupled reactions is represented. This provides a realistic presentation of the entire carbon fixation process via a system of linked differential equations. The team has also developed realistic simulations of crop canopy development and functioning to allow more accurate prediction of the microclimate and light energy distribution within the crop.

Modelling has allowed the identification of several targets for re-engineering. These include, a) relaxing the leaf's photoprotection mechanisms (which while important for protection of the plant in extreme environments, may be overly conservative in agriculture). Early results here show significantly enhanced carbon gains in engineered plants[36] , b) replacing the native photorespiratory pathway in C3 plants with more efficient bacterial pathways and other novel synthetic pathways. This is predicted to make photosynthesis more efficient and early results show a dramatic 40 percent increase in crop productivity from these manipulations[37] , c) enhanced regeneration of RuBP, a key C acceptor in the Calvin cycle. As global levels of carbon dioxide rise, the limitation imposed by regeneration is becoming greater. Maximizing the efficiency of RuBP regeneration is predicted to deliver a sustainable increase in crop productivity. d) Improving Rubiscos. In C3 photosynthesis, Rubisco initiates carbon assimilation through the carboxylation of RuBP but much analysis suggests that the efficiency of this enzyme can be increased. There is much natural variation to exploit and gene editing might be used to much benefit. e) There are many opportunities to enhance the efficiency with which carbon can enter both canopies and leaves. As suggested above, canopy structure can be optimised and leaf diffuse properties can be improved to decrease the resistance to diffusion of carbon dioxide through the mesophyll tissues to the sites of fixation. Mathematical modelling suggests that a large increase in photosynthesis could be achieved by re-engineering bicarbonate pumps and carboxysome structures (found in algae) into plant chloroplasts. RIPE is attempting this re-engineering, sourcing bicarbonate pumps from the green micro-alga, *Chlamydomonas*.

5.2 ENSA

The restricted availability of nitrogen, phosphorus and other major plant nutrients is one of the major limiting factors to crop growth in the developing world. Meanwhile, in the developed world, many farmers use unsustainable levels of inorganic fertilisers to promote crop production. While this has resulted in greatly enhanced yields of many crops, the environmental problems associated with excess fertiliser use in agriculture are a growing challenge for many. Reducing energy usage in the fertiliser production process and the GHG emissions and ground and surface water pollution issues generated by much farming practice are key targets for a more sustainable agriculture. Finding alternatives to inorganic fertilisers is critical for sustainable and secure food production. Bacteria and Archaea have evolved the capability to fix atmospheric nitrogen to ammonia, a form readily usable in biological processes[38] . In a parallel to the engineering approach taken by the RIPE consortium, this capability presents an opportunity to improve the nutrition of crop plants while using reduced amounts of fertiliser. The introduction into cereal crops of either the nitrogen fixing bacteria or the nitrogenase enzyme responsible for nitrogen fixation is the focus of the ENSA project. While both approaches are challenging, recent advances have laid the groundwork for biotechnological developments that can reduce the worldwide problem of overuse of fertiliser.

5.3 C4 Rice

Rice, one of the world's major food crops, is a 'C3-type' grass, relying on the operation of the Calvin Benson cycle to fix carbon and accumulate biomass. As we have discussed above, productivity of C3 photosynthesis is limited by its inherent inefficiency. On several occasions through time, evolution has overcome this inefficiency through the development of the C4 photosynthetic pathway, common in plants such as maize, sorghum and sugar cane. Such plants are more efficient at carbon assimilation than C3 species, and increasingly importantly as the climate changes, they show greater water use efficiency, higher nitrogen use efficiency and higher tolerance of high temperature. The rationale for the C4 rice project is that photosynthetic efficiency in rice can be improved by re-engineering the photosynthetic machinery to include components of the C4-type pathway. The hypothesis is that increased photosynthetic efficiency will result in greater crop yields that may also be achieved when water and nitrogen are in short supply.

Introducing the C4 pathway into a C3 plant requires re-engineering both anatomical and biochemical traits. C4 plants have a particular leaf structure called Kranz anatomy and to introduce this into rice, vein spacing in the leaves must be reduced. As the cells around the veins in rice leaves have no chloroplasts, it is important for C4 photosynthesis to activate chloroplast development in the bundle sheath cells.

The genes encoding the C4 pathway enzymes and most of the metabolite transporters in C4 plants have been identified. There are at least 12 genes involved and it is important to understand when individual genes should be switched on, at what level and where in the leaf this regulation should take place.

6 Engineering increasing resource use efficiency for climate-resilient plants and crops

6.1 Genetics

Increasingly, climate change models are predicting both decreasing rainfall and increasing vapour pressure deficit of the atmosphere for many regions which are crucial for food production (e.g. the Great Plains of the USA)[39, 40] . This is likely to be a growing challenge for the extra production of food that will be needed by 2050 and a variety of genetic and agronomic innovations are increasingly necessary to help farmers achieve 'more crop per drop' of water available. Water saving agriculture requires the use of less water per unit mass of production and achieving this is increasingly the norm for agriculture worldwide. It has long been recognised that comparatively high yields can be achieved in water-scarce environments by the introduction into superior genotypes traits that actually have little to do with drought resistance *per se*[41] . This is well illustrated by the high water use efficiency shown by crops which cover the ground quickly early in the growing season, thereby reducing the non-productive loss of water from bare soil. Selecting for high crop vigour is a popular trait in cropping systems for hot and dry cropping regions[42] .

While great success in increasing water use efficiency in agriculture has been achieved by agronomists and breeders working together (see below), modern genetics now also provide~~s~~ us with a way of using genetic engineering to increase the water use efficiency of individual leaves and plants. Water vapour is mostly lost from leaves through pores on the leaves called stomata, which also allow a low resistance pathway for the influx of CO_2 into leaves for photosynthetic assimilation. Stomata open in response to light and Glowaka et al. [43] have recently shown that expression of Photosystem II Subunit S (PsbS) impacts a chloroplast-derived signal for stomatal opening in the light. Transgenic tobacco plants with increased PsbS expression showed less stomatal opening in response to light, resulting in a 25% reduction in water loss per unit of CO_2 assimilated under field conditions. This is potentially an important development for crop science and the group suggests that since the role of PsbS is universal across higher plants, this manipulation should be effective across all crops.

6.2 Cropping Systems to allow more efficient use of water and fertiliser while promoting crop yielding

While there can be little doubt that genetics has played and will continue to play a major role in enhancing the resource use efficiency of world agriculture, there is increasing emphasis on the important role that novel farming systems can play in this regard. Systems modelling is a powerful way of scenario-testing as we seek new ways of growing to address the challenges of the climate emergency and the growing shortage of input resources[44] .

We have reported above on the support that the EAT Lancet commission has offered for the introduction into intensive world agriculture of farming systems based on agro-ecological principles and there is no doubt that resource productivity of many crops can be enhanced by this approach. This is not always the case, however, and it is increasingly recognised that more understanding of G x E x M (the interaction between genetics, environment and management) is required if farmers (and the planet) are to benefit from such approaches. One such agro-ecological system is 'Conservation Agriculture' (CA). As the world has woken up to the necessity of producing more food with fewer resources, conservation agriculture has received considerable attention in different parts of the world[45] . One of the important components of many CA systems is the application of minimum tillage (min till), which is promoted as a way of sustaining soil structure and quality, minimising erosion of soils, reducing growth of weeds and also saving water and nutrients and reducing energy use. Greenhouse gas emissions from soil may also be reduced with these farming systems.

In Australia, it initially seemed that CA was not suited to the production of wheat (one of the nation's most important food crops), as when the crop was grown using minimum tillage or a no tillage approach, important early season crop growth was limited. However, studies by agronomists at CSIRO Canberra showed that sterilizing the soil overcame limitations to the early growth of young wheat seedlings when the crop was grown using minimum tillage or a no tillage approach. Higher soil strengths can be directly limiting to root extension but the same group of researchers[46] ~~(Kirkegaard et al. 1995)~~ further elucidated the nature of this problem by showing that there is an interaction of physically-restricted root growth with inhibitory Pseudomonas bacteria around the root tips. This kind of growth limitation by bacteria may be particularly common when min till is applied in CA. When root growth is increased, in some cases, by selecting wheat genotypes with faster growing roots, the bacterial limitation can be minimised. This work has led directly to a growing understanding that one approach to CA does not produce optimal results in all soils and in all environments. This is a classic example of G x E x M in action and is illustrative of the benefits that can accrue when agronomists and geneticists are able to work together, a situation which is not that common in many parts of the world but which has been particularly effective in CSIRO.

Kirkegaard and Hunt[47] note that most G × E x M interactions considered by breeders and physiologists focus on in-crop management (e.g. sowing time, plant density, N management) but their recent work which has received considerable attention around the world highlights the opportunities that exist even before the crop in question is in the field. The argument is that appropriate management of prior crops and fallow periods (e.g. crop sequence, weed control, residue management) can make more water available to a crop grown on stored water, which is often the case with dry-land wheat production in southern Australia. A case study reveals that when wheat genotypes develop long coleoptiles at the seedling stage, this enables deeper sowing which increases the value of different pre- and in-crop management options to significantly increase the water-limited yield from 1.6 t ha^{-1} to 4.5 t ha^{-1}. The authors proposed that greater understanding of such interactions will increasingly be necessary to capture benefits from new varieties within the farming systems and climates of the future.

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A recently-published example of exploitation of genetic variation in the rate of crop development in the important Mediterranean growing regions of Australia shows increases in water-limited yield as slow-developing winter wheat genotypes sown in March are able to access water stored in the soil and available early in the summer[44] . Existing commercial spring wheat varieties which develop more quickly following sowing in May have less water available to them and miss out on the benefits of the longer growing seasons now common in Australia as the climate changes. The authors of the paper comment that by taking a slightly counter-intuitive approach by selecting slower-developing genotypes and planting earlier, national wheat yields could increase by 0.54 tonnes per hectare, which is about 20 per cent of the current Australian national yield.

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7 Sustainable water use in agriculture

Irrigation has long been recognised as a reliable way of increasing productivity of many crops in many regions of the world and this management option becomes increasingly important as our climate challenge becomes more severe. As the planet warms, crop water losses will increase[40] but, in most of the world's major food-producing regions water available for irrigation is becoming more scarce. If large amounts of ground water are extracted for supplemental irrigation, deeper water tables can be highly damaging to natural vegetation, even if it is deep rooted[25, 48] . In addition to serious environmental degradation, in north west China, desertification caused by over use of ground water is causing wide spread social and economic problems for a population in a region where agriculture was previously highly-productive. Ground water can also be of poor quality and irrigation with this water can generate a build-up of salinity in the soil, which may eventually mean that productive agriculture becomes impossible. As water is abstracted from the soil for irrigation, ingress of sea water can also cause salinity problems and in many areas (e.g. southern Spain and Israel), recycled and cleaned waste water can be used to reduce salinity levels in irrigation water. Most crops are intolerant of salinity but engineering of salt tolerance into new crops is of major interest as a way of combatting this challenge[49] .

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The challenges outlined above should make it clear that it is an urgent necessity to reduce the amount of water used in agriculture. More than 70% of the fresh water available to us on the planet is used one way or another in supplying the population with food. A large amount of this use is in irrigation but food processing of different kinds is also quite water-demanding. There are many ways of making water use in agriculture more sustainable. As outlined above, some of these are biological but at the moment, far more significant are the gains that can be achieved by engineering means. Simple approaches such as lining irrigation canals and reservoirs to reduce water leakage as well as covering canals and storage facilities to reduce evaporative water loss will all result in more productive water use. Much water can also be saved by metering water use in even the simplest of ways. Enormous amounts of water are wasted from inadequate transfer and storage equipment and facilities and in many regions, irrigation systems are just switched on for arbitrary periods and often left running in the rain! Methods of water delivery are still often very primitive with e.g. water from rain guns commonly thrown indiscriminately away from the crop onto headlands, farm tracks and even buildings.

Micro-irrigation methods such as mini-sprinklers, drip lines and even sub-surface lines are now widely used in some water scarce regions[50] . These will often require substantial investment in hardware but in some countries, government water-saving policies can result in subsidies for farmers. Drip lines are now often used under plastic mulches between the rows of even broad field crops. Use of only small quantities of water in micro-irrigation and the water saving from plastic mulching can result in very efficient water productivity even in very dry areas. The overuse of plastics in agriculture is a sensitive issue, however, and plastic mulches are now often replaced by crop residues and even with minimum tillage and precision re-seeding of the following year's crop, all of which can reduce wasteful water loss from the soil surface. The availability of precision water delivery systems, water metering capability and cost-effective means of monitoring both soil moisture and plant water status, mean that producers can now also use deficit irrigation and soil drying as a regulator of plant and crop growth and quality. Mild plant water deficits which can be delivered and regulated with the equipment described above, can increase crop harvest index, the proportion of fixed assimilate accumulated in reproductive plant parts (fruits and seeds) compared with vegetative plant parts. Accumulation of flavour and aroma volatiles and health-promoting compounds can be increased by mild water stress, thereby often increasing the value of agricultural products and the profitability of the production business[51,52] . In some agro-industries, regulated soil water deficits can be used simply to reduce the size of plants, thereby removing the necessity to use chemical growth regulators multiple times throughout the growing season. This use of this kind of technology is one way of enhancing the sustainability of agriculture. Another use of newer technology is remote sensing of crop water deficits over large areas in the field using drones or small aircraft. Leaf temperature can easily be sensed with what is now quite inexpensive technology and increases in leaf temperatures can be very well correlated with reductions of leaf water status (plant water stress). Irrigation systems can then be targeted to areas of crop requiring water, with a significant saving of water[53] .

In what is now very well-known work, Fereres and Soriano[54] have shown how 'luxury' water use from very open stomata can be reduced without significantly limiting carbon gain in photosynthesis. As a result of this, instantaneous plant water use efficiency is increased. More significant plant water deficit (from greater irrigation water saving) can reduce carbon gain and reduce cell growth independently of any impact on photosynthesis. Whether or not this reduces crop yield will depend on the timing of the water deficit and the nature of the plant product. Leaf size is generally quite sensitive to even mild plant water deficit. This in turn can limit radiation interception and if this occurs early in the season before the crop canopy has closed, there may be significant limitation in crop yield (leaves, fruits and roots). It should be clear then that different crops will be differentially sensitive to water deficits. As the climate challenge becomes more severe and water supplies are diminished still further, farmers will need to save water by applying deficit irrigation throughout the life of the crop

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and empirical experiments will be necessary to identify significant periods in stress sensitivity of different growth stages contributing to crop yielding[48] .

One very important example of how farmers might save water and thereby potentially save money as well as reducing the impact of crop production on the environment is work on rice production. Paddy rice feeds large numbers of people using a production system which has evolved to exploit large areas of standing water on flood plains in many of the hotter and wetter parts of the world This means that this crop is potentially very damaging to the environment in terms of the use of a significant amount of fresh water. Using conventional paddy rice production systems, one kilogram of rice grain requires 2500 L of water for its production and this means that one third of the world's freshwater is used to irrigate rice -half of all freshwater supplies for Asia. There are other problems with rice paddies as greenhouse gas (GHG) emissions are often high and in certain areas, accumulation of heavy metals and other carcinogens in rice grains can have very negative impacts on food safety for people for whom rice is often their only food staple[55].

Rice is a massively important food crop, consumed by more than 50% of the world's population. Therefore, it is critical to address the challenges of producing a sustainable and safe rice harvest. From the early 1990s, in a substantial research effort led by researchers at Cornell University, crop scientists from around the world have been developing a system of rice intensification, known as SRI (le Système de Riziculture Intensive). This is a cultivation system based on agro-ecological principles and aimed at increasing the productivity of irrigated rice by changing the management of plants, soil, water and nutrients. Components of SRI include significantly reducing plant populations, improving soil conditions and reducing irrigation intensity to promote root and plant development. Attention is also paid to improving plant establishment. Benefits of SRI have been demonstrated in many countries but there has also been much controversy over many results. Reported results include increases in yield of 20%-100%, up to a 90% reduction in seed requirement, and up to 50% water savings[56] . It is claimed that some SRI principles and practices have been adapted for other crops but in reality much work which seeks to reduce water use in agriculture has been motivated by a well-developed understanding of how soil drying impacts yield and how negative effects can be minimised. It is also possible that if applied with enough precision, a mild plant water deficit might actually stimulate yield and at the least, might result in an increase in root to shoot ratio which can almost certainly benefit crops in water scarce regions[57].

One of the best examples in the literature which effectively demonstrates how an understanding of the science underpinning yield development can be exploited to deliver higher water productivity (and thereby greater climate resilience and economic returns for farmers) is work in China with paddy rice[58] . In the work in question, deficit irrigation promotes remobilization of pre-stored carbon reserves in rice stems to promote enhanced grain filling. The authors report up to a 10% increase in grain yield accompanied by around a 30% reduction in water use, a substantial increase in crop water productivity (Fig.4 3). Extensive implementation in China has not only boosted rice production, but also reduced the costs of irrigation. The technique, termed alternate wetting and drying irrigation (AWD), a very specific version of DI, involves reducing water available to the plant to stimulate mild soil drying at the grain-filling stage, thereby greatly promoting whole plant senescence. The resulting carbon remobilization to grains is the basis of the increased yield under mild soil moisture deficit[59, 60] Physiological study has explained the mechanistic basis of this response[61] . Activities of key enzymes involved in sucrose to starch conversion in the grains are also enhanced during soil drying [62, 63]).

The application of AWD does not require outlay on expensive equipment to either deliver the water to the fields, or to assess the extent of soil drying[55] . This may be a key requirement of an innovation that might be exploited by the smallholder farmer. The wide uptake of AWD across Asia (both as a result of work of Yang and Zhang and the work on SRI discussed above) shows both the need for techniques and technology that will save water in agriculture but also the accessibility of this particular technique to the region's farmers.

One other target for intervention in smallholder farming in dryland regions may be the opportunity to manipulate soil biology. We saw above how overcoming a biological limitation to root growth of wheat could increase cropping resilience in water scarce regions[46] . Growth promoting rhizobacteria have also received some attention in this regard and Belimov et al.[64] (2009) have shown how a bacterium that reduces the accumulation of stress ethylene in the plant can reduce the impact of soil drying on the yielding of legumes (Fig. 54). Ethylene can accumulate in mildly stressed plants and will inhibit growth and potentially also nitrogen fixation. Bacteria that break down the precursors of this growth regulator can both increase yield and nitrogen content of seeds of plants in drying soil. Such bacteria are easy and inexpensive to culture and easy to apply to the soil. Local production of suitable bacteria might be encouraged in LDCs, which in itself would be a beneficial activity for rural communities. Cultures could then be available to farmers at an appropriate cost. There may be good opportunities in the future to engineer bacterial and fungal communities in the rhizosphere soil to enhance crop stress resilience.

8 Engineering to allow production of food with fewer people and less environmental damage

In many parts of the world, farmers are struggling to find the labour required to produce their food and particularly to harvest their crops. In the developed world this has led to a focus on the use of robotics and there are several companies currently developing robots for specific purposes in agriculture. Production of both soft and top fruit has been a massive success story in recent years in the UK and the emphasis on increasing the consumption of fruit in a healthy diet suggests that the demand for fruit pickers can only grow. Political changes and changes in currency value have restricted the availability of immigrant labour in recent years and fruit growers in the UK were 15%-30% short of seasonal pickers in summer of 2018, resulting in crop wastage. The situation in 2019 is apparently even more serious. This growing problem means that robotics is predicted to be the future of fruit picking in some parts of the world. One company, 'Fieldwork Robotics' working to address agricultural challenges estimate that their robot will be able to pick more than 25,000 raspberries a day. Robots will not be inexpensive but a performance of this kind will far outpace even the best human workers. Robots are also in development with one of Britain's main berry growers which supplies several major retailers in the UK and these robots could go into action in 2020.

In the future it seems likely that robots will plant seeds, create plant-by-plant maps of fields and kill weeds with lasers. The robots can be much smaller than tractors, allowing them to be used in small, irregularly shaped fields. Importantly, these small machines limit soil compaction, a problem for crops if larger machines are used indiscriminately across fields. These problems are now commonly minimised also with use of GPS, allowing the establishment of 'tramlines', where tractors repeatedly use exactly the same routes across fields.

We have discussed above the challenge for world agriculture in reducing its environmental footprint Globally, agriculture is responsible for more than 20% of GHG emissions and policy reforms are urgently needed if society is to deliver on COP21 commitments. A large scale change in land use is one development that will drive potentially beneficial changes in emissions. Chazdon and Brancalion[65] have very recently pointed out that an area the size of the US could be made available for planting trees around the world. The Intergovernmental Panel on Climate Change (IPCC) has previously estimated that if the world wanted to limit the global temperature rise to 1.5C, (as agreed by COP21), an extra 1bn hectares (2.4bn acres) of trees would be needed for potentially significant impact on

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atmospheric CO_2 accumulation. This new report aims to show where trees could be planted. The study suggests that the space available for trees could reduce CO_2 concentration in the atmosphere by 25%!

A strategy like this to reduce global warming would inevitably have some impact on our capacity to reach our food security targets unless we can revolutionize the way that we grow food. Emerging technologies make this much more feasible. There has been much discussion of the desirability of developing vertical farms to grow food in closer proximity to the market, thereby reducing transport costs but until recently, examples of such developments at scale have been hard to find. Very recently, Ocado, a food distribution company in the UK, has invested £17m in developing a number of vertical farms in close proximity to its distribution centres. The farms will grow leafy salads and herbs. The company believes that its investments in vertical farming will allow them to address consumer concerns about freshness and sustainability and build on new technologies that will revolutionise the way customers access fresh produce. Vertical farming mostly involves producing food in buildings, with crops grown on a series of stacked levels in a controlled environment. Europe's largest existing vertical farm, has more than 5,000 metres of indoor growing area, lit by 12km of LED lights and of course it can produce crops throughout the year, potentially producing 400 tons of crop per annum. Artificial lighting provided by LEDs means that there is no limit to the amount of stacking, thus potentially reducing the demand for land suitable for horticulture and some agriculture. The production and harvesting processes in such a system are very suitable for robotics, thereby reducing the labour requirement. Indoor farms can help save energy, fertiliser and water. Pesticide use can be limited via the use of integrated pest management tailored to enclosed controlled environments. The quality and potentially the safety of food can be increased. Food waste can also be reduced and farming systems of this type will undoubtedly make the food production systems more climate resilient. We are therefore bound to ask whether this the way ahead for production of increasing amounts of good quality food in the future?

While developments such as vertical farming for the most part require significant investment in technology, other forms of intensive protected cropping are already delivering increased environmental sustainability and high productivity. The simplest form of plastic covering can greatly reduce wasteful water loss from the soil between the crop plants, and agriculture in some of the hottest and driest parts of the world would not be possible without this innovation. However, there is much sensitivity about the use of plastics in agriculture and horticulture and so alternatives must be found [66]. Protected cropping in northern Europe has extended the growing season for many crops, which in many cases has transformed the profitability of the production industry in these regions. These are also important developments for environmental reasons, with a reduced need for imports of food impacting positively on GHG emissions by the industry. While leafy salads, berries and many other fruits and vegetables are still imported by northern European countries during their off-seasons, for these crops, plastic packaging provides necessary protection, storage and shelf life improvement. Without this, food wastage during transportation and storage would greatly increase, with a negative impact on sustainability. Changes in what have become standard production, storage and marketing practices for a productive industry must be made for environmental reasons but this should not be done without a full assessment of the broader impacts across the food system.

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9 Conclusions

This paper supports a general groundswell of opinion across the globe that society needs to more effectively feed a growing global population with a healthy diet while also defining and delivering the kinds of sustainable food systems that will minimise damage to our planet. Many researchers are clear that our current food and farming practices threaten both human and planetary health[1], and in an ambitious recent paper, Willett et al. [4] (2019) have attempted to define a healthy 'reference diet' for the planet. The paper then suggests that a universal definition of sustainable food production should use a system-wide assessment of environmental effects of a comprehensive set of environmental parameters at various scales. The commission summarises studies addressing environmental effects of overall dietary patterns. Applying a global food system modelling framework shows that it is possible to feed a healthy diet to a global population of nearly 10 billion people and importantly, do this within food production boundaries. Willett et al.[4] (2019) point out that to fulfil such an aim by 2050 will require nothing less than a 'great food transformation.' Although controversial for some, the EAT Lancet commission provides an interesting framework for urgently-needed policy discussions and future action by individuals and by society.

Recent developments in crop science and in crop genetics can be the basis of a revolution in our global food system to ensure an enhanced supply of good quality, nutritious and safe food. Of course, such a revolution requires more than changes in food production and supply and in some cases many of the required changes may not even be directly to do with food. However, we argue strongly that crop science has a key role to play in feeding more food to more people. The developing climate emergency means that the need for innovation in production of new genotypes and new crop production systems becomes ever more acute. Much existing crop science can be exploited in a revised knowledge exchange framework requiring the use of new technology now available to all. The smallholder community can benefit from easier access to crop science and also from the increased availability of new genotypes.

If we are to produce more while reducing the environmental footprint of food production and supply, then a total restructuring of the global food system may be required. One extreme transition in practice which would greatly enhance the sustainability of food production would be a shift to 'circular agriculture' and more specifically to a circular nutrient economy, including the recirculation of nutrients derived from human excreta [67]. A transition of this kind will require seismic shifts in wastewater management and urban infrastructure (an engineering challenge) as well as increased attention to the quality and safety of agricultural products (a challenge for biology).

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As argued by a recent report from UK Plant Sciences Federation[20], exploitation of new biology will require 'promotion of public-private partnerships and collaborations across the disciplines to effectively bridge the gap between discovery science and commercial application. This will also be the case for an engineering revolution. The science community must also engage more effectively with the general public and policy makers so that all understand the challenges, the opportunities and the concerns still held by many people over 'modern' food and farming.

Reference

1 Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M, Toulmin C. Food Security: The Challenge of Feeding 9 Billion People. *Science.* 2010, 327: 812-818

2 Foresight. The Future of Food and Farming. Executive Summary. The Government Office for Science, London. Available on UK Government web site, November 2019

3 FAO, IFAD, UNICEF, WFP, WHO report on the state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition. Available on the website of the UN Food and Agriculture Organisation (FAO), (November 2019.

4 Willett W, Rockstrom J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet*, 2019, 393: 447-492

5 The Paris Agreement of the UN Climate Change Convention. Available on the UNCCC website, November 2019

6 Benton T. The many faces of food security. *International Affairs* 2016, 92: 1505-1515

7 C4 RICE research project funded by the Gates Foundation and others Available on the website of the Consultative Group for International Agricultural Research (CGIAR) as part of their programme on . Available on the CGIAR website under climate-change-agriculture-and-food-security, November 2019.

8 Report of The Intergovernmental Panel on Climate Change (IPCC) focussing on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Available on the website of the IPCC, November 2019.

9 Haddad L, Hawkes C, Waage J, Webb P. Food systems and diets: Facing the challenges of the 21st century. London, UK: Global Panel on Agriculture and Food Systems for Nutrition, 2016. Available on the open access pages of City University (UK) Research Online, November 2019

10 Key findings of an Organisation for Economic Cooperation and Development (OECD) report on obesity rates in Europe. Data for the United Kingdom. Available on the website of the (OECD) November 2019.

11 Report from the World Health Organisation (WHO) on obesity. Available on WHO website November 2019.

12 Ericksen P J. Conceptualizing food systems for global environmental change research. *Global Environmental Change*, 2008, 18: 234-245

13 Zagmutt F J, Pouzou J G, Costard S. The EAT–Lancet Commission: a flawed approach? *The Lancet*, 2019, 394: 1140–1141

14 Kirkegaard J A, Conyers M K, Hunt J R, Kirkby C A, Watt M, Rebetzke G J. Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems & Environment,* 2014*,* 187: 133-145

15 Baulcombe D, Crute I, Davies W J, Dunwell J, Gale M, Jones J, Pretty J, Sutherland W, Toulmin C. Reaping the Benefits: Science and the sustainable intensification of global agriculture. *Royal Society. London*, 2009, 86p

16 Lipper L, Thornton P, Campbell B M, Baedeker T, Braimoh A, Bwalya M, Caron P, Cattaneo A, Garrity D, Henry K, Hottle R, Jackson L, Jarvis A, Kossam F, Mann W, McCarthy N, Meybeck A, Neufeldt H, Remington T, Sen PT, Sessa R, Shula R, Tibu A, Torquebiau E F. Climate-smart agriculture for food security. *Nature Climate Change*, 2014, 4:1068-1072

17 Bukovinszky T, Verheijen J, Zwever S, Klop E, Biesmeijer J C, Wackers F L, Prins H H T, Kleijn D. Exploring the relationships between landscape complexity, wild bee species richness and reproduction, and pollination services along a complexity gradient in the Netherlands. Biological Conservation 2014, 214: 312-319

18 Wilson E O. Half Earth: our planet's fight for life. 2016, Liveright Publishing, New York

19 Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature*, 2014, 515: 518-522

20 Growing the Future, a report from the UK Plant Science Federation on the future for British Plant Science Available on the website of the Royal Society of Biology, November 2019.

21 Collaborative training partnership for sustainable food production. Details available on website of the Lancaster Environment centre, November 2019

22 Stevens C J, Whittle R, Davies W J, Taylor J E. Raising awareness about food security using a massive open online course. *Plants, People and Planet*, 2019, DOI: 1002/ppp3. 10069

23 Distance learning food security programme for those with interest in or working within the Global Food System. Details available on website of the Lancaster Environment Centre, November 2019.

24 Zhang, W F, Cao G X, Li X L, Zhang H Y, Wang C, Liu Q Q, Chen X P, Cui Z L, Shen J B, Jiang R F, Mi G H, Miao Y X, Zhang F S, Dou Z X. et al (2016) Closing yield gaps in China by empowering smallholder farmers. *Nature*, 2016, 537: 624-625.

25 Jiao X, Lyu Y, Wu X, Haigang L, Cheng L, Zhang C, Yuan L, Jiang R, Jiang B, Rengel Z, Zhang F, Davies WJ, Shen J. Grain production versus resource and environmental costs:towards increasing sustainability of nutrient use in China*. Journal of Experimental Botany*, 2016, 67: 4935–4949

26 Jägerskog A, Jønch Clausen T. (eds.) Feeding a thirsty world: challenges and opportunities for a water and food secure future. 2012, Report 31 Stockholm

27 Kang S Z, Su X L, Tong L, Zhang J H, Zhang L, Davies W J. A warning from an ancient oasis: intensive human activities are leading to potential ecological and social catastrophe. *International Journal of Sustainable Development and World Ecology.* 2008, 15: 440-447

28 Kang S, Eltahir E A B. North China plain threatened by deadly heatwaves due to climate change and irrigation. *Nature Climate Change*, 2018, 9: 2894

29 Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang J, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, , Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Ying H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, 555: 363–366

30 Loboguerrero AM, Campbell B. Effective farmers confronting climate change. *CCAFS AgClim Letters*, 2019, July

31 The world's largest digital farmer to farmer network. Available on the Wefarm website, November 2019

32 The Global Plant Council (GPC) seeks to facilitate the development of plant science for global challenges such as world hunger, sustainability, environmental protection, and climate change. Information is available on the website of the GPC, November 2019

33 The Food and Agriculture Organisation (FAO) of the United Nations analyses information which allows us to predict food demand in 2050. Information on how to Feed the World in 2050 is available on the FAO website, November 2019

34 The RIPE Project funded by the Gates Foundation and others addresses the means of increasing food production using bio-engineering Information on the project is available on the wesite of the University of Illinois, November 2019

35The ENSA Project funded by the Gates Foundation and others focusses on engineering nitrogen symbiosis for Africa. Information is available on the ENSA website, November 2019

36 Kromdijk J, Głowacka K, Leonelli L, Gabilly S T, Iwai M, Niyogi K K. Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. *Science*, 2016, 354, 857-861.

37 South P F, Cavanagh A P, Liu H W, Ort D R. Synthetic glycolate metabolism pathways stimulate crop growth and crop productivity in the field. *Science*, 2019, 363: DOI: 10.1126/science.aat9077

38 Oldroyd GE, Dixon R. Biotechnological solutions to the nitrogen problem. Current Opinions in Biotechnology, 2014, 26:19-24.

39 Lobell D B, Roberts M J, Schlenker W, Braun N, Little B B, Rejesus R M, Hammer G L. Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest. *Science*, 2014, 344: 516-519

40 2014 Ort D, Long SP. Limits on yield in the corn belt. *Science*, 2014: 344,: 484-486.

41 Richards R. Defining selection criteria to improve yield under drought. *Plant Growth Regulation*, 1996, 20:157-166

42 Zhao Z, Rebetzke G J, Zheng B, Chapman S C, Wang E. Modelling impact of early vigour on yield in dryland regions. *Journal of Experimental Botany*, 2019, 70: 2535–2548

43 Glowaka K, Kromdijk J, Kucera K, Xie J, Cavanagh A P, Leonelli L, Leakey A D B, Ort D R, Niyogi K K, Long S P. Photosystem II subunit S overexpression increases the efficiency of water use in a field-grown crop. *Nature Communications*, 2018, 9:868 | DOI: 10.1038/s41467-018-03231-x

44 Hunt J R, Lilley J M, Trevaskis B, Flohr B M, Peake A, Fletcher A, Zwart A B, Gobbett D, Kirkegaard JA. Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change*, 2019, 9: 244-247

45 Vanlauwea B, Wendt B J, Giller K E, Corbeelsde M, Gerard B, Nolte C. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crops Research*, 2014, 155: 10-13

46 Kirkegaard J A, Munns R, James R A, Gardner P A, Angus J F. Reduced growth and yield of wheat with conservation cropping. II. Soil biological factors limit growth under direct drilling. *Australian Journal of Agricultural Research,* 1995, 46: 75-88

47 Kirkegaard J A, Hunt J R. Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany,* 2010, 61: 4129-4143

48 Du T S, Kang S, Zhang J, Davies W J. Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. *Journal of Experimental Botany* 2015, 66: 2253–2269

49 Munns R, Gilliham M. Salinity tolerance of crops – what is the cost? *New Phytologist* 2015, 208: 668-673. https://doi.org/10.1111/nph.13519

50 Fereres E, Orgaz F, Gonzales-Dugo V. Reflections on Food security under wáter scarcity. *Journal of Experimental Botany.* 2011, 62: 4079-4086

51 Chaves M M, dos Santos T P, Souza C, Pereira J S. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology*, 2007, 150: 237–252

52 Dodds P A A, Taylor J M, Else M A, Atkinson C J, Davies W J. Partial rootzone drying increases antioxidant activity in strawberries. *Acta Horticulturae*, 2007, 744: 295-302

53 Jones H G, Serraj R, Loveys B R, Xiong L, Wheaton A, Price A H. Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field. *Functional Plant Biology.* 2009, 36: 978–989.

54 Fereres E, Soriano M A. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany.* 2007, 58: 147-159

55 Price A H, Norton G J, Salt D E, Ebenhöh O, Meharg A A, Meharg C, Islam M R, Sarma R N, Dasgupta T, Ismail A M, McNally K L, Zhang H, Dodd I C, Davies W J. Alternate wetting and drying irrigation for rice in Bangladesh: is it sustainable and has plant breeding something to offer? *Food and Energy Security*, 2013, 2:120-129

56 Thakur A K, Stoop W A, Scientific underpinnings of the System of Rice Intensification (SRI): What is known so far? *Advances in Agronomy*, 2015, 135:147-189

57 Spollen W G, Sharp R E, Saab I N, Wu Y. Regulation of cell expansion in roots and shoots at low water potentials. In Water Deficits: responses from cell to community. Eds. JAC Smith and H Griffiths. 1993, 37-52. Bios Oxford

58 Yang J, Zhang J. Grain filling of cereals under soil drying. *New Phytologist*, 2006, 169: 223–236

59 Yang J, Zhang J, Wang Z, Zhu Q, Wang W. Remobilization of carbon reserves in response to water-deficit during grain filling of rice. *Field Crops Research*, 2001, 71: 47-55

60 Yang J, Zhang J, Liu L, Wang Z, Zhu Q. Carbon remobilization and grain filling in japonica/indica hybrid rice subjected to post-anthesis water deficits. *Agronomy Journal*, 2002, 94: 102-109

61 Yang J, Zhang J, Wang Z, Zhu Q, Wang W. Hormonal changes in the grains of rice subjected to water stress during grain filling. *Plant Physiology*, 2001, 127: 315-323

62 Yang J, Zhang J, Wang Z, Zhu Q. Activities of starch hydrolytic enzymes and sucrose-phosphate synthase in the stems of rice subjected to water stress during grain filling. *Journal of Experimental Botany*, 2010, 52: 2169-2179

63 Yang J, Zhang J, Wang Z, Xu G, Zhu Q. Activities of key enzymes in sucrose to starch conversion in wheat grains subjected to water deficit during grain filling. *Plant Physiology*, 2004, 135: 1621-1629

64 Belimov A A, Dodd I C, Hontzeas N, Theobald J C, Safronova V I, Davies W J. Rhizosphere bacteria containing 1 ‐ aminocyclopropane ‐ 1 ‐ carboxylate deaminase increase yield of plants grown in drying soil via both local and systemic hormone signalling. *New Phytologist*, 2009, 181: 413-423.

65 Chazdon R, Brancalion P. Restoring forests as a means to many ends. *Science*, 2019, 365, 6448: 24-25

66 Reducing the use of plastics in agriculture The Courtauld Commission for ~~wrap~~WRAP UK. Details can be found on the WRAP website, ~~as of 16~~ November 2019

67 Schroder2011] Schroder J J, Smit A L, Cordell D, Rosemarin A. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. *Chemosphere*, 2011, 84: 822-831

Fig 1. Key components of the global food system, modified from proposals made by Ericksen[12], 2008.

Fig 21. Schematic representation of a collaboration between the food market, industry practitioners, research providers and communication specialists to deliver effective knowledge exchange to those working within the UK Fresh Produce Supply Chain. Desirable changes in practice towards increased sustainability are identified by the farm assessment programme and the training programmes, their effects assessed via the collaborative research programme and subsequent recommendations communicated to practitioners via a communications portal.

Fig 32. A schematic representation of a Science and Technology Backyard (STB) as conceived by researchers at China Agricultural University (CAU). STB is a hub that connects the science community and the farming community to facilitate knowledge exchange. Potentially-beneficial management technologies are proposed and discussed with leading farmers to enable development of farm-applicable recommendations. Leading farmers test new practices and recommend appropriate innovation to other farmers. Through the hub, government and agribusinesses also engage and help extend innovation. Figure provided by Professors Jianbo Shen and Fusuo Zhang. Figure fcompiled from work of Cui et al. 2018

Fig 43. Grain yield, irrigation water use and water use efficiency of rice crops grown under traditional flooding irrigation (TF) and alternate wetting and drying irrigation (AWD). Data provided by Professor JC Yang.

Fig 54. Impact of soil bacteria (Variovorax paradoxus 5C2) and soil drying on growth, yield, water relations, chemical signalling and nodulation of peas grown in field soil. UC indicates untreated controls and 5C2 indicates plants treated with bacteria. Data extracted fromfrom Belimov et al. [64] 2009.

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Fig. 1


The Market
Farm Assessment
On-Line Training Programme(s)
Collaborative Research
Communications Portal
International Teaching Programmes
Suppliers and Producers
Students, Researchers and KE specialists

Fig. 2


Government
University
STB
Enterprise
Smallholder farmers
Transformation of agriculture in China
Farms across China
Agriculture

Fig. 3

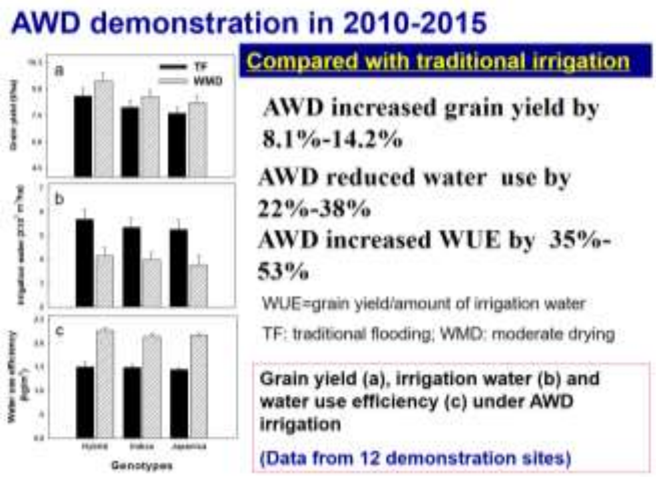
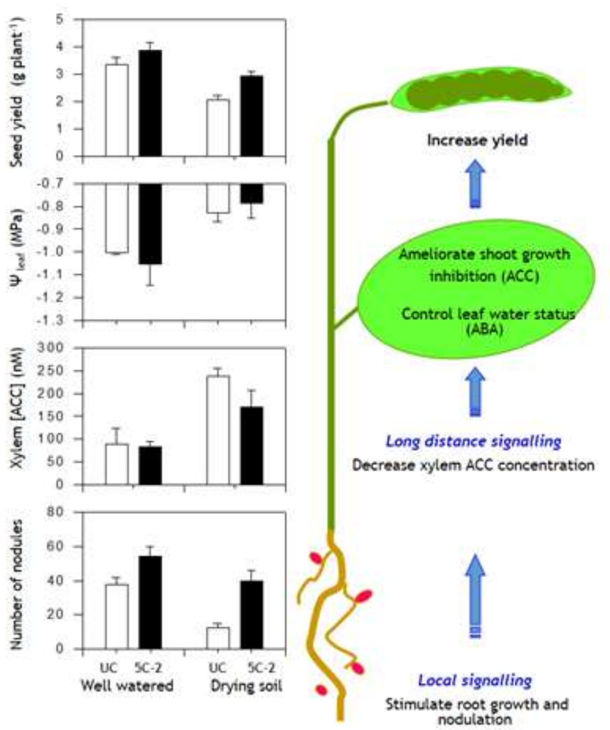

AWD demonstration in 2010-2015
Compared with traditional irrigation
TF
WMD
a
b
c
Genotypes
AWD increased grain yield by 8.1%-14.2%
AWD reduced water use by 22%-38%
AWD increased WUE by 35%-53%
WUE=grain yield/amount of irrigation water
TF: traditional flooding; WMD: moderate drying
Grain yield (a), irrigation water (b) and water use efficiency (c) under AWD irrigation
(Data from 12 demonstration sites)

Fig. 4



Seed yield (g plant⁻¹)
Ψ leaf (MPa)
Xylem [ACC] (nM)
Number of nodules
UC
5C-2
UC
5C-2
Well watered
Drying soil
Increase yield
Ameliorate shoot growth inhibition (ACC)
Control leaf water status (ABA)
Long distance signalling
Decrease xylem ACC concentration
Local signalling
Stimulate root growth and nodulation