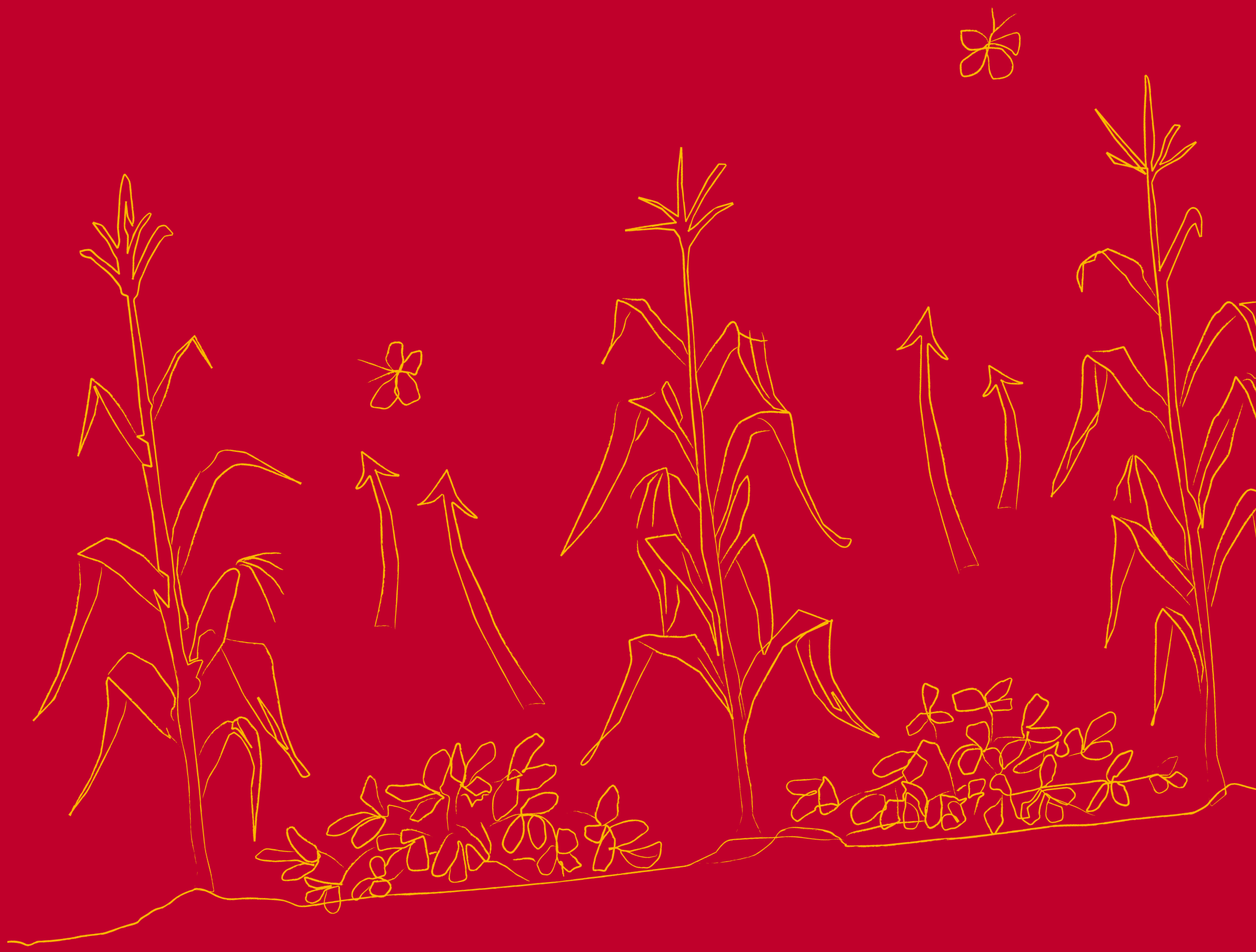
Reaping the benefits

Science and the sustainable intensification of global agriculture

October 2009



CELEBRATE 350 YEARS

THE ROYAL SOCIETY

Cover image: From an illustration of a push-pull system for pest control, courtesy of The Gatsby Charitable Foundation. *The Quiet Revolution: Push-Pull Technology and the African Farmer*. Gatsby Charitable Foundation 2005.

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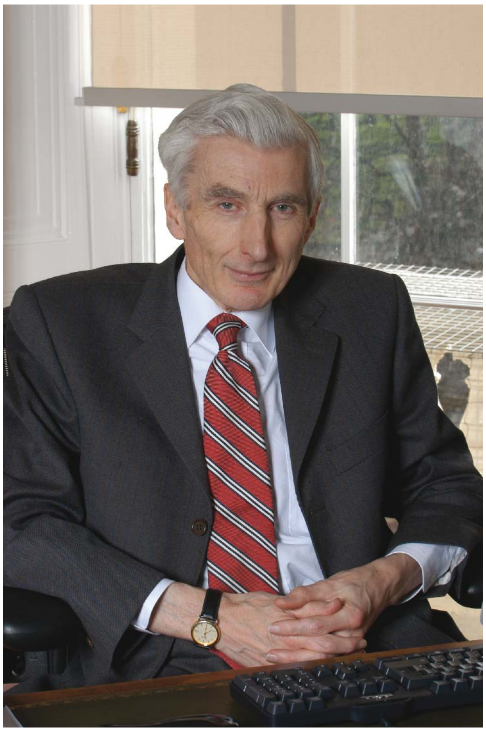

It is more than 200 years since Thomas Malthus offered his famously pessimistic prediction that the rise in human populations would outrun the growth in food supplies. But despite devastating regional famines, prognostications of mass starvation have not been fulfilled, even though the population has risen around six-fold since Malthus's time.

Nonetheless, projections for the coming decades are deeply disquieting. We are already unduly dependent on farming techniques that have harmful environmental impacts. To meet the needs of a growing population with changing consumption patterns, productivity must be enhanced, but it must be done so sustainably.

This report describes how the prudent application of recent and prospective biological advances can contribute to the 'sustainable intensification' of agriculture. It argues that a multi-pronged approach is needed. Improvements in farming practices and crop management are essential, but modern genetics must be utilised too.

There is a big gap between sophisticated UK laboratories and the reality of subsistence farming in Africa: to eliminate malnourishment requires an adequate economic and political infrastructure as well. But the message of this report is that scientific advances are necessary, even if they are not sufficient, if global food supplies are to be ensured.

Since the first 'green revolution' 50 years ago, international research institutes have made hugely valuable contributions to human welfare. UK laboratories have been at the forefront of these efforts. Their mission has never been as important as today, nor has biological knowledge ever offered such great potential. The challenge of learning how to feed the world cannot be left to the private sector: governmental support—increasingly (and gratifyingly) augmented by major charities—is crucial.

This authoritative and balanced report offers enlightening reading for all policy makers; its well judged recommendations should be heeded.

The Royal Society is grateful to all the members of the Working Group and especially to Sir David Baulcombe, its Chairman. We also acknowledge the valuable inputs from the Council's review group, and the efficient and professional support of the Society's Science Policy team. The Society would like to express special gratitude to Professor Mike Gale FRS, who died suddenly very soon after the final Working Group meeting. This report is dedicated to him and his family.

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The members of the working group involved in producing this report were as follows:

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This report has been reviewed by an independent panel of experts and also approved by the Council of the Royal Society.

Review Panel	
The Royal Society gratefully acknowledges the contribution of the reviewers. The review group were not asked to endorse the conclusions or recommendations of this report, nor did they see the final draft of the report before its release.	
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Summary

Food security is one of this century's key global challenges. By 2050 the world will require increased crop production in order to feed its predicted 9 billion people. This must be done in the face of changing consumption patterns, the impacts of climate change and the growing scarcity of water and land. Crop production methods will also have to sustain the environment, preserve natural resources and support livelihoods of farmers and rural populations around the world. There is a pressing need for the 'sustainable intensification' of global agriculture in which yields are increased without adverse environmental impact and without the cultivation of more land.

Addressing the need to secure a food supply for the whole world requires an urgent international effort with a clear sense of long-term challenges and possibilities. Biological science, especially publicly funded science, must play a vital role in the sustainable intensification of food crop production. The UK has a responsibility and the capacity to take a leading role in providing a range of scientific solutions to mitigate potential food shortages. This will require significant funding of cross-disciplinary science for food security.

The constraints on food crop production are well understood, but differ widely across regions. The availability of water and good soils are major limiting factors. Significant losses in crop yields occur due to pests, diseases and weed competition. The effects of climate change will further exacerbate the stresses on crop plants, potentially leading to dramatic yield reductions. Maintaining and enhancing the diversity of crop genetic resources is vital to facilitate crop breeding and thereby enhance the resilience of food crop production.

Addressing these constraints requires technologies and approaches that are underpinned by good science. Some of these technologies build on existing knowledge, while others are completely radical approaches, drawing on genomics and high-throughput analysis.

Novel research methods have the potential to contribute to food crop production through both genetic improvement of crops and new crop and soil management practices. Genetic improvements to crops can occur through breeding or genetic modification to introduce a range of desirable traits. The application of genetic methods has the potential to refine existing crops and provide incremental improvements. These methods also have the potential to introduce radical and highly significant improvements to crops by increasing photosynthetic efficiency, reducing the need for nitrogen or other fertilisers and unlocking some of the unrealised potential of crop genomes.

The science of crop management and agricultural practice also needs to be given particular emphasis as part of a food security grand challenge. These approaches can address key constraints in existing crop varieties and can be applied widely. Current approaches to maximising production within agricultural systems are unsustainable; new methodologies that utilise all elements of the agricultural system are needed, including better soil management and enhancement and exploitation of populations of beneficial soil microbes. Agronomy, soil science and agroecology—the relevant sciences—have been neglected in recent years.

Past debates about the use of new technologies for agriculture have tended to adopt an either/or approach, emphasising the merits of particular agricultural systems or technological approaches and the downsides of others. This has been seen most obviously with respect to genetically modified (GM) crops, the use of pesticides and the arguments for and against organic modes of production. These debates have failed to acknowledge that there is no technological panacea for the global challenge of sustainable and secure global food production. There will always be trade-offs and local complexities. This report considers both new crop varieties and appropriate agroecological crop and soil management practices and adopts an inclusive approach. No techniques or technologies should be ruled out. Global agriculture demands a diversity of approaches, specific to crops, localities, cultures and other circumstances. Such diversity demands that the breadth of relevant scientific enquiry is equally diverse, and that science needs to be combined with social, economic and political perspectives.

In addition to supporting high-quality science, the UK needs to maintain and build its capacity to innovate, in collaboration with international and national research centres. UK scientists and agronomists have in the past played a leading role in disciplines relevant to agriculture, but training in agricultural sciences and related topics has recently suffered from a lack of policy attention and support. Agricultural extension services, connecting farmers with new innovations, have been similarly neglected in the UK and elsewhere. There is a major need to review the support for and provision of extension services, particularly in developing countries.

The governance of innovation for agriculture needs to maximise opportunities for increasing production, while at the same time protecting societies, economies and the environment from negative side effects. Regulatory systems need to improve their assessment of benefits. Horizon scanning will ensure proactive consideration of technological options by governments. Assessment of benefits, risks and uncertainties should be seen broadly, and should include the wider impacts of new technologies and practices on economies and societies. Public and stakeholder dialogue—with NGOs, scientists and farmers in particular—needs to be a part of all governance frameworks.

Recommendations

1. Research Councils UK (RCUK) should develop a cross-council 'grand challenge' on global food crop security as a priority. This needs to secure at least £2 billion over 10 years to make a substantial difference. We believe this will require between £50 and £100 million per year of new government money in addition to existing research spending. This long-term UK programme should bring together all research councils, the Technology Strategy Board and key central government research funders (DFID and DEFRA) and be aligned with comparable international activities in this area. It should be informed by dialogue with farmers, other stakeholders and members of the public. The following recommendations justify allocation of these funds to excellent and relevant research, research training and technology transfer.

2. UK research funders should support public sector crop breeding and genomics programmes to understand, preserve and enhance the germplasm of priority crops and train the next generation of plant breeders. International programmes in collaboration with Consultative Group on International Agricultural Research (CGIAR) centres and others in Africa and India should include millet, sorghum and rice. The top UK priority should be wheat, followed by barley, oil seed rape, potato, vegetable brassicas and other horticultural crops. Public sector support for breeding needs to emphasise longer term strategic approaches than can be expected from the private sector and develop traits from public sector research.

3. RCUK should increase support for ecosystem-based approaches, agronomy and the related sciences that underpin improved crop and soil management.

4. RCUK, and BBSRC in particular, should support long-term high-risk approaches to high-return targets in genetic improvement of crops. These targets include GM crops with improved photosynthetic efficiency or nitrogen fixation. High risk approaches might also produce GM or conventionally bred crops with reduced environmental impact because they need lower fertiliser input or could be grown as perennials. Research into conventional breeding and GM approaches to increased yield and resistance to stress and disease should also continue to be funded.

5. Universities should work with funding bodies to reverse the decline in subjects relevant to a sustainable intensification of food crop production, such as agronomy, plant physiology, pathology and general botany, soil science, environmental microbiology, weed science and entomology. We recommend that attempts by universities and funding bodies to address this skills gap look globally. Studentships and postdoctoral research positions should provide targeted subsidies to scientists in developing countries to visit the UK and work with UK researchers.

6. In order to sustain research capacity and maximise the potential for research to be utilised, crop science research funded by BBSRC, DFID and others, together or separately, should have regular calls for proposals rather than one-off grant rounds. Grants awarded in phases will allow researchers to pursue successful ideas in the field or in new countries.

7. DFID should work with the CGIAR institutes to develop new mechanisms for international research collaborations with emerging scientific bases such as in China, Brazil, India and South Africa. Through its support for CGIAR, DFID should work with research funders and UK scientists to strengthen collaborations with international researchers. The UK should work with other partner countries to prioritise global agricultural research within the forthcoming European Commission eighth framework Programme.

8. Research that links UK science with developing countries, funded by DFID, BBSRC and others, should work with farmers and extension services in target countries to make sure that benefits are captured and made accessible to poor farmers.

9. As part of the RCUK grand challenge there should be support for joint initiatives between the public sector and industry in which the explicit aim is the translation and application of previously executed basic research.

10. The UK department for Business, Innovation and Skills should review relevant intellectual property systems to ensure that patenting or varietal protection of new seed varieties does not work against poverty alleviation, farmer-led innovation or publicly funded research efforts.

11. UK government should work with EU partner countries over the next five to ten years to develop a system of regulation for new agricultural processes and products, based on shared principles.

12. DFID and DEFRA should build on the work of the Food Research Partnership to establish an independent food security advisory function. This would work openly with stakeholders to help the government put future technological options into a broad social and economic context and appraise their benefits and uncertainties alongside alternatives. It would feed into and stimulate similar international efforts at CGIAR and UN level.

1 Introduction

Summary
Food security is an urgent challenge. It is a global problem that is set to worsen with current trends of population, consumption, climate change and resource scarcity. The last 50 years have seen remarkable growth in global agricultural production, but the impact on the environment has been unsustainable. The benefits of this green revolution have also been distributed unevenly; growth in Asia and America has not been matched in Africa. Science can potentially continue to provide dramatic improvements to crop production, but it must do so sustainably. Science and technology must therefore be understood in their broader social, economic and environmental contexts. The sustainable intensification of crop production requires a clear definition of agricultural sustainability. Improvements to food crop production should aim to reduce rather than exacerbate global inequalities if they are to contribute to economic development. This report follows other recent analyses, all arguing that major improvements are needed to the way that scientific research is funded and used.

1.1 An urgent challenge

Food security will be one of this century's key global challenges. Current trends of population, food demand and climate change could lead to a global crisis in the coming decades unless action is taken now. Securing food supply for the world requires a new, concerted and immediate international effort with a clear sense of long-term challenges and possibilities. Science must play a vital role in this response. The Royal Society has chosen to assess the role of biological sciences in meeting this challenge.

Although this report offers a UK perspective, our vision is global. This report's target is not just UK food production. We are interested in the broader contribution that the UK might make to increasing food production around the world. The UK is a world leader in plant and agricultural sciences and has long combined a variety of disciplines to contribute to the fight against global food insecurity. This report offers recommendations for science and policy to enhance the contribution made by UK scientists.

In 2008, food price shocks around the world demonstrated the importance and extraordinary interdependence of global systems of food production. For many of the world's poorest people who spend a large proportion of their incomes on food, the increase in food prices had an enormous impact. Food scarcity led to riots in Morocco, Mexico, Indonesia and elsewhere. This political instability was a result of a number of short-term pressures, but it highlighted a long-term problem of food security and its impact on human well-being. Prices have since fallen, but the volatility of global markets provides a clear warning against complacency. Our report builds on the 2008 International Assessment of Agricultural Knowledge, Science and Technology for Development report's conclusion that 'Business as usual is not an option' (IAASTD 2008a).

It is now clear that global food insecurity is a chronic problem that is set to worsen (see Box 1.1).

Box 1.1 Drivers for chronic food insecurity (von Braun 2007; Conway 2009)

- Increasing population;
- Changing and converging consumption patterns;
- Increasing per capita incomes, leading to increased resource consumption;
- Growing demand for livestock products (meat and dairy), particularly those fed on grain;
- Growing demand for biofuels;
- Increasing water and land scarcity;
- Adverse impacts of climate change;
- Slowing of increases in agricultural productivity.

The world population will increase up to at least the mid-21st century, and absolute demand for food will rise. Estimates of population increases over the coming decades vary, but the emerging consensus is that the world will have approximately 9 billion people by about 2050 (UN 2008). Predictions of future food demand also differ, but even the most optimistic scenarios require increases in food production of at least 50%. The demand for agricultural and food products caused by rising population and changing consumption patterns will become most acute in the next half-century.

Climate change is also set to have a profound impact on food production (IPCC 2007a). Rising temperatures, altered rainfall patterns and more frequent extreme events will increasingly affect crop production, often in those places that are already most vulnerable (Morton 2007). Notwithstanding the potential to adapt crops to changing environments, the need to mitigate climate change will increasingly challenge conventional, resource-intensive agricultural systems which depend on chemical inputs derived from fossil fuels and contribute significantly to greenhouse gas (GHG) emissions.

John Beddington, the UK Government Chief Scientific Adviser, has used the phrase 'perfect storm' to describe the future coincidence of food, water and energy insecurity (Beddington 2009). The food component of this 'storm' is unavoidably global. Food markets are highly globalised. Countries are substantially interdependent on each other for their food supplies and will share the impacts of the global instability generated by food insecurity. Following its own assessment of worrying trends to 2050, the Food and Agricultural Organisation of the United Nations concludes that, 'the result could well be enhanced risk of persistent food insecurity for a long time to come in a number of countries in the midst of a world with adequate food supplies and the potential to produce more' (FAO 2006).

Addressing future food insecurity requires action on many fronts, across different timescales. There are systemic challenges that need addressing now, and there is a need to build resilient global agricultural systems for the next 40 years. These systems of food crop production need to be underpinned by science and technology, as has been the case for the last 150 years.

This report aims to provide a balanced assessment of the challenges to world food crop production and the range of different approaches, drawing on the biological sciences that could potentially increase the quantity and quality of crop production over the next 40 years. The application of science and technology presents new opportunities, but may also bring new side effects. The report therefore considers what research and policy action is required to predict and respond to the impacts of new agricultural products and practices.

1.2 Trends in food crop production

Over the last 50 years there has been remarkable growth in agricultural production, with increases in food production across the world. Since the advent of the green revolution in the early 1960s, gross world food production (cereals, coarse grains, roots and tubers, pulses and oil crops) has grown from 1.84 billion tonnes in 1961 to 4.38 billion tonnes in 2007 (an increase of 138%) (see Figures 1.1, 1.2 and 1.3 for a representation of major cereals, roots, tubers and oil crops). This growth has differed across continents:

Proportions of major global cereals, roots, tubers and oil crops in 2007 (Area corresponds to total production). Source: FAOSTAT (2009)

Figure 1.1. Cereals, total 2,351,396,424 tonnes.

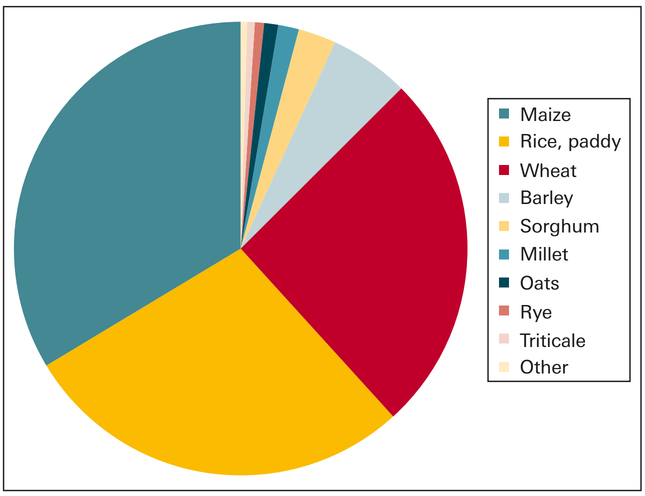


Figure 1.2. Roots and tubers, total 697,620,690 tonnes.

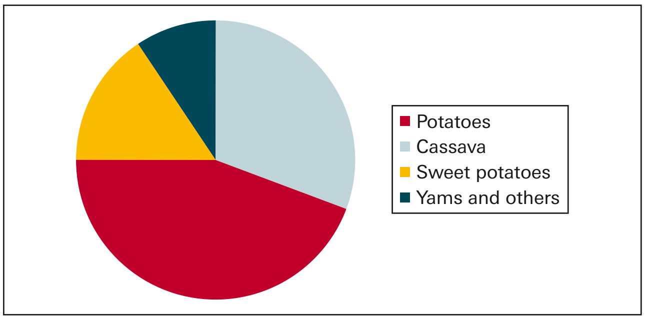
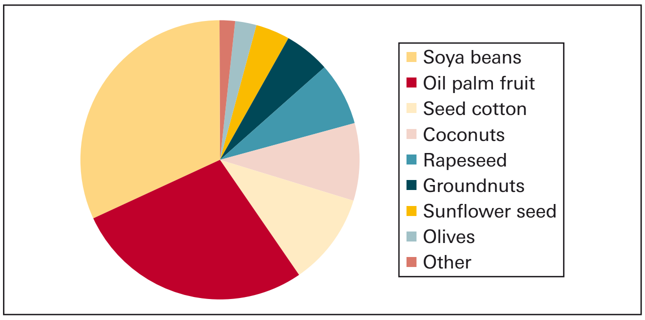


Figure 1.3. Oil crops, total 692,421,195 tonnes.



in Africa, it rose by 140%, in Latin America by almost 200%, and in Asia by 280%. The greatest increases have been in China, where a 5-fold increase occurred, mostly during the 1980s and 1990s. In industrialised countries, production started from a higher base, but still grew by 70% in Europe and doubled in the USA (FAOSTAT 2009).

Despite a substantial increase in numbers of people (from 3 billion in 1960 to 6.7 billion in 2009), per capita agricultural production has still outpaced population growth. For each person alive today, there is in theory an additional 29% more food compared with 1960. These aggregate figures again hide important regional differences. In Asia and Latin America, per capita food production increased by 98% and 61% respectively. Africa has fared less well, with food production per person falling from the 1970s and only just recovering to the 1960 level in 2005 (Figure 1.4). China has seen remarkable growth, more than trebling per capita food production over the same period (FAOSTAT 2009) (see Figure 1.5). These agricultural production gains have helped lift millions out of poverty and provided a platform for rural and urban economic growth in many parts of the world.

Beginning in the 1950s and expanding through the 1960s, agricultural development across many parts of the world saw changes in crop varietal development and input use that have come to be known as the 'green revolution'. This revolution encompassed changes to crop varieties (day-length insensitive, partitioning of carbohydrates to grain rather than straw, disease resistance), changes to agricultural practices (fertilisers, water management and pesticides) and broader social, economic and political change.

Figure 1.4. Changes in per capita agricultural production, part 1 (1961–2005).

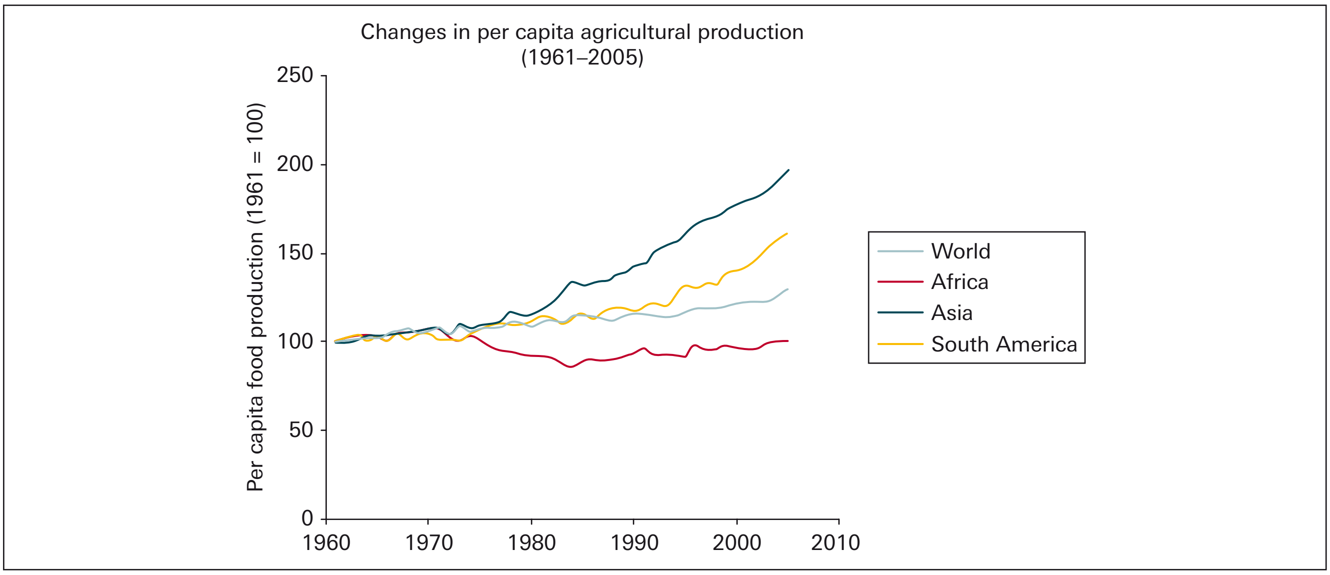
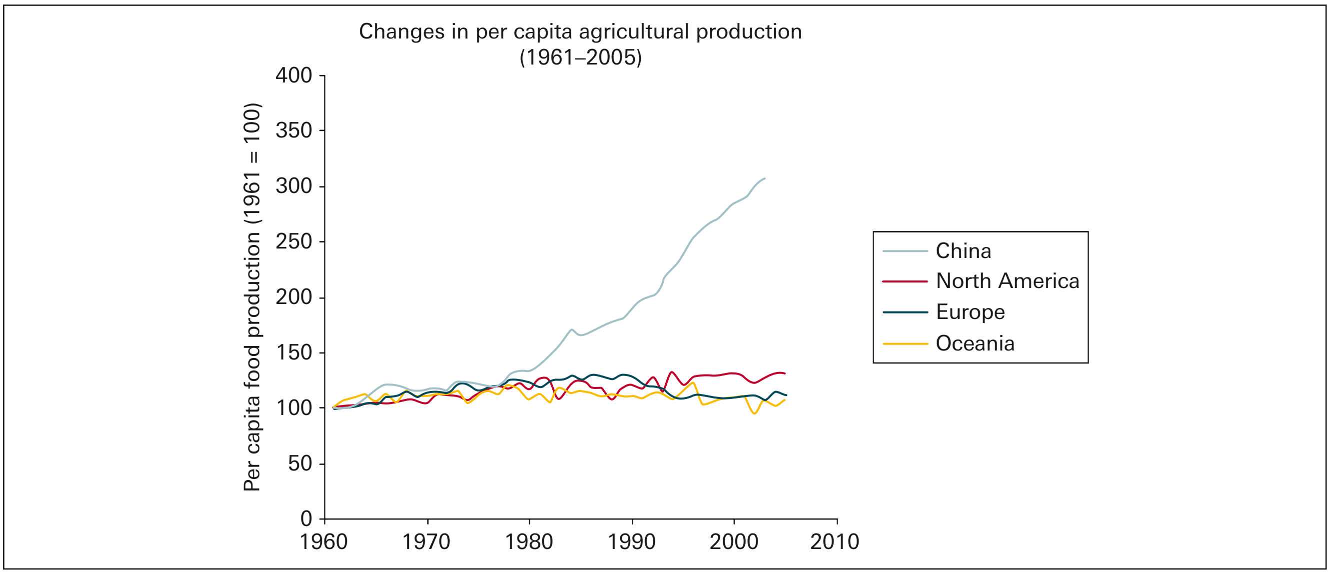


Figure 1.5. Changes in per capita agricultural production, part 2 (1961–2005).



New varieties of wheat were bred with two major genetic improvements—dwarfing (shorter stems) and resistance to stem rust. The genetic potential of these new crops was realised through changes in practice and greater use of mineral fertiliser and water. Dwarfing allowed for the increases in yield provided by nitrogen fertilisers without the crops lodging (falling over). Similar changes were made to rice varieties in Asia. New crops, new practices and new markets for inputs and outputs of agriculture helped not only with food shortages, but also with rapid economic development in a number of countries (Hossain *et al.* 2003).

The green revolution was also a revolution in the way in which research was organised. In Mexico, the International Maize and Wheat Improvement Center (CIMMYT) provided the institutional impetus for these new approaches to food production, while across Asia it came from International Rice Research Institute (IRRI), based in the Philippines. In 1971, these scientific bodies came together with others under the umbrella of the Consultative Group on International Agricultural Research (CGIAR), which continues to catalyse innovation and implement scientific advances for agriculture across the world.

The achievements of the green revolution have come at some cost. Increases in yield have been achieved without great expansion in land use, but this high-energy crop production has involved sharp increases in fertiliser, pesticide and water use, which can lead in turn to increased emissions of nitrates and pesticides into the environment and depletion of groundwater aquifers (Moss 2008) (see Figures 1.6 and 1.7). The benefits of increased yields have been distributed unevenly. The complexities of African agricultural landscapes, with mixed crops and poor access to credit, markets, seeds

Figure 1.6. World fertiliser consumption (1961–2005).

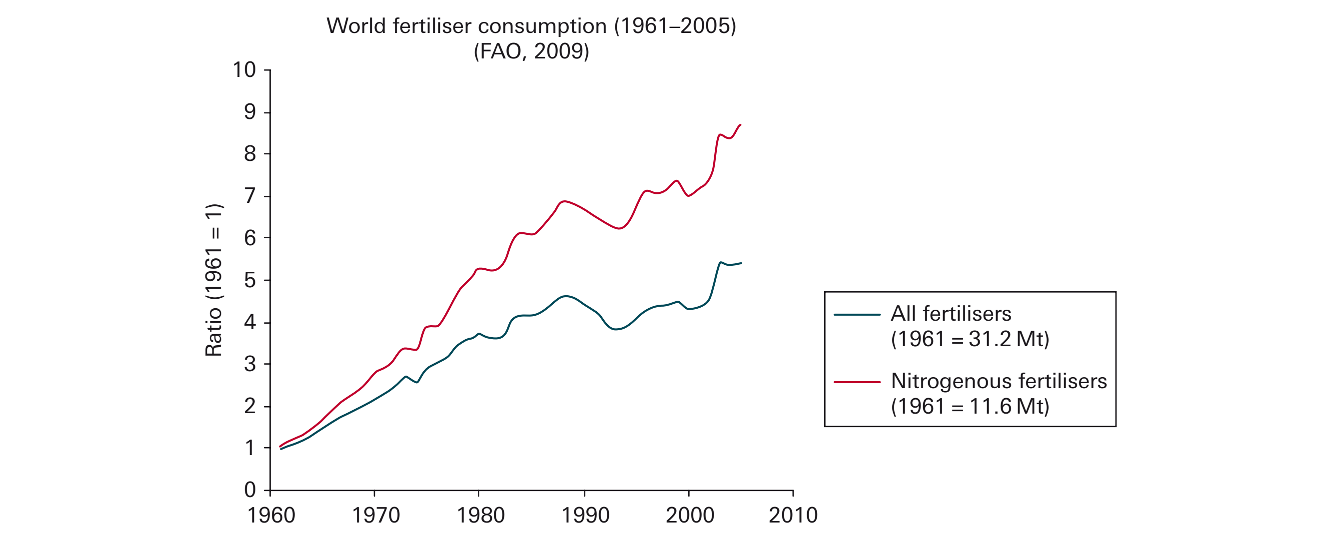
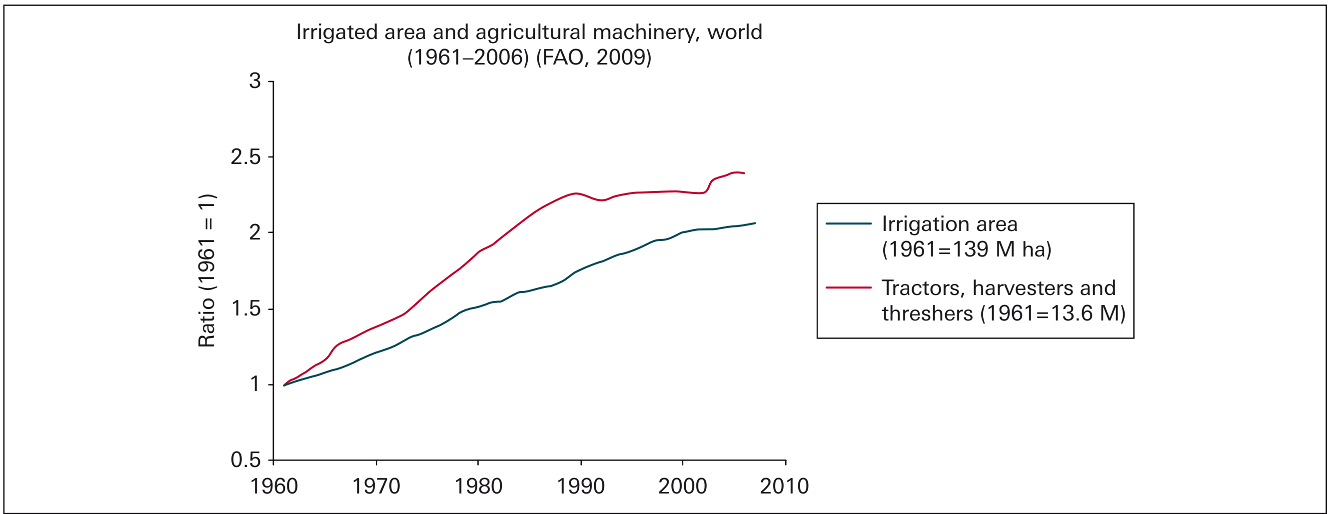


Figure 1.7. Irrigated area and agricultural machinery (1961–2006).



and fertilisers, did not suit green revolution crop varieties (Paarlberg 2006). Other social side effects of the green revolution include mechanisation replacing manual labour and worsening poverty in some rural areas (Conway 1997).

These successes and limitations of the first green revolution have led to many calls for renewed investment and collaboration directed at step changes in agricultural productivity, albeit with greater consideration of possible side effects. There have been calls for a 'greener revolution' (The Independent 2008), a 'doubly-green revolution' (Conway 1997) an 'evergreen revolution' (Swaminathan 2000), a 'blue revolution' (Annan 2000) and an 'African green revolution' (Sanchez *et al.* 2009a) which would replicate the successes of original efforts in new places, while this time being more equitable, resilient and socially and environmentally sustainable.

In 2007, the world's farmers produced 2.3 billion tonnes of grain (80% of which was wheat, rice and maize) and another 0.5 billion tonnes of roots and tubers (see Figures 1.1 and 1.2). Cereal production was 4.7% up on 2006 and 2.7 times the amount that was being produced 50 years ago (0.83 billion tonnes). However, a large proportion of this plant material is removed for livestock feed, and a growing amount for biofuel production. Since a peak of around 250 kg per person worldwide in 1995, per capita availability of cereal and roots has dropped back to near 1960s levels of around 220 kg/person of grain available for direct food use (FAOSTAT 2009). Reduced availability of these staples affects the world's poor most acutely.

The necessary changes to global agriculture are not just a matter of quantity. In addition to increasing yield, there are further challenges concerning food quality, nutritional benefit, distribution to match production with need, managing potentially adverse impacts, and reducing the environmental impact of technological change. All of these depend to a greater or lesser degree on scientific research. The green revolution was built on decades of substantial global investment in agricultural research. The outcomes of R&D can take many years to filter through to agricultural practice (Normile 2008), and it is therefore worrying that the intensity of investment in agricultural research and infrastructure has fallen in recent decades (World Bank 2008). As real food prices have fallen over time and markets have become globalised, there has been a growing complacency about food production and the global need and capacity to innovate.

1.3 Science in context

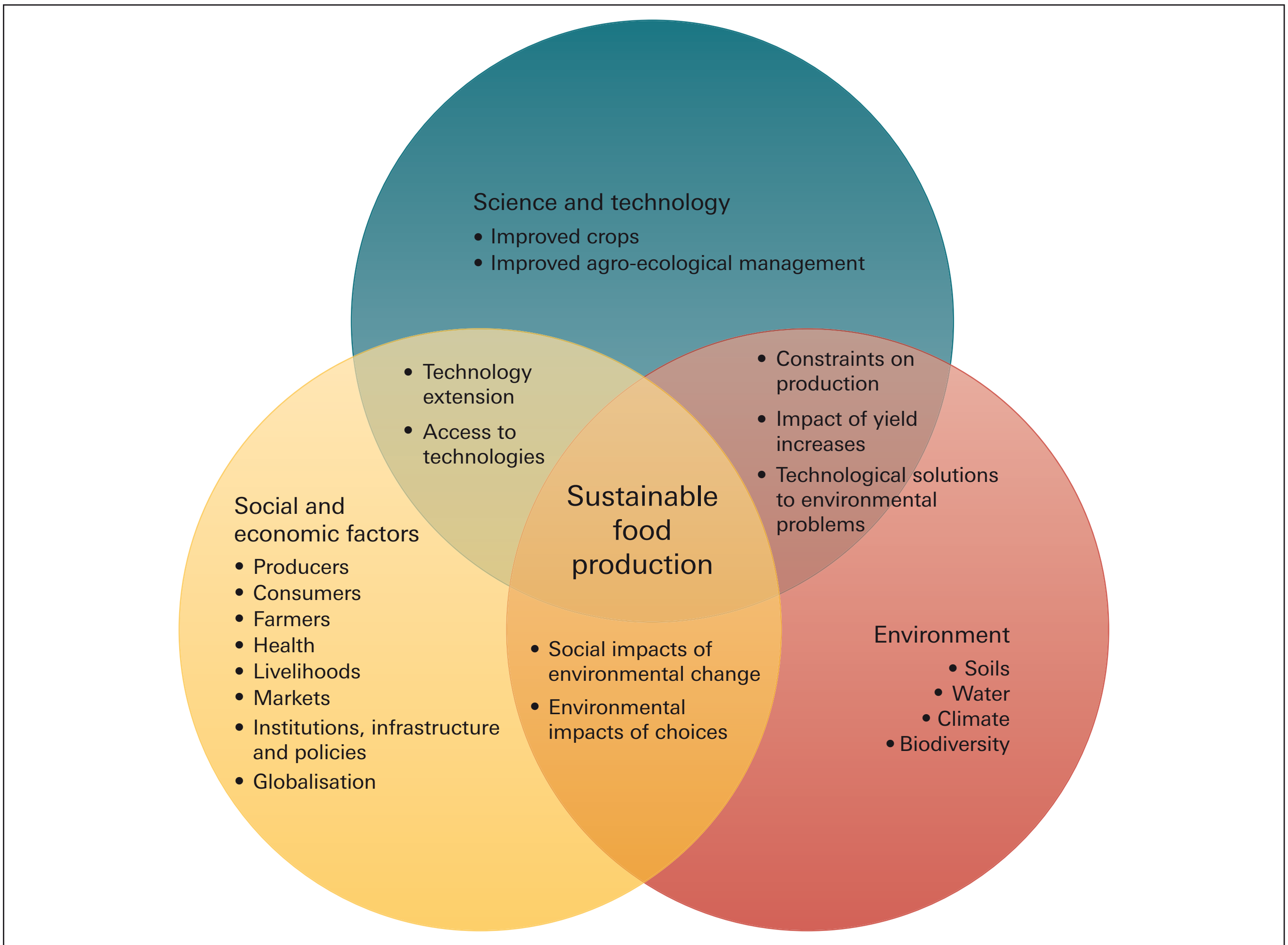
Our focus is on science and technology, but we recognise that agricultural systems rely on the interconnectedness of many different elements (IAASTD 2008). The global challenge of food security has many dimensions, only some of which are amenable to change through science and innovation. The diagram below (Figure 1.8) provides a logic for this complexity. Science necessarily interacts with social, economic and environmental systems. Improvements in food crop production may originate from scientific research, but for changes in production systems to be considered sustainable, they must take into account all three elements.

Social and economic factors, including prices for inputs and outputs, access to credit and markets, investment options, differential risks, transport costs, market control and uncertainty about market conditions constrain the options for farmers, traders and consumers. Political and policy structures such as land tenure, intellectual property law, research funding and regulation can similarly enable, encourage or constrain agriculture. All farmers except those who produce purely for subsistence experience acutely the economics of agriculture and food.

Domestic patterns of food production and consumption have become interconnected in global markets. The economics of food mean that small changes in production can lead to large fluctuations in price, especially when speculation on world markets is unconstrained. Many countries now rely on buying their food on open global food markets. But, as was demonstrated with the food price shocks, these can break down when they are most needed, when national governments seek to protect their own supplies.

Global food security is not only about producing enough food for the world's population. Questions of *access* need to run alongside those of *availability* (Ericksen 2008). Inequalities and complexities of food distribution mean that while around 1 billion people are currently malnourished, 1 billion are overweight and susceptible to diseases associated with obesity.

Figure 1.8. The complexity of agricultural systems.



As diets change, so demand for different types of food will shift radically, with large numbers of people going through a 'nutrition transition'. Increasing urbanisation and growing prosperity mean that people are more likely to adopt new diets, particularly consuming more meat, fats and refined cereals, and fewer traditional cereals, vegetables and fruit (Fitzhugh 1998; Popkin 1998; Delgado *et al.* 1999; Smil 2000a). Livestock production has increased dramatically, with a worldwide 4.4-fold increase in numbers of chickens since 1961 (to 17 billion), a 2.4-fold increase in pigs (to 9.9 billion), an 0.4–0.5-fold increase in numbers of cattle and buffalos (to 1.59 billion) and sheep and goats (to 1.96 billion) (see Figure 1.9) (Pretty 2008; FAOSTAT 2009). Some suggest that demand for livestock products will double by 2050. Already more than one-third of the world's grain is fed to domestic livestock (rising to nearly 70% in industrialised countries). As incomes rise in developing countries, so it is expected that demand for meat will tend towards the per capita consumption rates of 115 kg per year in the USA and 80 kg per year in the UK. Chinese per capita annual consumption has already increased from 4 to 54 kg in the past 50 years. On the current trajectory, livestock production will move further from extensive (pasture-based grazing) to intensive systems, placing even more demand on staple grains.

The natural environment can be seen as providing a set of benefits to agriculture (ecosystem services and organisms for biological control) and constraints (soil, water, climate, pests and diseases) that determine what can be grown, where, when and how. The primary constraints on crop production are well understood. These include biophysical factors such as radiant energy for photosynthesis (dependent on latitude), temperature (dependent on latitude and altitude), water, plant nutrients (primarily nitrogen, phosphorus and potassium), pests (vertebrates and invertebrates), diseases (bacteria, viruses and fungi), weeds (other plants) and the availability of suitable land. These constraints are the subject of Chapter 2 of this report.

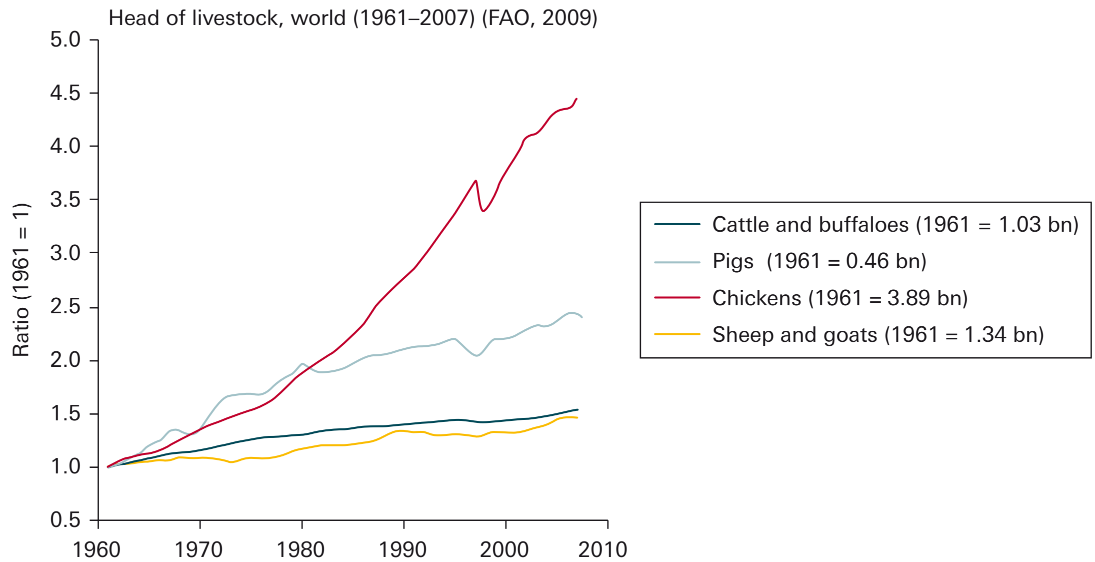
The effects of climate change on world agriculture are uncertain. Working Group 2 of the Intergovernmental Panel on Climate Change (IPCC) has estimated that global crop production will be threatened by global temperature increases of 1°C and begin to decline significantly at 3°C (Easterling *et al.* 2007). But this global picture flattens out regional variations that might bring catastrophic impacts on, for example, the drier tropical areas (Schmidhuber & Tubiello 2007). The social and economic consequences of environmental change (including changes to biodiversity and climate) will exacerbate the uncertainties faced by the world's poorest billion people.

1.4 The need for sustainable intensification

Land used for crop production has grown only slightly over the period 1961 to 2007 (total agricultural area has expanded 11% from 4.51 to 4.93 billion ha, and arable area 9% from 1.27 to 1.41 billion ha) (FAOSTAT 2009). Over the same period the human population grew from 3 to 6.7 billion (an increase of 123%). In industrialised countries, agricultural area has fallen by 3% over the same period, but has risen by 21% in developing countries. Half of the 1.4 billion ha of land used for arable crop production produces grain (approximately 700 million ha). In 1960 the area used to produce grain was 648 million ha.

Improvements to agricultural production are complicated by a number of pressures on land availability. As cities grow, they encroach on rural environments and often on high quality agricultural land (Montgomery 2007). The loss of soil globally is an increasingly serious problem (Fitter 2005). In many places, land that has previously grown food is being turned over to biofuels (Royal Society 2008a). In some countries use of land for food is prohibited by

Figure 1.9. Head of livestock (1961–2007).



protected area status. The ecosystem services provided by forests are in most cases too important to lose through their conversion to agricultural land. Following the recent food price shocks, there has been a rapid increase in demand for land in many regions as some food-importing countries have sought to secure their own food supplies. Much of this has been dominated by the private sector and foreign investors (Cotula *et al.* 2009). China, to give just one example, has successfully acquired the rights to grow palm oil on 2.8 million ha of Congolese land (The Economist 2009).

The global community faces an important choice: expand the area of agricultural land to increase gross production, or increase yields on existing agricultural land. Expanding agricultural land results in losses of vital ecosystem and biodiversity services, as well as damaging livelihoods for communities relying on these lands (Millennium Ecosystem Assessment 2005). Feedback effects are likely to elevate GHG emissions due to oxidation of carbon currently sequestered in soil, removal of carbon sinks, and increases in both nitrogen fertiliser and fossil fuel use. It is currently estimated that land-use change, primarily deforestation, is responsible for as much as 18% of global GHG emissions (IPCC 2007a; Millennium Ecosystem Assessment 2005). In this report, we argue for the sustainable intensification of global agriculture, which demands a clear definition of agricultural sustainability.

1.5 Agricultural sustainability

The concept of sustainability in the context of agricultural and food production is central to any future challenges (Pretty 2008). It incorporates four key principles:

1. Persistence: the capacity to continue to deliver desired outputs over long periods of time (human generations), thus conferring predictability;
2. Resilience: the capacity to absorb, utilise or even benefit from perturbations (shocks and stresses), and so persist without qualitative changes in structure;
3. Autarchy: the capacity to deliver desired outputs from inputs and resources (factors of production) acquired from within key system boundaries;
4. Benevolence: the capacity to produce desired outputs (food, fibre, fuel, oil) while sustaining the functioning of ecosystem services and not causing depletion of natural capital (eg minerals, biodiversity, soil, clean water).

Any system is by these principles and measures unsustainable if it depends on non-renewable inputs, cannot consistently and predictably deliver desired outputs, can only do this by requiring the cultivation of more land, and/or causes adverse and irreversible environmental impacts which threaten critical ecological functions.

The primary aim of agriculture is the efficient conversion of solar energy into various forms of chemical energy for human use. This encompasses crops grown for food, fuel, fibre and forage for animals. Agriculture involves the management of the interaction between crop genotypes or livestock breeds and their immediate agro-environment (physical and biological). The capacity to deliver from the system what is required and to be able to do this consistently over generations demands a continuity of agroecosystem functions.

As agricultural and environmental outcomes are pre-eminent objectives, sustainable agricultural systems cannot be defined by the acceptability of any particular technologies or practices. If a technology improves production without adverse ecological consequences, then it is likely to contribute to the system's sustainability. Sustainable agricultural systems are less vulnerable to shocks and stresses and also contribute to the delivery and maintenance of a range of valued public goods, such as clean water, carbon sequestration, flood protection, groundwater recharge and landscape amenity value.

A sustainable production system exhibits most of the following attributes:

1. Utilises crop varieties and livestock breeds with high productivity per externally derived input;
2. Avoids the unnecessary use of external inputs;
3. Harnesses agroecological processes such as nutrient cycling, biological nitrogen fixation, allelopathy, predation and parasitism;
4. Minimises the use of technologies or practices that have adverse impacts on the environment and human health;
5. Makes productive use of human capital in the form of knowledge and capacity to adapt and innovate and social capital to resolve common landscape-scale problems;
6. Quantifies and minimises the impacts of system management on externalities such as GHG emissions, clean water availability, carbon sequestration, conservation of biodiversity, and dispersal of pests, pathogens and weeds.

Productive and sustainable agricultural systems thus make the best use of crop varieties and livestock breeds through their agroecological or agronomic management. Science focuses on understanding and improving crop and animal genotypes as well as the conditions for agroecological management. It also seeks to improve the capacities of people and their institutions to deliver inputs, manage systems and distribute and use outputs.

1.6 Agriculture and sustainable economic development

Worldwide, agriculture accounts for 29% of global GDP and employs 65% of the workforce; 86% of rural people are involved in different aspects of the agricultural product and food chain (World Bank 2008). As well as being their livelihood, agriculture is for many people a key part of their society.

In the period from 1965 to 1985, poverty reduction across the world advanced further than in the previous two centuries (Lipton 2001). Agriculture provides a potential route to poverty alleviation for many people around the world, but the diversity of social, economic and environmental contexts means that what works to improve crop outputs and system sustainability in some places may not work in others (World Bank 2008).

To maintain such progress, agricultural systems in all parts of the world will have to make further improvements. Efforts to ensure access for poorer groups need to run alongside growth in aggregate food production. In many places, the challenge is to increase food production to solve immediate problems of hunger. In others, the focus will be more on adjustments which maintain food production whilst increasing the flow of environmental goods and services.

Sub-Saharan Africa has seen fewer productivity gains than the rest of the world. Here there is significant potential for productivity increases, but there are also real challenges that need to be overcome. In the case of African smallholder farmers, changes that improve upon current agricultural systems rather than importing a radically different set of practices tend to be more effective (Reij & Smaling 2008; Sanchez *et al.* 2009a). Linking biological science with local practices requires a clear understanding of farmers' own knowledge and innovations. There are past examples where science has seemingly offered 'solutions' to a problem but without success, because of a poor fit with local circumstances and a lack of local engagement with end-users at an early stage in the innovation process (Pretty 2002). In Burkina Faso, for example, researchers spent years developing systems of rainwater harvesting, but farmers did not adopt them. An NGO working closely with farmers has adapted simple soil and water conservation practices that have now led to significant improvements in food security and soil management (Hassame *et al.* 2000; Kaboré & Reij 2004). If agriculture continues to contribute to alleviating poverty, technologies for improving production need to be seen in their particular local social and economic contexts, as well as a broader context of public acceptance.

Past debates about the use of new technologies in food production systems have tended to adopt an either/or approach, emphasising the merits of particular agricultural systems or technological approaches and the down-sides of others. This has been seen most obviously with respect to genetically modified (GM) crops, the use of pesticides and the arguments for and against organic modes of production. The reality is that there is no technological panacea for the global challenge of sustainable and secure food production. There are always trade-offs and local complications. This report recognises that new crop varieties and appropriate agroecological practices are both needed to make the most of opportunities on all types of farms. We thus adopt an inclusive, both/and approach: no techniques or technologies should be ruled out before risks and benefits are assessed. Global agriculture demands a diversity of approaches that are specific to crops, localities, cultures and other circumstances. Such diversity demands that the breadth of relevant scientific enquiry is equally diverse, and that science needs to be combined with social, economic and political perspectives.

1.7 Other major studies

Our report follows a number of other reports and policy documents which have sought to describe and quantify the scale of the challenge of food security and food production from a variety of perspectives. Taken together, they provide a sense of likely future trends. The differences in analysis, emphasis and recommendations show the range of options available for tackling the general issue.

The most comprehensive recent analyses have been the World Bank's 2008 World Development Report and the International Assessment of Agricultural Knowledge, Science and Technology for Development, also published in 2008[1] (IAASTD 2008; World Bank 2008).

The 2008 World Development Report concluded that research and development are vital for global agriculture, and investment in R&D yields a high rate of return (43% per annum), yet it remains underfunded. The report describes significant gains from crop genetic improvement but it also identifies places, particularly Sub-Saharan Africa, where improved crop varieties have yet to make such an impact. The challenge of a growing population is compounded by new threats, such as pests, diseases and climate change, and this further indicates the need for constant research into new varieties and practices ('running to stand still'). Continued genetic improvement will be vital, but natural capital inputs to agriculture—including better soil and water management—will require new approaches too (World Bank 2008). The biggest gains from technology, the report concludes, come from combinations of improved crops and improved practices (the 'both/and' approach referred to above).

The IAASTD was sponsored by the Food and Agricultural Organisation (FAO), Global Environment Facility (GEF), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), United Nations Educational Scientific and Cultural Organisation (UNESCO), the World Bank and World Health Organisation (WHO), and its 4-year process was overseen by stakeholders from

1 Many recent reviews point back to a single report: Rosegrant MW, Msangi S, Sulser T & Ringler C (2008). *Future scenarios for agriculture. Plausible futures to 2030 and key trends in agricultural growth*. International Food Policy Research Institute. This was a Working Paper submitted for consideration in the 2008 World Development Report. The data from this paper appears to have been rewritten as a background paper for the WDR but not re-published.

governments and NGOs. The report concluded that the dominant model of agriculture needs to change if it is to meet the needs of the developing world, and it must do so in the face of some major uncertainties:

1. Current social and economic inequities and political uncertainties linked to war and conflicts;
2. Uncertainties about the ability to sustainably produce and access sufficient food;
3. Uncertainties about the future of world food prices;
4. Changes in the economics of fossil-based energy use;
5. The emergence of new competitors for natural resources;
6. Increasing chronic diseases that are partially a consequence of poor nutrition and poor food quality as well as food safety;
7. Changing environmental conditions and the growing awareness of human responsibility for the threats to maintenance of essential global ecosystem services.

Their report uses the term 'multifunctionality' to describe the interconnectedness of agriculture with societies, economies and the environment. This should not be interpreted as meaning that every field or farm is required to deliver more than one 'function'. But, over an agricultural landscape, the practices of land management for agricultural production need to take account of issues beyond just agricultural production. These externalities (both positive and negative) tend to be outside markets and they therefore demand particular attention in the context of system sustainability (see above) (IAASTD 2008).

The IAASTD considered a broad range of technological options for agriculture, and concluded that gains are likely to come from a mix of new applications of existing knowledge, introduction of new technologies and other non-scientific innovations in the development and implementation of appropriate economic and social policies (IAASTD 2008).

In the USA, the National Research Council has produced a report on *Emerging technologies to benefit farmers in Sub-Saharan Africa and South Asia*, exploring a range of technological options, across a range of sciences, with impacts both in the short and long term. Their report recognises the need to view these options in their social and economic context. It offers recommendations for priority research areas and wider policy needs (NRC 2008).

In the UK, there is a growing political awareness of the problem of global food security. In August 2009, the Department for Environment, Food and Rural Affairs (DEFRA) published a package of policy reports to outline the UK government's role (DEFRA 2009c). Their focus is on UK food security, but there is a recognition that, as the Prime Minister put it, 'The principal food security challenge for the UK is a global one'.[2] As decision makers at all levels begin to rediscover the need to think about food security, our report aims to inform the domestic and international debate, presenting the potential contribution of biological sciences.[3]

There is an emerging consensus from the various assessments produced over the past few years that the world will need to produce substantially higher yields of food for humans and livestock feed in the next half-century. However, there is no clear agreement on the exact increases required, as there are substantial uncertainties over actual numbers of people demanding food, their preferences and diets, the capacity to feed existing large numbers of hungry people, and the capacity of agricultural and natural systems themselves to produce more food.

These reports all express some optimism that the necessary increases in food production can be achieved, but opinions vary about the best way to address these challenges. Different assessments place different emphases on science, technology, markets, trade and social and political interventions. Most agree that the challenge of food security can only be met through a combination of measures across all relevant science and policy arenas. Those that focus on science and technology offer various options for improvement, but all agree that there is no simple 'magic bullet'. Their shared conclusion is that the complacency about food availability over the last two decades has resulted in a steady erosion of investment in relevant scientific research and that this needs to change.

1.8 Further UK work

Following the *Food matters* report from the Cabinet Office (2008), The UK government's Foresight group are conducting a major project on Global Food and Farming Futures, due to report in October 2010. The Foresight study has a broader remit than this study. Our hope is that this report will provide a useful evidence base of scientific challenges and possibilities on which Foresight can build. In addition, DEFRA is leading a National Ecosystem Assessment that will report in 2011, and this too will show the current and potential contribution of agricultural systems to environmental services.

1.9 About this report

Given the enormous complexity of systems for food production, and the uncertainties involved in developing innovations that will increase productivity without causing harm to important environmental services, our report

2 Government sets out 21st century challenges for food in the UK.' News Release, 7 July 2008. Available online at: http://www.cabinetoffice.gov.uk/newsroom/news_releases/2008/080707_food_report.aspx.

3 Other recent assessments of global food security and the role of science include UNEP (2009) and Evans (2009).

cannot hope to do justice to the complete issue. Instead we offer a tight focus on the possible contributions of biological science and technology, while remaining aware of the context in which this science sits and the necessity of a multidisciplinary approach. There are countless aspects of food systems, such as aquaculture, livestock, consumption and supply chains that demand attention beyond the references we provide. Similarly, there are areas of expertise and technology, including social sciences, economics, climatology, engineering, chemistry and in particular the use of agrochemicals, that are relevant but beyond the scope of this report.

Debates about the role of science and technology in food production have proved contentious in the past. Our report looks at a variety of approaches, and considers their future opportunities as well as the risks, complexities and uncertainties presented through research and implementation. As well as providing a rigorous scientific assessment, we hope this report can help to start a constructive debate about the future of agriculture around the world and the contribution that might be offered by UK science.

This report's next chapter assesses the technical and environmental constraints of food crop production such as water shortages, incidence of disease and rising temperatures. Chapter 3 considers in more detail the possibilities provided by the biological sciences for addressing some of these challenges. Chapter 4 addresses the impacts—intended and unintended—of different technological approaches to agriculture, considering environmental, health and socioeconomic issues. The final chapter contains our conclusions and recommendations for policy makers.

Chapter 3 contains case studies of science and technology in different contexts to illustrate the complexity of agriculture and the necessity of specific solutions for specific problems. Our case studies tell stories of where, why and how science has made a difference to food production.

1.10 Conduct of the study

A working group chaired by Sir David Baulcombe FRS was established to undertake this study. The working group first met in July 2008 and had a further seven meetings. The full membership of the working group is given at the start of this report. The working group were shocked and saddened by the death of Professor Mike Gale FRS soon after the final meeting. This report has benefited hugely from his contributions and is dedicated to him.

In order to obtain views from a wide range of experts, a call for evidence was issued on 7 August 2008 with a closing date of 6 October 2008. Responses were received from a range of individual academics, research institutes, industry representatives and non-governmental organisations. Details of the organisations and individuals who submitted written evidence are listed at the end of the report, and the evidence is available on the Royal Society website (royalsociety.org).

An oral evidence session at the Society and an evidence-gathering workshop in India were held in October 2008. A workshop with UK-based non-governmental organisations was held in May 2009. Reports of these workshops are available on the Society's website. All this evidence informed the working group's discussions, conclusions and recommendations. We are grateful to everyone who responded to the call for evidence, participated in the workshops and submitted additional evidence.

2 Constraints on future food crop production

Summary

The constraints on food crop production and distribution differ between regions and, in particular, between industrialised and developing countries. In most areas the effects of climate change will further exacerbate the stresses on crop plants, potentially leading to catastrophic yield reductions. Fresh water availability is a major limiting factor on agricultural productivity. Improvements in the water use efficiency of plants in irrigated systems present a significant challenge, particularly in the face of climate change. Soils are another essential but non-renewable resource for food crop production. Maintenance of soil fertility, health and nutrient availability is vital. Significant losses in crop yields occur through pests, diseases and weed competition; they account for a major inefficiency of resource use (eg water, fertiliser, energy and labour). Reducing these losses represents one of the most accessible means of increasing food supplies. The need to reduce greenhouse gas emissions means that agriculture will have to become less reliant on sources of non-renewable energy derived from fossil fuels. Ensuring the diversity of crop germplasm to facilitate crop breeding in a changing climate is just one of several challenges that need to be met to ensure resilience of production.

This chapter describes the many constraints that limit the production of food crops globally including soil fertility, water availability and the incidence of pests, diseases and weeds. These constraints are variable with climate change and differ greatly between industrialised and developing countries, for social, economic and geographic reasons. In industrialised countries there is typically much better access to irrigation, chemicals for disease and pest control, synthetic fertilisers and quality seeds, which substantially account for their higher yields. Chapter 3 considers the specific biological science-based technologies that could help address these various challenges.

2.1 Climate change

Climate change will aggravate the effects on crops of stresses such as heat, drought, salinity and submergence in water (IPCC 2007b). This conclusion is starkly illustrated by Lobell *et al.* (2008), who have conducted an analysis of climate risks for crops in 12 food-insecure regions. The study identified adaptation priorities, based on statistical crop models and climate projections for 2030. Their analysis reinforces the importance of improved crop germplasm (based on the access to and use of crop genetic resources collections) and improved agronomic practices as a strategy for climate change adaptation in agriculture. The important conclusion of their study is that there are a few target crops that will be particularly vulnerable to climate change in different regions. Adaptation strategies focused on these crops must be carried out in the face of other constraints such as labour shortages and rising energy costs. More specific climate change-related constraints are considered in the following sections.

2.2 Water

Of all the biotic and abiotic stresses affecting crop yield, drought has probably the greatest limiting effect (Boyer 1982). A high priority for the future is to develop genotypes that yield significantly with reduced amounts of water; this is discussed further in Section 3.3.2. This should be combined with the development of cropping systems where available water can be used with much greater efficiency.

Increased variability in rainfall will lead to a greater risk of drought during cropping seasons in many regions of the world. Rising temperature will increase rates of water loss to the atmosphere from plants and soil. Predictions also suggest large increases (hundreds of millions) in the number of people who will be exposed to increased water stress (IPCC 2008) across greater areas (OECD 2006). Although total water supply may increase in some regions, precipitation will be more variable and there will be additional risks of poor water quality and flooding, as well as salt water flooding in some regions.

2.2.1 Water and yield

Plants require water for growth and tissue expansion (Steduto *et al.* 2009). However, more than 90% of the water required by terrestrial plants is not 'used' in metabolism but is lost through transpiration (T). A distinction is often made between 'water-limited' and 'wet' environments. What is usually meant by the former is that water availability 'limits' crop productivity to below the maximum or potential production when water supply is less than the demand for water set by atmospheric conditions. Yield of most crops is restricted by water availability in most environments and ensuring appropriate water availability to plants during important developmental stages is a key challenge to increasing food crop production. There is an important difference between crops that remain alive during very severe droughts but may never yield significantly (desiccation resistance) and crops that sustain yields under water scarcity (drought resistance).

The term water use efficiency (WUE) can be used on different scales: harvest, farm, field, plant and down to the leaf. It can be applied to the water lost in producing just the economic yield, or the biological yield which can be all the above-ground biomass, or (more rarely) the total biomass. It can include or exclude the evaporation from the soil and plant surfaces directly. It can also be applied across different timescales. At the crop or field scale, it can be used for time spans of days or months, or the entire crop growing season, or per year. At the leaf or plant scale, it can be applied when considering the flow of CO_2 and water vapour into and out of leaves. The highest WUEs can often be achieved when productivities are very low. Improvements therefore need to be balanced against the need to maintain yields.

2.2.2 Water use and its impacts

Agriculture currently accounts for around 70% of annual use of global water resources (FAO 2002; WRI 2005). In hot, dry regions, much larger amounts of water are needed to produce the same grain yield than in less stressed regions (Wallace & Gregory 2002).

Most of the water used in agriculture is for irrigation. Globally, irrigated areas of land are increasing, although the rate of increase appears to be slowing (Faurèsa *et al.* 2003). Although irrigated areas account for less than 20% of the world's cropped land, they produce nearly 50% of the global food (Döll & Siebert 2002). Reduction in irrigated areas or the amount of irrigation could therefore have very serious impacts on global food supply.

Significant abstraction of water for irrigation has resulted in large reductions in river flows (Ma *et al.* 2003) leading to general environmental degradation and in extreme cases to an acceleration of desertification and more 'super' dust storms. Increased agricultural activity driving increased desertification can drive climate change at an increased rate. Water levels in many major regional aquifers and ground water levels in many regions have fallen to unprecedented levels (Wu 2007). Exploitation of land and unsustainable practices, particularly in arid regions, can result in severe degradation of soils and potential desertification, initiated by loss of vegetation and soil erosion.

Using predictions of future availability of irrigation water (eg Scholze *et al.* 2006), it will be important to identify the most vulnerable people, places and sectors (climate change hotspots) but there is currently a shortage of good quality information of this kind. At a regional scale, the major problems in water supply are in regions with low rainfall and high evaporative demand, and those with expanding populations, such as North Africa, Southern Africa and the Near East (Wallace & Gregory 2002; FAO 2003). Wealthy countries that are short of water often import food from elsewhere, meaning that 'virtual water' is traded, which may be to the detriment of the environment in the source country.

The food supply chain and other crop trades exert many pressures on global water resources, with a resultant strain on the human population and ecosystems worldwide (Chapagain & Orr 2008a). The production of food, biofuel and other commodities can drive over-abstraction and pollution of groundwater and freshwater ecosystems in many water-scarce parts of the world. Decisions on the use of water for irrigated agriculture are therefore increasingly moral and ethical choices, as well as economic ones. Understanding how much water a nation (or a business) requires—its water footprint (WF)—and how this water is consumed (different crops grown in different climatic zones with different cropping, processing and transport methods) is the first step in forming views on the appropriateness of different food choices.

The agricultural WF of the UK is 74.8 Gm^3/yr or 73% of the total WF. The internal WF of UK agriculture is 28.4 Gm^3/ yr while the external component is 46.4 Gm^3/yr. A larger share of the internal WF is related to livestock production and cereal products (wheat and barley), whereas the larger share of the external WF (EWF) is related to products originating from oil crops, cotton products, livestock products and stimulants (coffee, tea and cocoa). Most of the products responsible for the EWF are not grown in the UK, mainly because of unsuitable agro-climatic conditions (Chapagain & Orr 2008b).

Reducing the use of agricultural water is an aim that requires combined agronomic, physiological, biotechnological/genetic and engineering approaches which may be collectively described as water saving agriculture. As Kofi Annan, UN Secretary General, declared, 'we need a Blue Revolution in agriculture that focuses on increasing productivity per unit of water—more crop per drop' (UN 2000). This issue has been summarised recently by Pennisi (2008).

2.2.3 Increasing risks of flooding

Existing weather patterns leading to river and coastal flooding have a dramatic effect on crop production. Particularly sensitive areas in this context are the deltas of southeast Asia which provide much rice for local and regional consumption. The consequences of increasingly turbulent and unpredictable weather patterns, driven by climate change, have been discussed in many studies (eg Scholze *et al.* 2006). Rising sea levels leading to exacerbated coastal flooding are predicted to have dramatic effects on many countries.

2.3 Temperature

Recent reports suggest that global temperature increases are occurring more rapidly than previously predicted (Field 2009). In early February 2009, for example, southeastern Australia experienced temperatures of up to nearly 50°C. A risk of more frequent catastrophic crop failure is correlated with an increase in the frequency of extreme events (Semenov 2009).

Temperature is an important factor in controlling changes in the development of plants. An increase in temperature caused by climate change is predicted to speed plant development (Sadok *et al.* 2007). When combined with the lengthening of the cropping season, this change may increase yield. However, when assessing the effects of temperature on crop yield, it is necessary to take account of extremes, particularly if these occur during the sensitive stages of growth. Different developmental stages vary in sensitivity to temperature extremes. For instance, very significant reductions in the yield of wheat can be caused by high temperatures during and after flowering (Wardlaw & Moncur 1995). Rice is similarly sensitive to extreme daytime temperature and humidity during flowering and also suffers yield loss if night-time temperatures are high so that assimilate accumulation is reduced (Wassmann *et al.* 2009).

Climate change will cause soil temperatures as well as air temperatures to increase. This is already a problem for temperate crops grown in tropical regions. It is predicted that UK wheat yields in 2050 will be considerably reduced due to heat stress induced by climate change (Semenov 2009).

Exposure to frosts can also have a catastrophic effect on susceptible crops. Many crops of tropical origin are prone to chilling injury and their use in high latitudes is temperature limited. Fruit crops exposed to frost at the time of flowering may suffer complete yield failure. There are molecular approaches to understanding major genes affecting this response (Knox *et al.* 2008). There is a need for crops that can be autumn sown, which will survive and grow through the winter in low temperatures.

2.3.1 Indirect impacts of elevating temperatures

Elevated temperatures have various indirect effects including an increased water requirement. Combined stresses, particularly of drought and heat stress, can have particularly severe effects (Prasad *et al.* 2008). A second indirect effect of temperature is on plant defence and disease resistance (Wang *et al.* 2009c); high temperatures may extend the range of diseases (Evans *et al.* 2008). The ability of the highly invasive tasselled reed (*Phragmites australis*) to suppress other plants is also enhanced by high temperatures and its effects may be exacerbated under conditions of increased global warming (Rudrappa *et al.* 2009).

2.4 Ozone

Tropospheric O_3 concentrations are increasing at alarming rates due to energy generation, transport, agriculture, industrial processes, biomass burning and land use changes such as deforestation (eg Jaffe & Ray 2007; Royal Society 2008b). Ozone is considered to be the most damaging of all air pollutants to plants (Ashmore 2005). Most literature reports suggest that rising tropospheric O_3 pollution (itself the third-highest contributor to global warming) will suppress the global land carbon sink by reducing photosynthesis and stomatal conductance, leading to increased atmospheric CO_2 concentration and potentially also to further increased radiative forcing (Sitch *et al.* 2007). The most important direct effects of O_3 on terrestrial plants are those on leaf functioning and on leaf and root growth. Two of the most important factors determining O_3 sensitivity of crops and indeed of all plants are the control of the flux of O_3 into the leaf and the capacity of the leaf to deal with oxidative stress through detoxification and repair (Wieser & Matyssek 2007).

Current estimates of O_3-induced yield losses have been made for wheat, rice, maize and soya bean (Van Dingenen *et al.* 2008). Ozone concentrations for the year 2000 were estimated to have resulted in global crop losses of \$14–26 billion, which is significantly higher than estimated losses as a result of climate change. Among all crops, soya beans and wheat are especially sensitive. The greatest yield losses for wheat were in India (28%) and China (19%). Europe suffered the greatest relative yield loss for soya beans (20–27%). Maize, across all regions, was the least affected crop. The study predicts that by 2030, ambient O_3 pollution will reduce global wheat yields in most regions by a further 2–6% on top of the reductions reported in 2000 levels. Negative effects of O_3 have also been reported on crop quality for a range of crops (eg Agrawal 2007) and on protein contents of crop yield (Piikki *et al.* 2007). There may also be a direct effect of O_3 on reproductive processes, leading to reduced seed and fruit development and abortion of developing fruits.

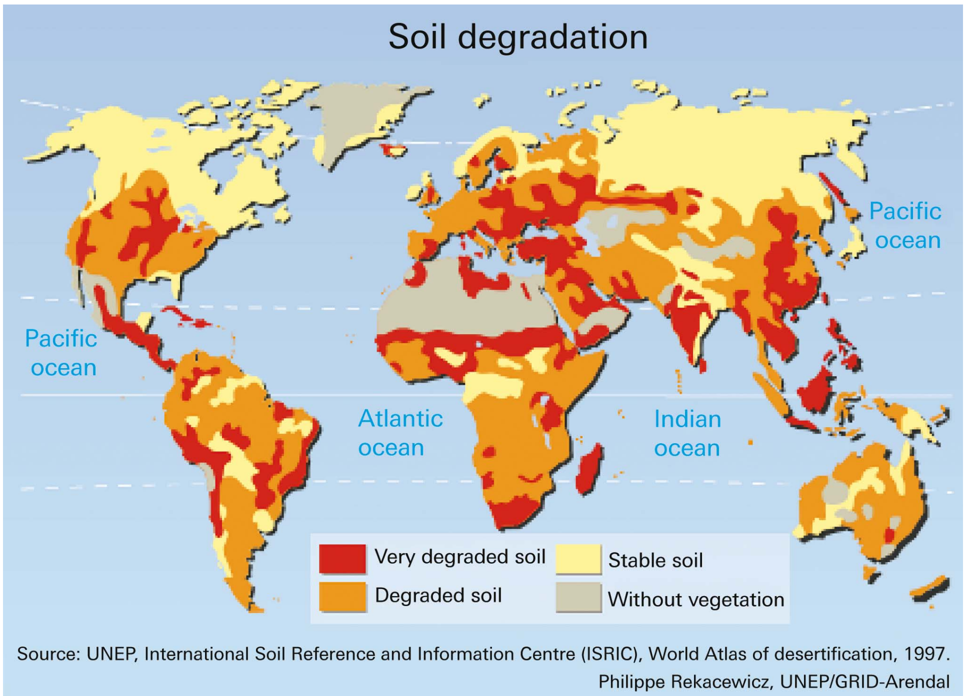
Recent reports suggest that O_3 concentrations within the range predicted for 2050 may increase transpiration and reduce drought tolerance by altering hormonal regulation of stomata and leaf growth (Mills *et al.* 2009). This may be particularly problematic for plant growth as high O_3 concentrations and hot and dry weather commonly occur together.

2.5 Soil factors

Soil is a non-renewable (at least over non-geological timescales) resource that is fundamental to sustainable crop production. Soil is subject to loss by erosion through the action of wind and water. This has serious consequences for crop productivity. Soil can also be damaged by industrial pollutants and physical compaction, and a substantial area of high quality agricultural soil is destroyed each year by rapid urbanisation in many countries. Continuing global soil degradation has been highlighted and maps have been constructed which indicate the scale, location and causes of the problem. A recent relevant initiative is GlobalSoilMap.net, a consortium that aims to make a new digital soil map of the world, predicting soil properties at fine resolution (Sanchez *et al.* 2009b). Soil degradation (see Figure 2.1) is of paramount importance and all present production and future predictions of crop yield depend upon the maintenance and improvement of soil quality. The availability of land with good quality soil for agriculture is a prerequisite for meeting production needs; as soil is lost or degraded and population increases, the area of land available to feed each human being is dangerously declining, creating a further imperative to increase yields.

Soil quality reflects the total properties of a soil and its fitness for purpose (which may differ with location and time) including fertility (crop nutrients), drainage and water-holding capacity, ease of cultivation (relating to physical structure and soil organic matter content), freedom from contaminants (biological and chemical) and biological

Figure 2.1. Global soil degradation. Source: UNEP (2009).



attributes, both beneficial and adverse. The latter relates to the population densities and identities of resident pests and diseases as well as the beneficial soil flora and fauna that sustain soil ecosystem functions (eg nitrification, aeration, nutrient cycling) and counter adverse impacts (eg denitrification or regulation of pest populations).

2.5.1 Microbiological properties of soil

The microbial diversity in a fertile soil has been compared to the biodiversity of a tropical rain forest (Beneddeti *et al.* 2005). Soil fungi and bacteria are critical for the recycling of carbon and major nutrients, particularly nitrogen, from organic inputs derived from plants and animals. Inputs of organic material in the form of crop residues and animal manures encourage the maintenance of an active microbial population, although the impact of soil use (eg for different crops) on microbial diversity is not well studied. Much soil microbial diversity is maintained in a dormant condition (spores and other resting structures) and the majority of microbial activity is associated with the zone surrounding plant roots (rhizosphere) where other impacts such as enhanced nutrient uptake (mycorrhizae) and amelioration of root diseases (biocontrol) can occur. Soil microbes also contribute to the maintenance of a friable soil structure.

2.5.2 Physical properties of soil

The physical properties of soil are determined by the underlying geology, the way it has been managed in the past and the way it is currently managed. A soil that is resistant to wind and water erosion is usually also a soil that readily allows water infiltration (ie is well drained) and has a high water-holding capacity. These characteristics are strongly correlated with adequate organic matter content resulting from animal manures and return of crop residues. Organic matter also encourages microbial activity and nutrient recycling.

A well-drained, well-aerated, friable soil that is not compacted promotes high crop productivity when water and nutrients are not limited. Good seed beds conducive to the germination, emergence and establishment of annual crops raised from seed are easier to prepare from well structured soils. In addition, the energy required for cultivation is significantly less in well structured soils. For example, it has been demonstrated that the energy savings from incorporating wheat straw into arable soils to improve soil conditioning are greater than the use of that straw as an off-take feedstock for the production of biofuels or electricity via combustion (Powlson *et al.* 2008).

In regions where soil of appropriate quality is in short supply, artificial growing media can be used. These may be solution culture, rockwool or coir in glasshouse production. Increasingly waste products may be digested to produce an inert growing substrate to which microbes and nutrients can be added. This approach can not only contribute to the production of artificial 'soils' but also result in the generation of CO_2 and energy that can be used in the production process.

2.5.3 Salinity

Of the land farmed in dry-land agriculture, about 2% is affected by secondary salinity. Of the irrigated land, 20% is salt affected (Athar & Ashraf 2009). Salinity is a soil condition characterised by a high concentration of soluble salts. Globally, more than 800 million ha of land are salt affected (6% of the world's total land area) (FAO 2006). Most of this salt-affected land has arisen from natural causes. Weathering of parental rocks releases soluble salts of various types. The other cause of accumulation is the deposition of salts carried in wind and rain. A significant amount of agricultural land has become saline as a result of irrigation or from bringing new land into cultivation, both of which cause water tables to rise and concentrate the salts in the root zone.

Plants differ greatly in their tolerance of salinity, as reflected in their different growth responses (Munns & Tester 2008). Of the major cereals, rice is the most sensitive and barley the most tolerant.

2.5.4 Toxicity

Aluminium (Al) is the third most abundant element in the Earth's crust. At low pH values (pH < 5.5), the toxic species of aluminium, Al^{3+}, is solubilised from aluminosilicate clay minerals into soil solutions and is toxic to crop plants (Kochian *et al.* 2004). Al toxicity mainly targets the root apex, resulting in inhibited root growth and function. As a result, Al toxicity leads to severe impairment in the acquisition of water and nutrients from the soil, which results in a significant reduction in crop yields on acid soils. As up to 50% of the world's potentially arable soils are acidic, with a significant proportion of these acid soils found in the tropics and sub-tropics in developing countries where food security is most at risk, Al stress represents one of the most important constraints for agricultural production worldwide (Kochian *et al.* 2004).

2.6 Crop nutrition

2.6.1 Major crop nutrients

The availability of nitrogen (nitrate or ammonium), phosphorus (phosphate) and potassium are crucial determinants of global sustainable crop yields. There is widespread nitrogen and phosphate deficiency in crop production which means that the potential yield of crop genotypes is not reached. This deficiency is particularly acute in the developing world where nutrient inputs are completely inadequate because they are unaffordable or unavailable.

Potassium is also a major crop nutrient and an appropriate balance between nitrogen and potassium is essential, since inadequate levels of available potassium reduce the capacity of the plant to exploit nitrogen. To ensure yield benefits from applied nitrogen a sufficiency of potassium is essential. Elevating available potassium will not influence yield when crops are grown at low nitrogen levels.

The discovery of a process for the synthesis of ammonia (the Haber–Bosch process) in 1908 heralded the start of 'industrial' agriculture. Global food security now depends completely on the chemical synthesis of nitrogen fertilisers and the mining of rock phosphate which is a non-renewable resource. Over 50% of the nitrogen in the global nitrogen cycle was synthesised industrially in the last 100 years (Smil 2000a, 2001). The Haber–Bosch process is energy demanding and currently uses hydrogen from natural gas. It would be highly desirable to find alternative sources of hydrogen, such as electrolysis powered by electricity generated from renewable sources. It is projected that synthetic nitrogen fixation will demand 2% of total global energy utilisation by 2050 (Glendining *et al.* 2009).

Provided there are no other constraints (such as insufficient water) there is a linear relationship between biomass accumulation and available soil nitrogen, up to an optimum. Optimum nitrogen nutrition is a key to obtaining the full genetic potential from improved or elite cultivars.

Nitrogen fertiliser application increases the economic and energy costs of agriculture, and also promotes release of nitrogen oxides that are themselves greenhouse gases. Nitrogen fertiliser use in crop production currently represents the dominant component of fossil fuel exploitation by agriculture (at least 40% for an intensively managed wheat crop where emissions are approximately 400 kg CO_2 per ha) (Glendining *et al.* 2009). Processes of denitrification also mean that nitrogen fertiliser use inevitably increases the emissions of NO_X (potent greenhouse gases) from agriculture (Harrison *et al.* 1995). The factors that influence NO_X emissions from soil are not well understood and require more research (Milne *et al.* 2005). Agricultural cropping and animal production systems are also important sources of atmospheric N_2O, a major greenhouse gas. Agricultural systems have been estimated to produce about a quarter of global N_2O emissions (Mosier *et al.* 1998). Consequently it would be highly desirable to achieve the same yield increment with less added synthetic nitrogen.

Biological nitrogen fixation (primarily by *Rhizobium* species) and recycling through green manures, composts and animal manure represent important ways in which reliance on synthetic nitrogen might be reduced and nitrogen losses to water and non-agricultural ecosystems minimised. However, the off-take of nitrogen in crops for human consumption, limited recycling of human waste to agriculture and leaching to water mean that substantial inputs of nitrogen derived from chemically synthesised ammonia or urea are essential to the maintenance of current yields.

In many soils, applied inorganic phosphate rapidly becomes inaccessible to plants due to its adsorption to soil mineral particles and occlusion in association with iron or aluminium oxides. In situations where available phosphate levels are low, mycorrhizal associations are critically important and phosphate deficiency is the primary constraint on yield.

It is possible to recycle phosphorus (super phosphate fertiliser, produced by treating animal bones with sulphuric acid was the first synthetic fertiliser), particularly from animal sources. However, loss to water and adsorption in soil mean that the supply of phosphorus in agricultural systems needs to be continuously replenished; mined rock phosphate represents the only substantial supply. The primary rock phosphate reserves in North America, North and South Africa, Russia and southeast Asia are likely to be exhausted before the end of the 21st century if trends continue (Smil 2000b; Zapata & Roy 2004).

2.6.2 Secondary, micro and functional crop nutrients

In different crops and cropping systems as well as different regions, yield and quality can be constrained by the availability in soil of nutrients that are required by crops in small concentrations. Deficiencies of sulphur (S), calcium (Ca) and magnesium (Mg) which are classed as secondary nutrients cause significant yield reductions in some crops and regions.

There are six micronutrients essential for plant growth: boron (B); copper (Cu); Iron (Fe); manganese (Mn); molybdenum (Mo) and Zinc (Zn). Micronutrient deficiency can usually be rectified when diagnosed and the significance of elevating the levels of some of these elements (eg Fe) in crops relates to their importance in human nutrition as much as crop nutrition.

There are five elements considered to be functional in plants but not essential: sodium (Na); vanadium (V); cobalt (Co); silicon (Si) and chlorine (Cl). Of these, Si has relevance in the context of crop production as a competitor for arsenic (As) uptake (Ma *et al.* 2008). Arsenic may accumulate at dangerous levels in the diets of those who depend on rice grown in soil and water containing high As concentrations and low Si.

2.7 Pests, diseases and weed competition

Pests, diseases and weeds have a significant impact on the sustainability of food crop production. Disease-induced losses essentially represent wasted inputs of energy, water, nutrients and labour. Worldwide crop losses due to weeds, pests and diseases have been estimated for eight major crops (wheat, barley, rice, maize, soy, cotton, sugar beet and potato) as 26–40%. In the absence of control measures such as resistant varieties, crop protection chemicals and crop rotations, losses would be 50–80% (Oerke & Dehne 2004).

2.7.1 Pests

Pests can cause significant losses of food production, and there are chemical and non-chemical approaches to minimising these losses (Yudelman *et al*. 1998). Table 2.1 lists the major pests of maize, rice and wheat.

Locusts, larvae of Lepidoptera, and other herbivorous chewing insects can cause very substantial crop losses as can root-attacking nematodes and sucking insects such as aphids and leaf-hoppers; the latter are also important vectors of diseases caused by viruses and phytoplasma. Corn borer and corn rootworm cause much damage; rootworm also affects nitrogen and WUE by damaging the root system. Damage to cobs by corn borers facilitates the entry of fungi such as *Fusarium* and *Aspergillus* species that contaminate the seed with poisonous mycotoxins.

Many crops, especially fruit and vegetables, are prone to rot after harvest and before or during transport to consumers. Seeds from cereal and legumes are prone to losses from bruchid beetles, grain and meal moths. Temperature and humidity control can reduce, though not eliminate, these losses.

Arthropods and nematodes can also act as disease vectors. Aphids and leaf hoppers, for example, can act as vectors of viruses and phytoplasmas. Many different genera of nematodes cause plant disease, usually by infecting and colonising roots. Feeding occurs through a hollow stylet that can penetrate plant cell walls. Most are endoparasites, invading root tissues and carrying out most of their feeding from inside the root. Two genera of endoparasitic nematodes are the source of much crop damage in wheat, potato, soya beans and many other crops. These are the cyst nematodes (*Heterodera* sp. and *Globodera* sp.) and root knot nematodes (*Meloidogyne* sp.). Nematodes are particularly difficult to control with pesticides. Soil fumigation with methyl bromide has been widely used until recently, but the use of this toxic chemical is now severely restricted although there are few alternatives.

Vertebrate pests are also a significant problem. Rodents and other large herbivores can inflict significant losses on crops during their growth and development as well as post harvest. In industrialised countries, these losses are usually adequately controlled by regulating the populations of rats, rabbits or deer using poisons, gassing or shooting. In developing countries, recourse to such methods of control is more limited and losses can be considerable in field as well as plantation crops (Sridhara 2006).

2.7.2 Diseases

Diseases have an impact on loss of crops, pre and post harvest. There is a cost associated with their control through crop-protective chemistry and resistant varieties. Significant losses are caused to crop yields from a variety of fungi and oomycetes (microscopic fungus-like organisms), bacteria and viruses across a range of crops. Some examples are summarised in Table 2.2.

2.7.3 Weed competition

Among biotic constraints on crop protection, weeds have the highest loss potential (32%), followed by pests and pathogens (18 and 15% respectively) (Oerke & Dehne 2004). Losses due to weed competition represent a

Table 2.1. Major pests of maize, rice and wheat.

Crop	Pests
Maize	Armyworms—common, fall, true (*Pseudaletia unipuncta, Spodoptera frugiperda, Pseudaletia unipunct*)
	Borers—Europeran corn, lesser cornstalk, potato stem, stalk (*Ostrinia nubilalis, Elasmopalpus lignosellus, Hydraecia micacea*, *Papaipema nebris*)
	Corn delphacid (*Peregrinus maidis*)
	Corn earworm (*Helicoverpa zea*)
	Corn flea beetle (*Chaetocnema pulicaria*)
	Corn leaf aphid (*Rhopalosiphum maidis*)
	Corn silkfly (*Euxesta stigmatis*)
	Cutworms—black, western bean (*Agrotis ipsilon, Striacosta albicosta*)
	Rootworm—corn, western corn (*Diabrotica virgifera, Diabrotica barberi*)
Rice	Rice gall midge (*Orselia oryzae*)
	Rice bug (*Leptocorisa oratorius*, *L. chinensis*, *L. Acuta*)
	Hispa (*Dicladispa armigera*)
	Rice leaffolder (*Cnaphalocrocis medinalis*, *Marasmia patnalis*, *M. Exigua*)
	Stemborer (*Chilo suppressalis, Scirpophaga incertulas*)
	Rats (various species)
	Rice weevils (*Sitophilus oryzae*)
Wheat	Aphids (various species)
	Armyworms, cutworms, stalk borers and wireworms (various species)
	Cereal leaf beetle (*Oulema melanopa*)
	Flies—hessian, sawfly (*Mayetiola destructor, Cephus cinctus*)
	Mites (various species)
	Nematodes— cereal cyst, seed gall, root knot (*Heterodera avenae, Anguina tritici, Meloidogyne* spp.)
	Slugs, snails, grasshoppers, and crickets (various species)
	Stink bugs (various species)
	Thrips (various species)
	Wheat stem maggot (*Meromyze Americana*)
	White grubs (various species)

significant waste of resources (water and nutrients) that would otherwise be available to the crop. Weeds essentially represent unwanted production of a biomass that can also impede efficient harvesting. There is an increasing problem of resistance to herbicides and the establishment of populations of some weed species which are no longer readily controlled. The outstanding success of the development of herbicide-resistant crops that enables the use of a broad-spectrum herbicide such as glyphosate has been a major advance in the reliability of weed control in maize and soya bean, although reports of weeds with glyphosate resistance are also increasing. The need for variety of herbicides with a range of modes of action to be available is an essential component of effective weed management. The effects of weed competition have been extensively discussed elsewhere (for example, see Zimdahl 2004).

Weeds can cause severe losses in wheat, with dwarf varieties particularly vulnerable. Similarly in maize, weeds are a major problem for seedlings. One of the major challenges to cereal production in Sub-Saharan Africa is the widespread occurrence of parasitic weeds. Probably the most important is *Striga*, which infests an estimated 20–40 million ha of farmland cultivated by poor farmers throughout this region. The tiny seeds are carried in run-off eroded soil and contaminate traded seed to infest an ever-increasing area. In Kenya, an estimated 75,000 ha of land is infested with *Striga* (80% of farmland in Western Kenya). Every year *Striga* damage to crops accounts for an estimated US$7 billion in yield loss (about 4 million tons) in Sub-Saharan Africa, and affects the welfare and livelihood of over 100 million people (Scholes & Press 2008).

2.8 Energy and greenhouse gas emissions

Production in many developing countries is constrained by energy inputs. Animals or human labour are often used for soil cultivation; to provide the energy required to do

Table 2.2. Examples of diseases affecting a selection of crops.

Crop	Pathogen, disease, bacteria or virus	Effect
Apples and pears	Fireblight disease *(Erwina amylovora*)	Destructive bacterial disease that kills blossoms, shoots, limbs and sometimes entire trees.
Banana	Black Sigatoka disease (*Mycosphaerella fijiensis*)	Necessitates weekly sprays with fungicides in major banana producing areas. Since the major worldwide commercial cultivar (Cavendish) is susceptible, there is concern that security of supply may be undermined.
	Panama disease (Fusarium)	As the disease progresses, younger and younger leaves collapse until the entire canopy consists of dead or dying leaves.
	Xanthomonas wilt (*Xanthomonas campestris*)	Pathogen enters the vascular system of the plant, destroying the fruit bunches and eventually killing the entire plant.
Barley	Powdery mildew (*Blumeria graminis*)	Fast evolving and severe constraint on barley production necessitating regular fungicide applications in northern Europe.
Beans	Bacterial blight (several species)	Losses occur from death of plants, partial loss of leaves, and pod-spotting quality factors.
Brassicas	Black-rot (*Xanthomonas campestris*)	Seed-borne vascular disease that can cause affected leaves to drop prematurely and distortion of leaves, dwarfing and plant death.
Cassava	Cassava mosaic virus (*Geminiviridae* family)	Plant pathogenic virus that may cause either a mosaic appearance to plant leaves, or chlorosis, a loss of chlorophyll.
Citrus fruit	Citrus canker (*Xanthomonas axonopodis*)	Infection causes lesions on the leaves, stems and fruit of citrus trees, including lime, oranges and grapefruit. A fruit infected with canker is safe to eat but too unsightly to be sold.
Potato	Potato late blight (*Phytophthora infestans*)	Causes devastating losses necessitating widespread fungicide applications.
	Bacterial wilt (*Ralstonia solanacearum*)	Very destructive, especially during hot and wet seasons. Plants wilt and die suddenly.
Rice	Many fungal diseases (particularly *Magnaporthe grisea*)	Despite intensive breeding for resistance, losses are still considerable in Africa and Asia.
Soya bean	Soya bean rust (*Phakopsora pakirhizi*)	Causes a major reduction in yields in Brazil.
Tomato	Bacterial speck disease (*Pseudomonas syringae*)	Cool, moist environmental conditions contribute to the development of the disease, which has now established itself as a major production problem in northern USA.
Wheat	Ug99: a race of stem rust caused by *Puccinia graminis* (see Case study 3.5)	Overcomes previously effective disease resistance genes; currently affecting yields in Africa.

work, they need food. In developing countries, where mechanisation may be limited, the energy inputs required to grow food (from human and animal labour) represent a significant part of the constraint on production. In the UK, agriculture uses about 1.5% of UK total energy and accounts for 0.8% of total carbon emissions (Warwick HRI 2007).

In addition to CO_2, the other significant greenhouse gas associated with crop production is N_2O, as discussed in Section 2.6.1. Agriculture accounts for the majority of the N_2O emissions in the UK (DEFRA 2009a).

2.9 Maintenance of genetic resources and germplasm availability

Genetic variation in crops and their relatives is vital for agricultural development. Many modern varieties have incorporated traits, for example disease resistance, that were transferred by conventional breeding using different varieties, landraces and relatives. However, genetic uniformity and a narrowing genetic base may lead to decreased resilience in the face of environmental stress (as discussed further in Chapter 4) and the potential for continued novelty and improvements in the future depends to a great extent on the availability of diverse genetic resources.

Yet crop genetic diversity has declined steeply in recent decades. In India, for example, 30,000 rice varieties were once grown, yet now most acreage is under a few higher yielding varieties. The preservation of genetic diversity in genebanks is essential if crop genetic improvement is to continue. Preservation of resources for the major crops is expensive. One estimate for the crops of the CGIAR Institutes is that an endowment of several hundred million dollars would be required to maintain the existing genebanks in perpetuity (Koo *et al.* 2003). A recent example of institutional innovation is the Global Crop Diversity Trust's new seed bank in Svalbard.[4] It is clear that efforts to ensure germplasm conservation must remain a priority for all crops and all environments.

The constraints that limit the production of food crops globally include soil fertility, water availability, pests, diseases and weeds. The nature of these constraints varies at a regional level and they will be affected by climate change over the next 30 years. The following chapter describes a range of biological science-based technologies that should help address these various challenges.

4 See http://www.croptrust.org/main.

3 Developments in biological science with potential benefits for food crop production

Summary
Over the next 40 years, biological science-based technologies and approaches have the potential to improve food crop production in a sustainable way. Some of these technologies build on existing knowledge and technologies, while others are completely radical approaches which will require a great deal of further research. Genetic improvements to crops can occur through breeding or GM to introduce a range of desirable traits. Improvements to crop management and agricultural practice can also address the constraints identified in the previous chapter. There are potential synergies between genetic and agroecological approaches. Different approaches will be needed for different regions and circumstances. There is a need to balance investment in radical new approaches that may have major consequences on productivity with investment in approaches which deliver modest improvements on a shorter timescale.

3.1 Introduction

Major historical advances in crop production processes (such as plant breeding, fertilisers and crop protection chemicals) have resulted in substantial increases in the production of food crops. So far, the increases in production have effectively kept pace with the increase in net global population but, as described in Chapters 1 and 2, the future challenge to feed an increased global population is unlikely to be met by existing technology. In this chapter we describe recent developments in biological science that could be translated into new technologies to help meet this challenge through the genetic improvement of crops and changes in crop management.

The science underpinning food crop production—as in all areas of biology—is being revolutionised by several new technological developments, including those in imaging and various types of biochemical analysis. These methods are now very sensitive and they can be applied in a high throughput mode so that many plants—sometimes many thousands of plants—can be analysed in a single experiment. Imaging tools enable whole plants to be analysed, living subcellular structures to be viewed and the chemical constituents of cells to be characterised in detail. The most powerful and informative new methods available in research are based on the ability to determine genome sequences relatively quickly and cheaply.

Additional power is added to these technologies through the widespread use of computing technologies to handle large datasets. The biological processes relevant to productivity of food crops can now be dissected more completely and there is an unprecedented opportunity to translate this research into the genetic improvement of crops or changes in crop management.

To illustrate the potential for a revolution in crop science we first describe the new research tools. It should be stressed that, although many of these tools are concerned with genetic and genomic analysis of food crops, the output of the research is not necessarily in genetic improvement. The identification of a gene or set of genes associated with improved performance of a crop could be used just as easily to elucidate a novel crop management strategy.

The final section of this chapter describes ways in which the output of the research tools can be translated into technology for improved food crop production. Throughout the chapter we have indicated (where possible) whether such applications are expected in the short (up to 5 years), medium (5–15 years) or long (greater than 15 years) term. However, it is difficult to predict the exact pace of development and breadth of use of new technologies as these will depend on factors such as social issues, economic markets and research infrastructure that are discussed in Chapter 4.

3.2 Tools for research and technology

The research tools described in this section are either for genetic (Section 3.2.1) or phenotypic analysis (Section 3.2.2) of plants. The genetic analysis targets their DNA whereas the phenotypic investigations involve their biochemical, physiological or morphological characteristics. Most of the research tools described here provide information that is then used to develop new varieties or crop management practices. However, there are some instances, for example with genetic modification (GM), when the research tools can also be used in applied technology.

3.2.1 Genetic analysis

3.2.1.1 Genome sequencing

Complete genome sequences of crop plants and microbes are particularly important because they provide detail about all of an organism's genes and the proteins that the organism can synthesise. When linked with new methodologies for assigning function to genes and high throughput technologies for analysis of RNA, proteins and small molecule metabolites (Section 3.2.2.2), the analysis of genome sequences is referred to as genomics and it provides a powerful framework for the dissection of complex biological processes in detail.

Genes or combinations of genes affecting crop production can be easily identified using genomics. In genetic improvement strategies these genes can be targeted in breeding programmes or they can be transferred into crops by GM as described in more detail below. However, it should be stressed that the information from genomic studies is also important for the science that underpins changes in crop management. The information about genes, proteins and metabolites in crop plants allows strategies for crop management to be developed that maximise agronomic performance of crops in a sustainable way.

New methodologies for determining DNA sequences are orders of magnitude more efficient than the methods used for the first generation of genome sequences from model organisms and man. There are several versions of these new methods and it is likely that others will emerge in the near future. Sequencing a genome is currently being transformed from a multimillion pound project into one costing less than one million pounds for a completely new genome and a few thousand pounds for an individual of a species for which a full genome is already available. Generating the DNA sequence data is now straightforward and cheap: the computational analysis and annotation of the sequence is the most expensive and time-consuming part of a genome project.

Genome sequencing methods were first applied to the model plant species *Arabidopsis* and we now have complete genome sequence data of *Arabidopsis thaliana*, rice, maize, sorghum, soya bean, poplar, grapevine and papaya. With the introduction of the new sequencing technology it is likely that ongoing genome projects for wheat, potato, tomato, sunflower, apple, pear, peach, strawberry and other crops can be accelerated.[5] Other crop genome sequences could be completed in relatively short times and it will be possible to generate data from several varieties of previously sequenced crops.

3.2.1.2 Marker technology

Plant breeding is a well established method for improving the performance of crop plants by making defined crosses between genetically distinct parents, screening progeny for desired trait combinations and selecting preferred individuals with better combinations of characteristics that can then be bulked and developed into lines and varieties. The procedures for screening progeny for desired traits are often the most challenging stages in conventional plant breeding because many plant lines have to be tested for phenotypes that may be difficult to assay. Disease resistance, for example, can normally be identified only after extensive testing of multiple plants in each line for susceptibility. Similarly, yield enhancements cannot be identified by collecting the products from a single plant; the products from several plants need to be combined and measured accurately in replicated tests. The advances described below allow these screening procedures to be streamlined.

Breeders and geneticists can often show that defined traits are conferred by specific genes, or are associated with quantitative trait loci (QTL)—stretches of DNA strongly associated with the gene for a particular trait. These traits are often difficult to measure, requiring laborious and incompletely reliable assessment methods. It therefore makes breeding easier if instead of measuring the trait, a molecular DNA genetic marker linked to the QTL can be monitored in progeny. This method is cheaper and more reliable. In addition, undesirable traits are often genetically linked to desired traits. This is known as linkage drag. DNA markers help identify rare plants in a breeding program in which the desired trait is retained but deleterious traits are left behind. This is referred to as marker-assisted selection (MAS). DNA marker technology has evolved through several stages. In its most advanced form, it is based on a genome sequence and generates dense genetic maps in which the markers are very close to, or may actually represent, the gene of interest. More complex applications of MAS involve selection for traits affected by multiple genetic loci.

An example of the application of MAS is in the development of submergence-tolerant rice. In rice, the major genetic determinants of flooding tolerance have been identified and, using this information, MAS has been employed to develop flooding tolerant varieties (Hattori *et al.* 2009; Singh *et al.* 2009; Voesenek & Bailey-Serres 2009). Many other examples of MAS suggest that this approach will be increasingly important in breeding as genome sequence data become available for more crop plants.

3.2.1.3 Genetic modification

Traditional and marker-assisted plant breeding involve the introduction of novel traits into crops by crossing as described above. The crosses might involve different genotypes of the crop or they might involve the crop and a related species (interspecific crosses). Progeny of the crosses are selected for traits of interest using DNA markers. Traditional plant breeding is slow, taking 10 years or more for a breeding cycle. Furthermore, breeding of some crops which are not propagated by seed, such as potato and banana, is extremely difficult. In molecular GM, novel genes are introduced, either individually or in small groups, into a crop plant. The genes inserted may either be from the same species (this is known as cisgenics) or from another species (transgenics). These methods circumvent the crossing cycle associated with conventional genetic improvement and in cisgenic approaches they allow transfer of genes within a species but without the complication of linkage drag.

GM-based methods are used widely as a routine tool in research and they have greatly facilitated major advances in plant biology over the last 25 years. They are particularly important in the ongoing task of assigning function to each of the 10,000 to 20,000 genes which have been identified in each species and in elucidating the cellular mechanisms in plant biology. The application of GM techniques in crop plants, however, has been controversial. In the USA,

5 See http://www.Phytozome.net.

Argentina, Brazil, India and Canada, GM crops are grown widely (125 million ha in 2008), whereas in Europe and Africa (except South Africa) they are largely absent (ISAAA 2008).

The first generation of GM technologies, including those that are the basis of commercial applications, involve the insertion of novel genes into the recipient genome and selection for best performance (see Case study 3.1). Since plant genomes are predominantly non-coding DNA the insertion site does not normally disrupt essential genes. However, a novel approach to GM involves the use of engineered zinc finger proteins that can be targeted at specific sequence motifs in the genome to disrupt specific genes or to introduce mutational changes at defined sites adjacent to the zinc finger target site (Shukla *et al.* 2009; Townsend *et al.* 2009). This is an exciting new development because the modifications are introduced so precisely. Published examples of this technology involve maize and the outputs could be developed as products in the 5–10 year period. In principle the method could be transferred into other crop species within 5 years. New genotypes and lines could be developed within 10 years.

GM should not be viewed as a single technology—potential benefits and complications vary depending on the nature of the gene being transferred and the plant into which it is transferred. In this chapter we consider the potential benefits of GM in crop plant improvement alongside innovations in conventional breeding and crop management. Chapter 4 addresses the potential complications of GM alongside those of other innovations in crop technology.

Case study 3.1. Genetic modification of maize for insect resistance

Bt toxin and the corn borer

The caterpillars of the European corn borer moth can cause significant yield losses to maize by damaging the ears and stalk of the plants. *Bacillus thuringiensis* (*Bt*) is a bacterium which produces hundreds of 'crystal' proteins toxic to a range of insect pests, including corn borer caterpillars. *Bt* bacterial preparations rich in crystal protein have been used as an insecticide for some crops since the 1930s.

Development of transgenic maize

A transgenic (GM) maize resistant to the corn borer was created by inserting a single gene for a *Bt* crystal protein into the maize genome. This causes the maize plants to produce the protein, which is ingested by pests when they eat the plant. Transgenic *Bt* crops express a very high level of toxin, making this a highly effective approach. Because damage caused by insect feeding allows entry of mycotoxin-producing fungi, a secondary benefit is that *Bt* maize also has lower levels of fungal mycotoxins in the grain than non-*Bt* maize, thus enhancing its safety as food or feed (Munkvold & Hellmich 2000; Wu 2007). To date, this type of *Bt* maize is the only GM crop approved for commercial cultivation in Europe (first approved in 1998) (Brookes 2008; GMO Compass 2008). In the US, many GM maize lines on the market also make a different *Bt* protein targeted against corn rootworm.

Constant exposure of insect pests to the *Bt* toxin creates an evolutionary pressure for the development of resistance. However, the use of non-*Bt* crop refuges allows sufficient numbers of the *Bt*-susceptible pests to survive to lessen this evolutionary pressure.

Recent developments

Most *Bt* maize grown commercially now has more than one *Bt* gene, giving resistance to a variety of pests. The latest version for release in 2010 has six *Bt* genes (Dow AgroSciences 2009). This maize variety also allows a reduction in the size of the non-*Bt* refuge needed to avoid resistance in target pests.

Bt cotton varieties are grown widely throughout the world and additionally *Bt* genes are being introduced into many other crops, including vegetables, as a means of providing resistance to insect pests.

Non-target organisms

As the toxin is contained within the plant rather than sprayed on the field, it only acts directly against insects that feed on the plant. Some laboratory tests seemed to indicate that the pollen of *Bt* maize presents a threat to monarch butterflies. However, further studies showed that *Bt* maize pollen did not in fact pose a threat as the density of pollen on the milkweed leaves on which monarch caterpillars feed is much lower than that which would cause harm. This is because there is only a short time during which the caterpillars might be exposed to *Bt* pollen and only a portion of caterpillars feed on milkweed in close proximity to *Bt* maize fields (Sears *et al.* 2001; Wolfenbarger *et al.* 2008). Control of insect pests with insecticides poses a greater risk of damage to non-target organisms than control with transgenic *Bt* protein.

There have been some reports of other insects becoming pests in *Bt* cotton areas in China, and it is possible that this could also happen for *Bt* maize (Wang *et al.* 2008). However, the increase in insecticide use for the control of secondary insects in cotton is far smaller than the reduction in total insecticide use due to *Bt* cotton adoption (Wang *et al.* 2009d).

3.2.2 Phenotype analysis

Marker-assisted plant breeding places the emphasis on DNA screening rather than on detailed analysis of the plant phenotype. However, the breeding cycle is further enhanced whenever plant phenotypes can be analysed with higher resolution and greater precision than previously. In this section we describe various developments in phenotype analysis that can be combined with MAS to enhance the identification of crop plants with agronomically useful genes or combinations of genes.

3.2.2.1 Phenotyping platforms

It is now possible to screen many different plant genotypes quickly and simultaneously for the traits expressed (phenotype) using 'phenotyping platforms' (Finkel 2009) . These systems involve the use of precisely defined environmental conditions and sophisticated imaging and other recording methods to monitor the growth and development of crop plants (Xie *et al.* 2006; Rajendran *et al.* 2009). When combined with high-resolution genetic maps or with mutant collections in which a high proportion of genes in a genome are disrupted, these platforms are a very effective way of revealing sets of genes that influence agronomically significant phenotypes. Trait data can often be obtained automatically. For instance, root platforms now allow dynamic characterisation of root system architecture and sites of root water uptake in hundreds of plants using non-invasive systems built on computer tomography (de Dorlodot *et al.* 2007). Other systems make it possible to introduce drought stress and measure biomass, transpiration, leaf growth and architecture, root growth and architecture and soil water uptake in many plants in a single experiment.

These phenotyping platforms are sophisticated, resource-intensive facilities and they are not appropriate for local breeding institutions. However, they are an essential component of the research infrastructure in leading national and international research centres where they are required for full exploitation of high-resolution genetic maps and genome sequence data.

3.2.2.2 High throughput analysis of small molecules

Plants make an enormous diversity of small molecules, which include mediators of communication between plants, between microbes and between plants and microbes. High throughput analysis (a technique which allows the fast analysis of a large number of molecules in parallel) based on mass spectrometry now allows these small molecule populations to be better described (Schauer & Fernie 2006). In some instances functions can be assigned to these small molecules by combining mass spectrometry output with expression profiling and phenotype analysis. These high throughput approaches have revolutionised our ability to analyze the natural chemicals in plants and other organisms: it is no longer necessary to devise separate assay methods for each type of chemical because in a single sample it is now possible to identify thousands of compounds.

Application of these methods now allows a chemical profile of individual plants in the progeny of breeding crosses or following particular crop management strategies. Individual compounds or sets of compounds can then be used as indicators of useful traits in the way that DNA markers are used as described in Section 3.2.1.1. In large-scale breeding programmes and trials of new crop management practice it may be easier and more efficient to assay the compounds rather than the traits when there are many plant lines or crop treatments under investigation. In effect this would be a 'metabolic marker' approach that could be used together with, or instead of, DNA markers.

Recent work illustrates the potential of this approach: a set of metabolites was identified that is associated with plant acclimation to cold (Guy *et al.* 2008). This work was carried out in the model species *Arabidopsis* but similar analyses could be repeated in crops and applied to a variety of traits. These assays would provide metabolic markers, for example, of crucial stress-sensitive stages of development of our major crops, eg grain abortion and early seed growth under drought or other crucial traits. The development of these methods is not as well advanced as DNA MAS but they are likely to be an important complementary approach over the next five years.

In the longer term new technologies for chemical characterisation also link to the development of novel crop protection chemicals. Many of the existing crop protection chemicals are based on natural compounds found in plants. Some herbicides are plant hormone derivatives and compounds to protect from disease may be based on chemicals in plants involved in signalling during disease resistance. With the availability of high throughput methods to characterise the chemical composition of crop plants there is a long-term opportunity to identify novel compounds that can be applied to crop plants sustainably.

3.2.2.3 Isotopic analysis for drought resistance or high water use efficiency

In 1982 Farquhar and co-workers developed a method for assessing water use efficiency of crops using the ratio of the abundance of the natural isotopes of carbon, ^{13}C and ^{12}C (Farquhar *et al.* 1994). During diffusion and biochemical fixation of CO_2, the ratio $^{13}C/^{12}C$ is different from the normal abundance in the atmosphere. The ratio depends on the balance between diffusion into the leaf and demand, so a measure of the ratio gives a measure of water use efficiency. The approach has now been used to investigate water use efficiency in many crops. In C3 plants, the technique has led directly to the selection of improved crop varieties, most notably Q15 in wheat (Condon *et al.* 2004). However, it is not suitable for screening C4 plants such as maize.

3.2.2.4 Modelling

Progress in breeding for high and stable yields in crop plants under many kinds of environmental stress would be greatly speeded up if it were possible to predict the consequences for the phenotype of a plant of changing the genotype. There are many reports of traits selected for their impact on drought responses of plants. However, for many reasons, prediction of the impact of these on yields is not straightforward. It is now well established that any trait can confer a positive, negative or neutral effect depending on the environment under which the plant is growing. Even in the most successful field analyses, a given allele of a gene usually results in a positive effect in only half of the environments in which it is tested. Developing a capacity to allow prediction from genotype to phenotype is complicated by interactions between genetic controls (of functioning, growth and development) and the environment. Plant modelling can help us navigate a path through this complexity. Combining field studies and genetic analyses using modelling allows prediction of different effects of an allele at different sites (Hammer *et al.* 2006). The analysis provides some estimate of the frequency with which this allele will have positive effects over years at a given site. This scenario-testing allows informed decisions to be made on variety development for different climatic regions and will help capture the interactions between genotype and environmental factors. Within this framework, physiological simulation will show how different traits interact. Genetic simulation allows some control of sources of error and helps determine what level of 'knowledge' is required to enable faster advances than existing breeding methods.

There is great potential for further research into the modelling of water use in different plant genotypes and the use of remote sensing and biosensors to optimise the use of irrigation water. Computer modelling is likely to have applications in both the long and the short term. In the short term, for example, it can be a useful research avenue because it allows irrigation regimes to be optimised depending on the genotype of plant and other environmental parameters including soil type and sunlight. In the longer term, modelling and supercomputing could be used as part of genetic improvement strategies, using both GM and conventional breeding, to design the optimal plant for a high CO_2 world (Zhu *et al.* 2007).

3.3 Applications of research

In the following sections we describe how research tools could be used to develop new technologies in food crop production in order to address the constraints identified in Chapter 2. We have considered abiotic stress, biotic stress, soils, mineral nutrition of crops and nutritional quality of crop products as separate topics. However, in many instances, a new technology will address multiple topics. These topics include reference to both genetic and crop management strategies. First, we consider possible genetic improvements to enhance yield potential.

3.3.1 Genetic yield potential

F1 hybrid crops (first generation offspring of different parents) often exhibit greater vigour than either parent. This phenomenon—hybrid vigour or heterosis—is not well understood but its existence points to additional unrealised yield potential in plant genomes up to 50% greater than that of inbred crops (Duvick 1997; Lippman & Zamir 2007) (see Case study 3.2). F2 or later generation hybrids may also exhibit transgressive segregation—traits that are beyond the range of the parents. In the F2 or later progeny of a cross between tomato relatives, for example, the fruit may be redder and larger than those of either parent (Tanksley & McCouch 1997). Harnessing these effects is not straightforward because they could involve multiple genetic loci and contributions of the two genomes that are either unequal or synergistic. F1 hybrid seed can be produced when self-fertilisation is prevented but in many species, such as wheat, production of F1 hybrid seed is currently difficult and expensive.

To exploit heterosis with existing technology it is necessary to hybridise related plant genotypes for each round of seed production. The complicated procedures for production of F1 hybrid seed are not appropriate for many developing countries where the infrastructure does not exist for maintenance of the required seed supplies. If the F1 hybrid seed could be propagated asexually then the repeated cycles of seed production could be avoided and the benefits of heterosis could be realised more widely. In such a situation it would be easier to maintain supplies of seeds: it would be possible even for farmers to maintain seeds. Asexual propagation of hybrid seed would also facilitate exploitation of transgressive segregation.

One approach to the propagation of hybrid seeds involves exploitation of a process—apomixis—in which plants produce seed in the absence of sexual reproduction. Some species are naturally apomictic and it is likely that other species including crops can be made apomictic by mutation or GM. Examples in which apomixis would be advantageous include wheat, in which self-fertilisation and sexual production cannot be easily prevented. It would also be useful in crops like cassava and potato in which seed from self-fertilisation does not breed true. Apomixis is an area of active research but it may take more than 10 years to translate this research into a successful breeding programme.

Modification of photosynthetic efficiency could also result in massive yield increases. One approach to this involves attempts to introduce a C4 photosynthetic pathway into plants (Hibberd *et al.* 2008) as an alternative to the standard C3 pathway. C4 photosynthesis is found in drought-tolerant grasses such as maize and sorghum, but not in wheat and rice. It seems that the C3 to C4 transition has evolved independently several times in different plant species and that the key enzymes are present in both C4 and C3 plants (Wang *et al.* 2009b). It may be possible to engineer this transition by GM targeted at key regulatory proteins affecting the expression of enzymes in the C4 pathway. Comparative genomic information from rice, maize and sorghum (Paterson *et al.* 2009) will help in this objective. Alternatively, a recent report describes how the transfer of five bacterial genes introduced a metabolic shunt into the photosynthetic pathway of a C3 plant that mimicked some of the effects of C4 metabolism including

Case study 3.2. The development of hybrid maize

Hybrid vigour

While testing his theory on the origin of species, Darwin compared inbred and cross-pollinated (hybrid) maize and found that the hybrids were taller than the inbred plants and were more tolerant of cooler growing conditions. This 'hybrid vigour' (heterosis) was further studied by William Beal at Michigan State College, who observed increased grain yields in hybrids of different varieties.

Single and double crosses

In the early 1900s, experiments were conducted in which plants were self-pollinated for several generations to produce pure-breeding lines, which were then crossed to produce hybrids. The resulting high-yielding hybrids could be produced every year. These hybrid seeds could easily be produced by removing the tassels from one block of inbred maize plants to allow pollination by an adjacent block of a second inbred line. This is more easily done on a large scale with maize than other cereal crops as maize is wind pollinated and the male and female flowers are on separate organs.

However, as seed yields of the inbred parents were low with this method, the cost of hybrid seed was too high for farmers. When an additional, 'double cross' was performed (by crossing two of the single cross hybrids to produce the seed sold to farmers), yields were better than open pollinated varieties although not as good as the best single crosses. Seed production from 'double crosses' between high-yielding single cross hybrid parents became routine in the 1930s. Because of the doubling of yields, adoption of hybrid maize increased from 0 to 50% of Iowa's corn acreage in just six years following its release in 1932.

Commercial development

Farmers could either grow hybrid maize by purchasing the single cross parent seed and performing the cross on their farm, or by purchasing ready to plant hybrid seed from farmer cooperatives or commercial seed companies. The latter emerged as the preferred choice.

Although hybrid maize was first developed in the 1930s, the basis of hybrid vigour is still unknown. Further improvements in yield have largely resulted from improvements in the yield of the inbred lines. By the 1960s, the inbred lines were high yielding enough to use as seed parent and produce single cross hybrids for sale (which had a higher yield and were cheaper to produce than the best double crosses). Yields are now 4–5 times greater than those achieved with self-pollinated varieties in the 1920s. The aim of commercial seed companies is to increase yields again from about 150 to 300 bushels per acre by 2030.

Source: Duvick (2001).

increased biomass production and light energy harvesting (Kebeish *et al.* 2007).

Transfer of C4 metabolism into rice could achieve a yield increase of up to 50% (Hibberd *et al.* 2008), but the real gain could be a substantial increase in water use efficiency, a character normally associated with C4 plants. Engineering a *bona fide* C4 metabolism into a C3 plant may take at least 10 years but the metabolic shunt method could be achieved sooner.

3.3.2 Abiotic stress

Abiotic stress describes the impact of non-living factors such as drought, salinity, heat and toxic heavy metals. Genetic improvement and modified management of crops both have a role to play in dealing with abiotic stress.

3.3.2.1 Crop management strategies to mitigate the effects of abiotic stress

There are diverse crop management strategies to mitigate the effects of abiotic stress. Some of these strategies have been derived empirically. The use of seed mixtures has been trialled to increase the robustness of yield against environmental stresses (see Case study 3.3). For example, genotypes of beans selected for high capacity to acquire phosphorus often have shallow roots (Lynch 2007). This can cause problems for crops in water-scarce environments, where deep roots can be advantageous for water scavenging. Mixtures of genotypes can be planted to buffer the crop yield against combinations of stresses. In such mixtures, it is possible that shallow rooted genotypes may also benefit from the extraction of water by deep rooters in the community (Caldwell & Richards 1989). Development of these techniques requires an understanding of the different crop ideotypes that are helpful to combat different environmental stresses.

Turner (2004) has shown how wheat yields in Western Australia have increased by around 3-fold in 70 years, as rainfall has decreased. This has been achieved largely by changing the planting date of the crop to cover the ground while there is water available in the soil. This greatly reduces unproductive water loss via soil evaporation.

Other options which would not require major scientific advances for their initial implementation, where

Case study 3.3. Seed mixtures to increase robustness of yield under complex environmental stress

The architecture of plant root systems is important for the acquisition of resources and specific root structures are best adapted to particular abiotic stresses (Lynch 2007). Root structure can therefore be limiting to growth and yield in variable environments, as the plant will only be adapted to one particular set of conditions.

Root size, root placement and root length are determined by interactions between the plant's genotype and the environment in which it grows. Crop management techniques can be used to optimise these characteristics. In addition, production of root hairs and cortical air spaces can enhance root function. There is substantial genetic variation in all these variables and there is often a trade-off between different root morphologies (Ho *et al.* 2004). For example, water acquisition might be optimised at the expense of phosphorus acquisition. This can be a problem for plant improvement because plants are always impacted by complex stresses rather than by single environmental variables. For instance, soil drying will reduce both water and nutrient availability to roots.

Genotypes that result in a deep tap root are best adapted to drought-prone environments, particularly when the drought occurs late in the season when reproductive structures are developing. Genotypes that result in roots close to the surface of the soil scavenge effectively for immobile nutrients and are generally better adapted to low-phosphorus environments. Plant improvements to develop dimorphic root systems, with maintenance of adequate root biomass in both shallow and deep soil layers, appear to be helpful in environments where both water and phosphorus are co-limiting.

Where plant improvement is not possible and distribution of rainfall is erratic, sowing a mixture of seeds of varieties with shallow and deep root types might produce more stable crop yields. When soil water is in plentiful supply, plants having shallow roots would improve nutrient efficiency and probably also improve yield in low-phosphorus soils. When water supply is limiting, plants having deeper root systems would provide some tolerance to drought during growing seasons when a shallow rooted crop might otherwise not yield. The most appropriate mixture of root types for a particular geographic or climatic region might depend on soil fertility and the likelihood of drought (Beaver & Osorno 2009).

Additional source: Ho *et al.* (2005).

appropriate, include conservation agriculture, intercropping and agroforestry methods in which plants are protected from stress by other adjacent species. Intercropping is the practice of growing two or more crops in the same place at the same time. Particularly in the tropics, intercropping cereals with vegetables, and maintaining leguminous tree cover to provide shade, wood and mulch, could improve overall ecosystem performance (Gliessman 1998; Leakey *et al.* 2005; Scherr & McNeely 2008). Intercropping has potential in both industrialised and non-industrialised agriculture as a strategy to mitigate abiotic stress. It may also aid control of weeds, pests and diseases. These approaches are often based on traditional practice and with more research into interactions between plants they could be more widely adopted.

Regulated deficit irrigation regimes, in which plants are mildly stressed to activate stress tolerance mechanisms, increase water use efficiency of the plant (Davies *et al.* 2002). They can be combined with methods such as protected cropping and mulching the soil. There is an energy cost to this but in combination with deficit irrigation very high water use efficiencies can be achieved. Deficit irrigation can also be used as an effective tool for growth regulation, reducing vegetative growth in favour of reproductive development in fruit crops and thereby enhancing 'crop yield per drop of water' and crop quality (Loveys *et al.* 2002). In monocarpic cereals (which die after seeding), where a substantial proportion of grain yield can be derived from resources remobilised from the stem, grain yield can be substantially increased by deficit irrigation treatments after flowering. If plant death is delayed, for example by too much nitrogen in the soil, grain yields can be restricted by substantial accumulation of stem carbohydrates. These can be mobilised to the grains by mild soil drying.

In some instances there is good crop yield under drought provided that the transpiration rate is maintained or increased. However, there is always a risk of crop failure with this strategy if the drought conditions are extreme. Decreasing cumulative water loss (eg by reducing stomatal conductance, leaf growth or the length of the cropping cycle) to increase water use efficiency (biomass accumulation per unit of transpired water) is a more conservative strategy which generally results in yield restriction. Increasing water uptake from soils (while ensuring that water is available at critical developmental periods) can be a useful strategy, which is why phenotyping of root characteristics is receiving so much research attention.

Many crops around the world are now grown with protection against environmental extremes. This is commonly plastic film fashioned into a simple tunnel structure. This structure will often result in an increase in crop quality and can also greatly increase the water use efficiency. Recently, films with altered spectral properties have been used to modify plant morphology, fruit quality (Ordidge *et al.* 2009) and to improve pest and disease control. An advanced example of protected cropping to enhance resource use efficiency is the use of the seawater greenhouse (Seawater Greenhouse 2009). Here, solar energy is used to power seawater evaporators and then pump the resulting cool air through the greenhouse, which lets in photosynthetically useful light while reducing the infra-red heat load. This can reduce the air temperature by up to 15°C compared to the outside air temperature. At the other end of the greenhouse from the evaporators, the water vapour is condensed. Some of this fresh water is used to water the crops, while the rest can be used for cleaning the solar mirrors. The nutrients to grow the plants could come from local seaweed or even be extracted from the seawater itself.

It is likely that there could be great benefit from additional research into the science that underpins these various crop management strategies. Very few of the examples given above have benefited from the research tools referred to in 3.2.

3.3.2.2 Genetic improvement of tolerance or resistance to abiotic stress

Commercial and conventionally bred wheat genotypes with high water use efficiency and a yield increased by 10–15% are now available in Australia but this yield advantage is seen only in dry-land, low-yielding environments (Condon *et al.* 2002). In other examples drought tolerance was developed but was not found useful in the field. The drought tolerance was defined by survival under very severe stresses, but it did not provide any yield advantage under the stress conditions usually experienced in productive field situations. However, drought tolerance is a complex concept strongly dependent on the phenotyping methods used. It will be important to ensure that these methods identify the genotypes with yield advantage under the mild stress conditions usually experienced in commercial agriculture.

Several GM lines have been developed with drought and other stress tolerances, but they remain to be tested in the field. These include crops with over-expression of bacterial RNA chaperones (Castiglione *et al.* 2008), and NF-Y class transcriptional regulators (Nelson *et al.* 2007) in which drought tolerance is reported. RNA silencing to down-regulate poly ADP ribose polymerase (Vanderauwera *et al.* 2007), and over-expression of a cyanobacterial flavodoxin (Tognetti *et al.* 2006) may also increase tolerance to a whole range of stresses in plants. These approaches have been successful in controlled conditions and are undergoing regulatory approval. In addition, several targeted genetic approaches to salt tolerance involving GM have shown promise: these include modified expression of genes involved in the transport of Na+ (HKT) and those in the salt-overly sensitive (SOS) signal transduction pathway.

Genetic approaches may also be taken to overcoming aluminium toxicity. These may involve introduction of aluminium resistance genes encoding transporters of organic acids (OAs) such as citrate or malate (Delhaize *et al.* 2009; Liu *et al.* 2009; Ryan *et al.* 2009). In the rhizosphere, the released OAs form non-toxic complexes with Al^{3+} ions.

3.3.3 Biotic stresses including weeds, pests and diseases

Biotic stresses cause major losses to crops during cultivation periods and also during post-harvest storage. For that reason there has been intensive research into genetic and crop management strategies to mitigate these losses. In many respects this research into plant defence has been highly effective and there are many examples of current and emerging crop protection strategies, as described below. However, complete success is impossible because weeds, pests and pathogens can evolve so that they can overcome defence systems in plants or agricultural ecosystems.

3.3.3.1 Crop management strategies to mitigate the effects of biotic stress

Integrated pest management

Integrated pest management strategies may address multiple challenges and do not necessarily require genetic changes to the crop. In many instances they exploit natural defence systems and avoid the application of synthetic crop protection chemicals. For instance, the push-pull approach to *Striga* (witchweed) and stem borer infestation of maize involves intercropping with Desmodium and Napier grass (see Case study 3.4). Other integrated crop/pest management successes may be explainable through conceptually similar mechanisms or may involve pesticides/herbicides produced by the crop itself. More complete understanding of volatile and allelochemical secretions from plants would help the development of these approaches.

Other crop management strategies

Other crop management strategies may also help control pests and diseases. These approaches include use of biological control agents such as sterile insects that displace fertile members of the pest population, and cultivation methods including rotations and physical barriers to pests and diseases such as traps and screens. Pest and disease forecasting based on environment-driven models enable more effective and efficient timing of control measures. Thresholds can be established based on monitoring crops to determine whether intervention is necessary—monitoring systems can be very sophisticated based on semiochemicals or potentially automated assessment of air-borne spores or volatiles.

Crop protection chemicals

Chemicals are used widely to protect against weeds, pests and diseases. These compounds are the mainstay of global crop protection and they are likely to remain so for the foreseeable future. However, they increase the likelihood of

Case study 3.4. Integrated pest management: push-pull systems (vuta sukuma)[6] in East Africa

Maize pests in East Africa

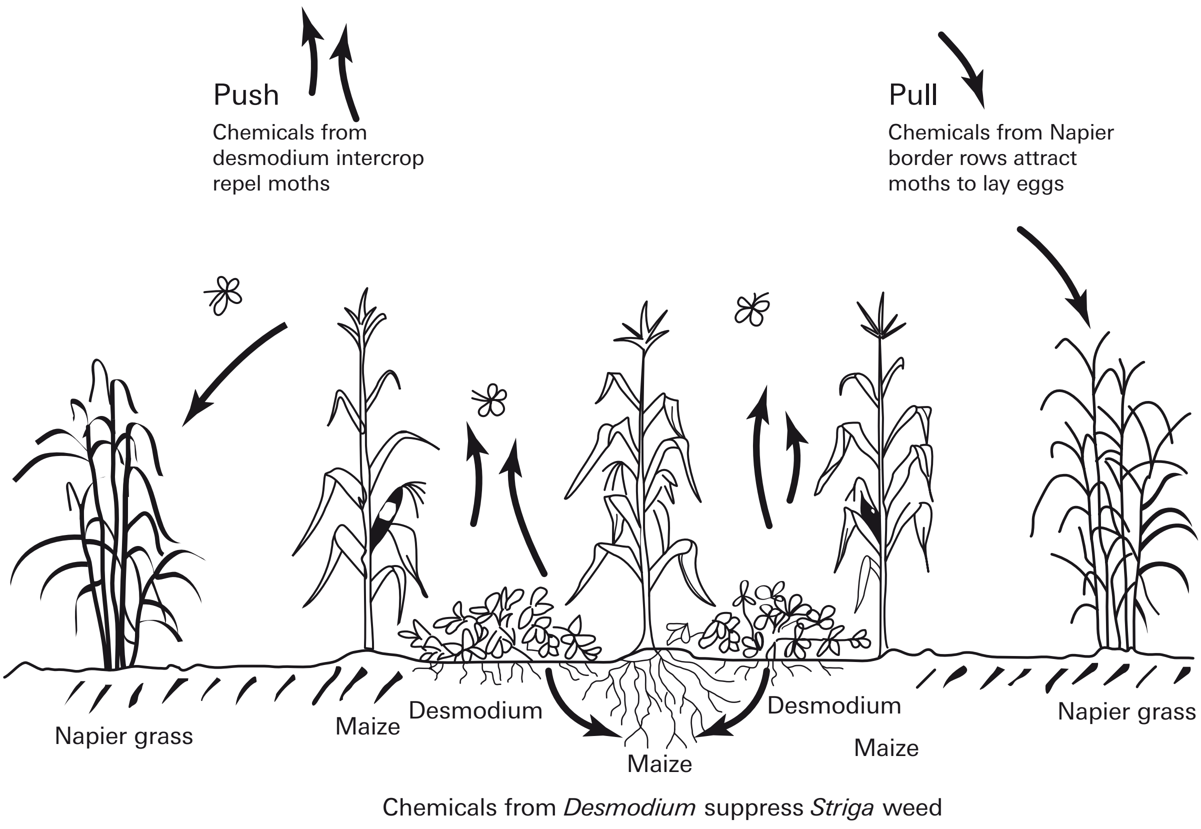
Maize is an important crop in East Africa for food security and cash income for farmers. The maize stalk borer (*Busseola fusca*) and spotted stem borer (*Chilo partellus*) are major pests. The larvae of these moths can cause yield losses of 30–40% (Amudavi *et al.* 2007; Hassanali *et al.* 2008). A further constraint is the parasitic weed *Striga hermonthica* (witchweed) which causes a loss of 30–50% to Africa's agricultural economy on 40% of its arable land (Amudavi *et al.* 2007).

Push-pull system

A 'push-pull' system for integrated pest management in maize crops has been developed by the International Centre for Insect Physiology and Ecology (Kenya) and Rothamsted research (Cook *et al.* 2007; Hassanali *et al.* 2008). This system combines knowledge of agro-biodiversity and the chemical ecology of these stem borers with *Striga* management, and is summarised in the diagram below. Different components of the system are designed to *push* away pests and to *pull* in their natural enemies.

The maize field is first surrounded by a border of the forage grass *Pennisetum purpureum* (Napier grass). Napier grass is more attractive to the moths than maize for laying their eggs (the 'pull' (*vuta*) aspect). The Napier grass produces a gum-like substance which kills the pest when the stem borer larvae enter the stem. Napier grass thus helps to eliminate the stem borer in addition to attracting it away from the maize.

In addition, rows of maize are intercropped with rows of the forage legume silverleaf (*Desmodium uncinatum*). *Desmodium* releases semiochemicals which repel the stem borer moths away from the maize (the 'push' (*sukuma*) aspect). An alternative repellent intercrop is molasses grass (*Melinis miniutiflora*) which also produces semiochemicals that attract natural enemies of the stem borer moth (Whitfield 2001). *Desmodium* has the additional benefit of fixing atmospheric nitrogen, thereby contributing to crop nutrition. Remarkably, *Desmodium* has also been found to be toxic to *Striga*, so has an additional crop protection benefit. Finally, the ground cover provided by *Desmodium* helps with soil and water conservation.



Source: *The Gatsby Charitable Foundation, The Quiet Revolution: Push-Pull Technology and the African Farmer*

Results and uptake

Push-pull has increased yields of farmers in areas of Kenya where stem borer and *Striga* are prevalent by more than 100% (Amudavi *et al.* 2007). It has been adopted by more than 10,000 farmers in Kenya, Uganda and Tanzania

6 This system is sometimes referred to by an alternative Swahili spelling: *vutu sukumu*.

(Amudavi *et al.* 2007). Promotion of the push-pull strategy has taken place through the public extension system, NGOs, the private sector, mass media (including radio shows and printed media), and farmer field schools. Push-pull systems are of relatively low cost as they do not require as many purchased inputs compared to the application of pesticides. They illustrate the hybrid nature of the science—both work on elements of the cropping system and their agroecological interactions.

What next?

One of the limits to the uptake of push-pull has been the availability of *Desmodium* seed. This will need to be addressed if uptake is to be increased. Work is being undertaken to further understand and increase the performance of all push-pull components (for instance, through research into pests and diseases of the companion crops). Development of push-pull strategies for crops other than maize is another goal.

Additional sources: Amudavi *et al.* (2008); Khan *et al.* (2008a, b & c).

resistant organisms, so careful management is required to prolong their useful life. Population genetics can contribute to good practice. In addition there is a potential hazard because most current crop protection chemicals are fungicides or insecticides. They are toxic for the pest or pathogen and there is always a risk, as with DDT (dichloro-diphenyl-trichloroethane), that non-target organisms will also be affected.

Chemical science for the development of new crop protection chemicals is largely outside the scope of this report. However, there is potential for a novel class of crop protection chemicals that are fundamentally different from those most widely used at present. The novel compounds would resemble chemicals present in plants that activate or prime natural resistance mechanisms and, because they do not target pests and pathogens directly, they could have environmental advantages over currently used compounds (van Hulten *et al.* 2006; Beckers & Conrath 2007). β-Aminobutyric acid, for example, is a naturally occurring compound that primes defence mechanisms to be activated more rapidly and to a higher level by pathogens. Naturally occurring salicylic acid and derivatives induce disease resistance mechanisms in plants in the absence of pathogens so that the treated plant is resistant. Similarly jasmonic acid treatment of seedlings has also been reported to 'prime' disease and pest resistance.

In one application a plant-derived primer of defence is applied to seeds (World Intellectual Property Organisation, Patent Application WO 2008/00710). The plants developing from these seeds are reported to have a persistent defence against insect pests with the outlook that long-lived protection can be achieved without the need to apply chemicals in the field. This property would have significant benefits to farmers and the environment and subject to development tests there is the prospect that these primer compounds could be introduced within a 5–10 year period.

The use of high throughput analysis of small molecules (Section 3.2.2.2) in plants will lead to the identification of other novel chemicals involved in disease resistance pathways in crops and may allow the development of additional crop protection chemicals targeted at the plant rather than the pest over a 10 year period or greater.

Herbicides

Herbicides are a special case among crop protection chemicals because the weedy target and the protected crop are both plants; the challenge is to kill the weed but not kill the crop. Some herbicides damage cereals and other grasses less than broad leaved (dicotyledonous) plants. However, GM and conventional breeding approaches enable the creation of crops that resist broad spectrum herbicides such as glyphosate (which targets the shikimic acid pathway), Basta/bialophos (which targets glutamine synthase), the sulphonylureas and imidazolinones (which target acetohydroxyacid synthase) and 2,4-D (an auxin mimic) (Duke 2004). The benefits of these herbicide-resistant crops are potentially limited by the evolution of weeds that resist the herbicide. It is clear, for example, that extensive use of glyphosate in North America has led to glyphosate-resistant weeds (Duke 2004), and consequently the use of glyphosate will need to be combined with other herbicides for effective weed control. However, it should be noted that herbicide tolerance in weeds will evolve irrespective of whether the herbicide is applied to herbicide-resistant crops or as part of a conventional weed control strategy (Beckie 2006).

In sorghum crops, the treatment of seeds of herbicide-tolerant hybrids has been found to be effective at tackling infestations of the weed *Striga* (Tuinstra *et al.* 2009). Similarly, CIMMYT, in collaboration with the Weizmann Institute of Science (Israel), with funding from the Rockefeller Foundation, has developed a unique product for *Striga* control in maize. It combines low-dose herbicide seed coating applied to herbicide-resistant maize seed that can leave a field virtually clear of emerging *Striga* blooms throughout the season (Kanampiu *et al.* 2003; De Groote *et al.* 2008). This imidazolinone-resistant maize was produced by artificial selection rather than GM methods. Conventional breeding approaches also show promise (IITA 2008).

Control of weeds in conventional cropping systems is achieved by tillage combined with herbicide application. However, the use of herbicide-resistant plants provides good weed control with little or no tillage and so a secondary benefit from the use of these crops has been the spread of reduced tillage systems in which soil erosion is reduced (Duke 2004; Beckie *et al.* 2006). The use of herbicide-resistant crops—either GM or conventionally bred—is an approach available now for major crops and it could be introduced for others in the near future.

3.3.3.2 Genetic protection against weeds, pests and diseases

Disease resistance in plants: R genes

A classic approach to control of diseases in plants is based on disease resistance (R) genes that are typically present in some but not all cultivars of a crop species and its wild relatives. Transfer of these genes by crosses between resistant and susceptible cultivars has been successful but is a lengthy process and may be associated with a yield penalty due to linkage of the desired gene to genes that confer deleterious traits. This breeding approach can now be greatly accelerated through the use of MAS (see Section 3.2.1.2). As an alternative, the cloned R gene can be transferred between cultivars or species using GM (see reference to cisgenic approaches in Section 3.2.1.3).

Two topical examples of disease resistance problems involve late blight in potato and stem rust in wheat. Potato yields are threatened by the emergence of new strains of late blight (Song *et al.* 2003; Fry 2008) but fortunately there has been considerable effort to identify and clone new genetic sources of resistance from wild potato relatives (Song *et al.* 2003). Extension of this approach will allow a rich diversity of cloned late blight R genes to be deployed in various GM combinations to maximise durability of resistance.

Similarly, in wheat there is a pressing need to develop resistance against a new highly virulent strain of stem rust (Ug99) that is spreading from east Africa (Case study 3.5). There are a few cultivars, but many wild wheat relatives carry R genes providing resistance to Ug99 and, once isolated, these R genes could be transferred easily into a range of wheat cultivars using GM.

There are many other examples of diseases in crops that could be controlled by R genes transferred by MAS (Section 3.2.1.2). There is the possibility that research projects initiated in 2009 could be translated into useful field resistance within 10 years. Both GM and MAS approaches would be greatly accelerated by more extensive crop genome sequences. However, irrespective of whether the approach is conventional or GM, there is a need to manage the use of resistant varieties so that resistant breaking pests and pathogens are not selected for the field.

Control of pests and disease using defence pathway genes

Other genetic approaches to the control of invertebrate pests also involve the transfer of plant genes between plants. However, unlike R genes which are involved in the recognition of pathogens, the transferred genes encode proteins responsible for the production of defence compounds (such as alkaloids, cyanogenic glycosides and glucosinolates). Sorghum, for example, makes a cyanogenic glycoside called dhurrin. The entire pathway for dhurrin biosynthesis from tyrosine, via two cytochromes P450 and a glucosyl transferase, has been transferred from sorghum to *Arabidopsis*, where it confers enhanced resistance to the flea beetle *Phyllotreta nemorum* (Tattersall *et al.* 2001; Kristensen *et al.* 2005).

Case study 3.5. Breeding for resistance: UG99

Stem rust in wheat crops

Stem rust is a fungal disease which produces blister-like pustules on cereal crops including wheat, and can cause substantial (50–70%) losses. A new race of stem rust, UG99, was identified in Uganda in 1998. UG99 spread in 2006 to Yemen and Sudan, has now reached Iran, and is predicted to spread towards North Africa, the Middle East and West South Asia where large areas of susceptible wheat varieties are grown under conditions favourable to the fungus. There are fears of a global epidemic. Some wheat strains were initially resistant to UG99, but new variants of UG99 have since arisen that cause stem rust on these previously resistant varieties.

Types of rust resistance

There are two types of resistance: race-specific resistance and adult plant resistance (APR). Race-specific resistance results from a single resistance gene that recognises a specific gene in the stem rust fungus. A mutation that enables the stem rust fungus to overcome this resistance gene will result in renewed susceptibility to the disease. APR depends on several different genes and therefore a mutation in the rust enabling it to overcome APR is less likely. However, this type of resistance is usually more prominent in mature plants than in young seedlings. Two APR genes have recently been isolated (Fu *et al.* 2009; Krattinger *et al.* 2009). It has been proposed that APR varieties of wheat could be planted in primary risk areas for UG99, with combinations of race-resistant varieties planted in secondary risk regions (Singh *et al.* 2008).

Current status

Since 2005, led by CIMMYT, wheat varieties and land races from 22 countries and international centres were screened in Kenya and Ethiopia to look for additional sources of UG99 resistance. Forty-six different stem resistance genes have been catalogued, but the majority of these confer race-specific resistance. Some high yielding wheat varieties with durable resistance have been developed, and the next step is to ensure that these varieties are readily available in susceptible regions. The migration of UG99 is being carefully monitored (CIMMYT 2009).

It would be necessary to confirm that the newly produced compounds did not affect the palatability or safety of the food products from the engineered crops. However, as the dhurrin pathway in this example is transferred from a crop plant (sorghum), there is no reason in principle why the approach would be incompatible with safe food and it could be used to transfer insect resistance in, for example, potato leaves. The example also establishes the principle that complete metabolic pathways can be transferred between plants using gene technology without having complex secondary effects (Kristensen *et al.* 2005).

Artificial resistance mechanisms

One of the most successful GM approaches to disease resistance, particularly to plant viruses, involves a concept known as parasite-derived resistance. A gene from a pathogen or parasite is introduced either intact or as a fragment into the genome of a host organism in the expectation that its RNA or protein product would interfere with the parasite such that the transformed plant would be resistant (Fuchs & Gonsalves 2007). Parasite-derived resistance can operate through RNA- or protein-based mechanisms and probably the best established examples involve resistance against viruses. Parasite-derived resistance in GM papaya against papaya ring spot virus is used very successfully in Hawaii and could be employed in many other examples.

RNA-based, parasite-derived resistance against nematodes and herbivorous insects is starting to be tested (Huang *et al.* 2006; McCarter 2009). The initial results indicate that in the longer term (10 years or more) this approach could underpin useful technologies for crop protection against pests and pathogens other than viruses.

Another approach allows control of invertebrate pests with plants that are engineered to make insecticidal proteins. One of the most successful applications of GM technology involves crops engineered to make the insecticidal protein from *Bt* (Gould 1998; O'Callaghan *et al.* 2005). These plants show elevated resistance to insects such as corn borer, corn rootworm and cotton boll weevil and, due to careful management with refugia as discussed in Section 3.3.3.2 (*The need to manage disease resistance*) (Gould 1998), there are only a few indications of insects evolving to overcome the resistance in the field. The *Bt* approach has been or could be used to protect maize, cotton, potato, brassicas and other plants against various pests and it may even be effective against nematodes (Wei *et al.* 2003). The use of GM *Bt* crops has resulted in substantial reductions in the application of insecticides that are toxic to non-target insects and farmers (Qaim 2009). The next generation of *Bt* maize lines are designed to express six different *Bt* genes giving resistance to a range of pests.

Bt crops were planted on 46 million ha in 2008 (ISAAA 2008). Warning signs that target insects may evolve the ability to overcome the resistance in glasshouse and field conditions (Tabashnik 2008; Tabashnik *et al.* 2009) and the sustainability of this approach may require that it is used as part of integrated pest management (Section 3.3.3.1—*Integrated pest management*) rather than in blanket monocultures.

Genetic control of post-harvest losses

Major losses of crops occur after harvest, during storage or transit. Such losses are currently estimated at 20% (Pimentel 2002). In some instances post-harvest losses can be reduced by improved storage, drying and processing. Solutions may be related to engineering and material science (Bindraban & Rabbinge 2004). However, storage potential of food crop products to extend the period of availability and minimise losses in store is an important trait which may be enhanced through biological mechanisms. There is scope in some instances for pre- and post-harvest crop losses to be mitigated by genetic improvement. In some respects this topic is an extension of pest and disease resistance because the damage to the harvested crop is often caused by insects or fungi. The solutions, therefore, overlap with approaches to prevent pest and pathogen attack and include the use of pesticides or pest-resistant varieties of crop.

However, there are additional approaches that are specific to post-harvest storage. A famous example involves ripening-resistant tomatoes in which softening of cell walls during ripening is suppressed (Brummell & Harpster 2001). These fruit can be harvested when ripe and do not spoil rapidly during storage. A higher proportion of these fruit can be harvested using mechanical devices than with conventional varieties and the post-harvest losses are reduced. This outcome can be achieved by both breeding and GM approaches and one of the first generation of GM crops included tomato in which ripening-related polygacturonase was suppressed. It is likely that similar improvements could be obtained with a variety of soft and perishable fruits although additional research may be needed to identify the relevant target enzymes (Matas *et al.* 2009).

Longer term genetic strategies

Plants protect themselves against disease via multiple defence mechanisms. Most plant species are completely resistant to the pathogens that are specialised to infect other plants ('non-host resistance'—NHR). For example, rice is resistant to cereal rusts, and tobacco is resistant to potato late blight. Understanding the molecular basis for NHR could enable more durable resistance to be engineered into crops. It might be possible, for example, to transfer NHR genes between species using GM and there has been good recent progress towards identification of the relevant genes (Lipka *et al.* 2005; Jones & Dangl 2006).

A second genetic approach to NHR is based on genomic studies of plant pathogens. From this work various pathogen-derived molecules ('effectors') that suppress host defences have been identified (Ellis *et al.* 2009). Better understanding of effectors may enable modification of their host targets to reduce susceptibility, and may also help prioritise R genes that recognise the most indispensable effectors; such R genes will be more difficult for the pathogen to overcome. It might be possible, for example, to identify genes conferring quantitatively expressed or partial resistance genes in the host that could be involved in interactions with these effectors. Such partial resistance genes may be more durable in the field than the R genes (Section 3.3.3.2 – *Disease resistance in plants: R genes*) deployed in conventional resistance strategies (Leach *et al.* 2001). Stacking of such genes via MAS could accelerate the production of cultivars carrying multiple partial resistance genes and, once the genes have been defined, assist introgression via cisgenic GM methods. However, with approaches based on either host factors or the effectors of the pathogen, there is still considerable additional work to be done and it is likely that it will take 10–20 years before these scientific studies could be translated into technologies that are useful in the field.

The need to manage disease resistance

Even when genetic pest and disease resistance is available it should be managed carefully to prevent selection of resistance-breaking strains of the pest or pathogen. Various strategies are available, including the use of refugia, in which a reservoir of susceptible plants allows the pest to survive without selection for resistance-breaking strains. This approach has been successful with insect-resistant plants (Gould 1998) but depends upon the requirement for sexual reproduction in the pest species and it would not be applicable to pathogens and pests that multiply asexually. A second crop management strategy involves the use of mixed seed in which the different genotypes carry variant resistance genes. Such strategies would be expected, based on theoretical considerations discussed by Jones and Dangl (2006), to confer more durable disease resistance than single gene resistance in unmixed seed and this prediction is supported by observation (Finckh *et al.* 2000).

The use of seed mixtures could be introduced in the short term with certain major crops but unfortunately the utility of this concept has not been widely investigated and the mechanisms associated with resistance in mixtures is not well understood. Disease resistance strategies including GM and conventionally bred crops would therefore benefit in the medium and long term from further investigation of resistance in mixed populations of field-grown crops.

3.3.4 Mineral nutrition of crops

Nutrient uptake efficiency can be a major limiting factor in crop yield. An understanding of soils and soil microflora is particularly important for the development of enhanced nutrient uptake efficiency. In addition, it will be possible to breed or engineer cultivars with an enhanced capacity to take up nutrients through modifications of the root system. The examples given below refer primarily to phosphorus (P) uptake but similar considerations apply to nitrogen (N), potassium (K) and micronutrients.

3.3.4.1 Crop management for improved uptake of mineral nutrients

McCully (1995) and others have called for the study of 'real root systems', including the microorganisms in the zone surrounding the plant roots which can have both beneficial and damaging effects on plant growth and development. Some of these associations, for instance mycorrhizae (symbiotic associations between a fungus and plant roots), have been much studied while other less-studied plant–microbe interactions may allow some scope for enhanced crop performance, particularly under environmental stress (Belimov *et al.* 2009).

Mycorrhizae are particularly important because most plant species acquire P via mycorrhizal symbioses: of the various types of mycorrhizal symbiosis, the arbuscular mycorrhiza (AM), formed with fungi in the phylum Glomeromycota, is most relevant to agriculture. Some have concluded that future agriculture will certainly involve an explicit role for AM fungi, either by cultural practices that favour the persistence of the mycelium in soil (eg reduced cultivation) or by direct modification of the fungal community (Leigh *et al.* 2009).

In addition, genetic variation in rhizosphere modification through the efflux of protons, organic acids and enzymes is important for the mobilisation of nutrients such as phosphorus and transition metals, and the avoidance of aluminium toxicity.

There is a need for predicting the performance of particular plant–fungus combinations in a range of environmental conditions and methods of manipulating (by appropriate cultural practices) the fungal community so as to promote the most effective fungi. Fundamentally, this means improving biological understanding of AM fungi. In the absence of P inputs to agricultural soils, ignoring the contribution of mycorrhizal fungi would be unwise.

3.3.4.2 Genetic improvement for improved mineral nutrition of crops

Since the main problem in P acquisition is the slow rate of diffusion through soil, one solution is to have a more widely dispersed root system. (Similar considerations apply to root scavenging for water.) Cultivars that have shallow angles of branching of the main lateral roots concentrate more root growth in relatively P-rich surface layers. There has been good progress towards understanding the genetic basis of variation in root system architecture (Lynch 2007). There is also good understanding of the functional relationships and trade-offs associated with the costs of the developed root system and the benefits of P acquisition. Variation in the length and density of root hairs is important for the acquisition of immobile nutrients such as phosphorus and potassium. Genetic variation in root cortical aerenchyma formation and secondary development ('root etiolation') are important in reducing the metabolic costs of root growth and soil exploration (Lynch 2007).

Lynch has argued that genetic variation in these traits is associated with substantial yield gains in low-fertility soils and that crop genotypes with greater yield in infertile soils will substantially improve the productivity and sustainability of low-input agroecosystems (Lynch 2007). In high-input agroecosystems, these traits will reduce the environmental impacts of intensive fertilisation.

Engineering of nitrogen fixation into non-legume crops has been a long-standing target of biotechnologists. Three approaches have been envisioned. The first involves modification of crop plants so that they support symbiosis with a nitrogen-fixing bacterium or blue-green alga. The second approach involves transfer of bacterial nitrogenase genes into the chloroplasts of crop plants. These approaches are both still long term, there is little research activity in this area and it is unlikely that they could be harnessed to develop a nitrogen fixing crop within the next 15 years. A third approach is to move the plant genes required for production of a symbiotic nitrogen-fixing nodule from leguminous plants to others that cannot currently support such a symbiosis. As the plant genes required for nodule development become better understood, this prospect now appears less fanciful, but is still at least 10 years away (Markmann & Parniske 2009).

3.3.5 Soils

Intensive cultivation of soils damages soil structure and leads to overuse of groundwater resources. Soils become cracked, and seedbed preparation increasingly requires frequent ploughing. This damage both increases costs and reduces yield. Zero-till systems of production have been developed to address these problems. This requires a new generation of cheap and affordable machinery. Zero-till sites have reported increased yield, as well as evidence of reduced greenhouse gas emissions, fewer weeds, more beneficial insects and improved water use efficiency (Hobbs *et al.* 2008; see also Case study 3.6).

Double digging is a method of deep soil preparation which can be used to improve soil fertility and structure. The idea of double dug beds is being widely promoted by local NGOs in Kenya. Double dug beds are combined with composts and animal manures to improve the soil. A considerable initial investment in labour is required, but the better water-holding capacity and higher organic matter mean that they are able to sustain vegetable growth long into the dry season. Once the investment is made, little more has to be done for the next two to three years. Many vegetable and fruit crops can be cultivated, including kales, onions, tomatoes, cabbage, passion fruit, pigeon peas, spinach, peppers, green beans and soya. The use of double dug beds in Kenya has improved food security. In particular, the health of children has improved through increased vegetable consumption and longer periods of available food (Pretty *et al.* 2003).

Biochar (charcoal) addition to soils is an ancient practice which has recently begun to assume wider significance. As a by-product of the pyrolysis of plant-derived biomass (for energy generation without releasing carbon), incorporation of biochar represents a means of sequestering carbon (due to its long half-life in soil) and there is increasing evidence that it can also reduce nutrient leaching and impact on the slow release of nutrients to enhance crop yields (Marris 2006).

Case study 3.6. Conservation agriculture in Burkina Faso, West Africa

The predominant ecosystem type in southwest Burkina Faso is moist savannah with tropical grassland and widely spaced trees. This region is sometimes referred to as a potential breadbasket for Africa due to its high crop and livestock productivity potential. However, productivity is currently low across much of the region due to poor soil nutrient fertility, variable rainfall and inadequate biomass availability. Farmers usually grow a range of subsistence crops—mainly maize, pearl millet, sorghum, groundnut and cowpea.

Over 20 million ha of savannah land (with similar agroecology to Burkina Faso) have been sustainably intensified and diversified in Brazil using conservation agriculture principles. From 2002 to 2007, an FAO conservation agriculture pilot study was carried out in five communities in Burkina Faso, with the following aims:

- to expand crop choices to increase production of livestock feed;
- to improve soil-crop-water management for sustainable production intensification; and
- to diversify and expand the range of food, feed and tree crops and their integration with livestock into the existing cotton- and maize-based systems.

What is conservation agriculture?

Conservation agriculture is resource-saving agricultural crop production that aims to deliver high and sustained production levels while conserving the environment. Interventions such as mechanical soil tillage are minimised (or eliminated), and external inputs such as agrochemicals are applied in a manner which minimises any disruption to biological processes. The key features of conservation agriculture are:

- Minimum mechanical soil disturbance.

Crops are planted directly into the soil. In conventional agriculture, soil tillage leads in the long term to reduction in soil organic matter which in turn leads to soil erosion.

- Permanent organic soil cover.

This provides nutrients for crops and maintains soil structure. Cover can be provided either by crop residues or a cover crop such as *Mucuna*, which prevents the loss of topsoil, suppresses weeds and fixes nitrogen.

- Diversified crop rotations (in annual crops) or crop associations (in perennial crops).

Adoption in Burkina Faso

The FAO and Institut National pour de l'Environnement et de Recherches Agricoles (INERA) funded a 5-year farmer participatory project to test and select technologies aimed at overcoming the limitations of the current cotton and maize based crop-livestock production systems. This took place at five pilot locations in southwest Burkina Faso, and involved the following components:

- minimum till;
- crop rotation;
- crop cover management;
- farmer field schools for integrated production and pest management.

Land was prepared using animal-drawn trampling knife rollers, which minimised disturbance to the soil, and flattened vegetation and residues. Direct seeding then took place by hand using Brazilian-made jab planters and animal-drawn seed disc drills. This minimised soil disturbance during seeding and achieved efficient plant spacing. The range of crops in the cropping system was extended. New cereal–legume associations were introduced. Improved cereals were used and legumes provided additional benefits: soya beans for vegetable oil and *mucuna* for ground cover. *Brachiaria* and species of local grasses were also grown for the production of silage for livestock, to increase soil organic matter and to provide surface protection. Cassava was introduced as a new crop for both food and feed. Living fences of fodder trees such as *Acacia* and *Ziziphus* were also planted around the sites to protect crops and residues from livestock during the dry season. As well as providing a 'living fence', using trees in this way can also provide erosion control, biofuels and fruit.

Results

The technologies introduced through the pilot project have resulted in substantial increases in agricultural production, thereby increasing food security and farmer income. The increased livestock feed availability during the dry season has helped smallholders enhance their income from livestock products, while also improving soil moisture supply and soil health. Conservation agriculture technologies for crop diversification and crop intensification are now ready for scaling up and further adaptation.

Source: FAO (2009a, b); Kassam *et al.* (2009).

3.3.5.1 Perennial crops

The conversion of annual crops into perennial plants could help sustain the health of cultivated soils. Perennials make up most of the world's natural terrestrial biomass. In contrast, grain and oilseed crops that are the foundation of the human diet are normally grown as annual crops. To date there are no perennial species that produce adequate grain harvests. However, there are breeding programs aimed at developing perennial grain crops in wheat, sorghum, sunflower, intermediate wheatgrass and other species (Cox *et al.* 2006). Perennial crops would store more carbon, maintain better soil and water quality and would be consistent with minimum till practice. These crops would also manage nutrients more conservatively than conventional annual crops, and they would have greater biomass and resource management capacity. Given adequate support these efforts could lead to the development of perennial crops within 10 years (Cox *et al.* 2006).

Other approaches to perenniality involving GM and based on an ability to regulate the transition from vegetative to floral meristems in plants could be developed in the 10–15 year period and would be based on recent progress towards understanding the genes that influence perenniality (Wang *et al.* 2009a). The widespread use of herbicide-resistant crops allows good weed control without tillage and so promotes the health of cultivated soils (Cook 2006).

3.3.6 Nutritional quality

It is generally accepted that diversity is the preferred approach to a balanced diet. However, when a diverse diet or supplements are not available, both genetic and non-genetic approaches can be used to enhance the nutritional content of a stable crop and avoid 'hidden hunger' due to shortage of micronutrients. The preferred strategy to eliminate hidden hunger will always involve strategies to increase the diversity of diet with increased access to fruit and vegetables. However, in regions where the lack of infrastructure or other factors prevents diversification of the diet, the introduction of biofortified varieties may provide a good short-term solution. The advantage of a biofortification approach is that it capitalises on a regular intake of a staple food that will be consumed over a long period even in the absence of international development agencies. The requirement for a one-off investment to develop the appropriate seeds is also a consideration (Nestel *et al.* 2006). The importance of nutritional content and the dietary contribution of food crops to achieve nutritional security, especially vitamin A, zinc and iron, is widely recognised (Copenhagen Consensus 2008). However, the importance of palatability to the consumer must not be ignored. Nutritional quality can also be enhanced by the removal of toxic components through crop management and by genetic enhancement.

3.3.6.1 Crop management to enhance nutritional quality

There are several methods by which the nutritional content of the harvested crop can be improved through targeted management and particularly by the use of fertilisers containing trace elements. These include production systems to improve grain quality and nutritional value. There has been an increased focus on agronomic biofortification within the international fertiliser industry (White & Broadley 2005; Bruulsema *et al.* 2008). Whole crop management systems exist to improve quality, health and nutrition, for instance in cassava (Nassar 2006). However, the full potential of these approaches requires further research into the processes through which the nutrient content of crops can be influenced by fertiliser applications.

Mild drought stresses have been shown to result in enhanced flavour and aroma in some food crops (Santos *et al.* 2007) in addition to enhanced concentration of health related metabolites (such as ascorbic acid and other antioxidants).

3.3.6.2 Genetic improvement of crops to enhance nutritional quality in regions with diet deficiency

Golden rice is a transgenic line that could help to combat vitamin A deficiency (Dawe *et al.* 2002). The first generation of Golden rice varieties contained only low levels of β-carotene and there was some scepticism as to whether their introduction would mitigate vitamin A deficiency and benefit poor, rice-dependent households. However, there are now lines with much higher levels of β-carotene (Paine *et al.* 2005) and good evidence from clinical trials that it is an effective source of vitamin A (Tang *et al.* 2009).

A trial of orange-fleshed sweet potato in Mozambique also illustrates how vitamin A deficiency can be mitigated by supplies of biofortified staple crops (see Case study 3.7). Genetic improvement of cassava can enhance nutritional quality (protein, carotenoids and minerals) using wild relatives.[7] The HarvestPlus programme (see also Case study 3.7) is working to improve the nutritional quality of maize and rice. Recently, rice plants have been engineered with elevated iron levels in the rice kernels (Wirth *et al.* 2009).

Case study 3.7. Biofortification of orange-fleshed sweet potatoes for combating vitamin A deficiency

Vitamin A deficiency

Vitamin A is needed for good eyesight, and extreme deficiency leads to blindness. It is estimated that worldwide, 250,000 preschool children go blind due to vitamin A deficiency every year (Bouis 2008). One method of combating micronutrient deficiency is through the use of supplements or fortified foods. However, this is not an option for the rural poor, who may live too far from the nearest market and cannot afford to buy these products. An alternative method of enhancing Vitamin A in the diet is through biofortification. This involves breeding staple crops which have high levels of micronutrients.

How is it done?

The micronutrient content of staple foods can be increased through conventional breeding where adequate germplasm variation is available. The HarvestPlus programme is working towards producing sweet potato lines with high levels of the vitamin A precursor β-carotene. The target level of β-carotene depends on the levels available to the consumer following cooking and digestion, and whether the sweet potato will be the sole source of vitamin A in the diet. Studies have shown that feeding β-carotene-rich sweet potato to school children increases their vitamin A stores in the liver (van Jaarsveld *et al.* 2005). Orange-fleshed sweet potato lines with high levels of the vitamin A precursor β-carotene have been identified.

Micronutrient-dense traits are generally stable across all environments, which makes it easier to share germplasm internationally. Furthermore, micronutrient traits can be combined with traits for high yield.

7 'Decades of cassava research bear fruit.' Available online at: http://www.idrc.ca/en/ev-5615-201-1-DO_TOPIC.html.

Cost

Costs of developing biofortified sweet potatoes are largely associated with the initial research and development of biofortified varieties, after which costs are low. An international system is already in place to develop modern varieties of staple foods (including sweet potato) and so the key cost component lies in enhancing the micronutrient.

Uptake

Sweet potato is used because this is already a locally consumed food. These modified sweet potatoes have a slightly different colour and flavour from conventionally grown varieties. However, women farmers in Africa have been willing to try growing them and feeding them to their children. Once seeds have been made available to farmers, the seed from that harvest can be saved to re-plant in subsequent years, which makes it a cheap and sustainable system for the farmers. Therefore, after the initial cost of developing the biofortified seed the costs are low.

What next?

Further research is needed to determine how uptake of the biofortified crop might be increased.

Additional sources: Nestal *et al.* (2006); Tanumihardjo (2008).

3.3.6.3 Genetic improvement of crops to enhance nutritional quality in regions with varied diets

There are proposed genetic improvements of plants with claims of enhanced nutritional content for use in industrialised countries. These include GM soya bean and oilseed rape with near-zero trans-fat potential and high concentrations of long-chain omega-3 and omega-6 fatty acids (Kinney 2006). Fruit and vegetables have also been developed with high levels of cancer protecting compounds, such as flavonoids in the purple tomato (Butelli *et al.* 2008).

3.3.6.4 The use of lost and orphan crops for improved nutrition

Many 'lost crops' with high nutritional value exist and have potential for domestication (National Academies 2008). It should not be difficult to select nut and fruit species with desirable attributes for different needs. Removing or inactivating pathways producing compounds that are toxic to humans could enable plants that are productive in poor, drought-prone areas to be grown as valuable crops. Improvement of minor (orphan) crops is necessary to ensure dietary diversity and the provision of particular plant-derived raw materials. It may also be possible to engineer the removal of toxic metabolites from plants that could crop well in hostile environments. However, it could be argued that in light of the urgency of potential food shortages, the domestication of orphan crops should not be a priority.

3.3.6.5 Toxins and toxic elements

Fungi producing mycotoxins that are damaging to human health infest sites of insect damage in cereal grains. Reduced levels of mycotoxins can be achieved, therefore, through the use of *Bt* maize produced by GM (Section 3.3.3.2—*Artificial resistance mechanisms*) (Bakan *et al.* 2002). The Sterile Insect Technique (SIT) is a proven species-specific technology that uses sterile insects to interfere with the breeding dynamics of selected insect pests (Dyck *et al.* 2005). This may be useful for maintaining low levels of mycotoxins and for control of other aspects of post-harvest quality. Like the *Bt* crops, it could be considered as a science-based approach available for use in the short term.

Other sources of food toxicity in some areas of Asia derive from the contamination of crops grown in soils polluted by arsenic, cadmium and mercury. This is a major problem that could be resolved through breeding and GM technologies targeted to the genes involved in toxic element accumulation. However, these genes have yet to be identified and this approach would have to be considered as long term, over a period of 10 years or more. Phytoremediation might also be useful in these situations, involving GM or other plants that have the ability to sequester toxic compounds from the soil (Salt *et al.* 1998; Zhao & McGrath 2009).

Toxins may also be produced in the plant. In cassava, for example, cyanogenic glycosides render many varieties toxic, necessitating extensive food processing prior to safe consumption. GM or marker-assisted breeding approaches could reduce levels of such toxins (Siritunga & Sayre 2003), though a less toxic (to humans) cassava might also be more susceptible to pests.

3.3.6.6 Animal food quality

There is scope for improving the quality of crops for animal foods as with human foods. However, there are also some specialised examples in which genetics can be used to improve the usefulness of crops as animal foods. Phytic acid in grain for animal feed immobilises phosphate and is poorly metabolised by monogastric animals. It passes through the gut of these animals, resulting in phosphate-rich manure that contributes to waterway eutrophication. Low phytic acid grain (Shukla *et al.* 2009) used for poultry food may reduce phosphate pollution from chicken or pig farms and thereby contribute to sustainable food production. Such grains have been developed by random (Shi *et al.* 2005) or targeted mutation (Shukla *et al.* 2009; see Section 3.2.1.1) and by GM (Bilyeu *et al.* 2008).

Oily fish such as salmon and herring provide omega-3 fatty acids for the human diet. These molecules are synthesised by phytoplankton that are eaten and then move up the marine food chain. In fish farming these compounds are provided through fishmeal. For each unit of product, several units of fishmeal have to be provided so that the sustainability of fish farming is vulnerable to shortages of wild fish supply. However, it is now possible to engineer oilseeds such as soya bean to produce SDA, an omega-3 fatty acid precursor (Monsanto 2009). This material could enter the fish feed or indeed chicken feed chain, resulting in fish or chicken in the human diet enhanced with omega-3 fatty acids. It is likely that this innovation could be applied in the near future.

3.4 Conclusion

A range of technologies and practices have been described in this chapter which could be used to increase food crop production and improve nutritional quality in light of the various challenges described in Chapter 2. Some of these are starting to be used widely. Others have likely future benefits over the next two decades. Opportunities exist for the application of existing technologies, the development of new crops and practices and the longer term investigation of radical new approaches which might result in dramatic changes in productivity. It should be stressed that no one approach should be ruled out in favour of another. Different approaches will be appropriate in different circumstances. Furthermore, the largest improvements stand to be gained where both the 'seeds and breeds' and management aspects of a system are optimised. This in turn requires the necessary social and human capital. When considering how these approaches might translate into use in the field, it is essential to consider possible impacts, side effects and wider consequences. These are discussed in the next chapter.

4 Consequences and complications of innovation in food crops

Summary

Changes to agricultural technologies and practices have both positive and negative consequences for the environment, human health, societies and economies. Potential adverse impacts on the environment include those on biodiversity and the provision of ecosystem services. The sustainable intensification of agriculture requires a new understanding of these impacts so that interventions can be targeted to minimise adverse effects on the environment. Potential health and environmental impacts of new crop traits need to be well understood and managed. Little proactive attention is given to the economic context of changes to agriculture. Increasing production without consideration of economic and social conditions can amplify rather than reduce income inequities. For technologies to be successful and sustainable, they need to fit with local economic contexts. Farmers' own expertise needs to feed into processes of research and innovation. Systems for extending and translating knowledge into changed practices need to be improved.

When problems are complex, new technologies rarely provide straightforward solutions. Technological innovations can introduce unintended complications, necessitating trade-offs between costs and benefits. This chapter highlights some of the potential consequences associated with new technologies and practices for food crop production. We consider the environment, human health, social issues, markets and research infrastructure as separate factors, although we acknowledge their interrelatedness. Our conclusion is that innovation towards the sustainable intensification of agriculture must take into account these complexities, demanding improved scientific understanding and good governance.

4.1 The natural environment and externalities

The primary objective of agricultural systems is to produce food, fibre, fuel or other products for human or livestock consumption. But meeting the objectives of food production may have intended or unintended side effects (Robinson & Sutherland 2002; Green *et al.* 2005; Millennium Ecosystem Assessment 2005; Birdlife International 2008a).[8] Agriculture can negatively affect the environment through the overuse of natural resources as inputs or through exporting pollutants from pesticides and fertiliser use. Such effects are called negative externalities because they are costs that are not factored into market prices (Baumol & Oates 1988; Dobbs & Pretty 2004). Sensitive agricultural practices can contribute to the accumulation of natural capital by improving soil quality, biodiversity, and water services.

Externalities in the agricultural sector have at least four features:

1. their costs and benefits are often neglected;
2. they often occur with a time lag;
3. they can damage the welfare of groups whose interests are not well represented in political or decision-making processes; and
4. the identity of the source of the externality is not always known.

The central challenge for new technologies and practices in food crop production is to find ways of increasing production while minimising any negative impacts and at the same time increasing the stocks of natural capital (see Table 4.1).

4.1.1 Ecosystem services

Changes to crop production practices have resulted in the degradation of the physical environment, topsoil loss, water table effects, desertification and even local climate change (Tilman *et al.* 2002) (see Case study 4.1). This impact can be caused by increased intensity of agriculture or conversion of habitat for farming. External impacts include the consequences of fertiliser and pesticide use on nutrients and toxins in groundwater and surface waters.

It is now accepted that ecosystems such as forests and wetlands provide a range of services including air quality regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation and climate regulation at a range of scales from local to global (EASAC 2009) (see Box 4.1). Agriculture relies upon, but also has impacts upon, these ecosystem services. As agricultural systems shape the assets on which they rely for inputs, a vital feedback loop occurs from outcomes to inputs. Sustainable agricultural systems should have a positive effect on natural, social and human capital, while unsustainable ones feed back to deplete these assets.

8 See also the papers in the special issue of Philosophical Transactions of the Royal Society of London B **363**, 1491, 447–466.

Table 4.1. Potential side effects of differing agricultural technologies and practices.

Technology or practice	Examples of potential negative side effects	Examples of potential positive side effects
Agroforestry—for increasing yields and rehabilitating degraded lands, especially leguminous trees	Nitrogen leaching of leguminous trees Pest harbouring in new habitats	Increased carbon sequestration in soils and timber Mixed habitats for beneficial organisms Reduced salinity and water logging
Beetle banks and flowering strips	Loss of productive agricultural land	Reduced insecticide use and losses to watercourses
Engineering with nano-emulsions, mechanisation and robotics	Escape of nano-particles [a]	Reduced losses of important nutrients, water and pest control agents to environment
Herbicide-tolerant crop	Reduced in-field biodiversity Herbicide resistant weeds based either on the crop or flow of a gene into crop relatives	Reduced use of harmful herbicide Increased soil carbon if zero-tillage system also used
Insecticide	Loss of higher trophic level organisms (eg predators, bees) Adverse effects on human health Pollution of ground and surface water	Indirect effect of reducing land required for agriculture
Insect-resistant crop	Insects may be selected for their ability to overcome the resistance	Reduced use of insecticides
IPM—use of both manufactured products and ecological management	Likely to be lower than for traditional use of pesticides [b]	Reduced losses of beneficial insects and arthropods Reduced water pollution Addition of fish to wetland rice-based systems
Manures and composts	Losses of nutrients to surface and ground water Losses of N_2O to atmosphere	Reduced fertiliser use (if a substitute) Increased soil quality and texture
Mineral fertiliser	Nitrogen and phosphorus losses to ground and surface water Losses of N_2O to atmosphere Eutrophication of surface water	Indirect effect of reducing land required for agriculture
Multiple or mixed cropping with legumes, use of green manures	Possible increase in nitrogen leaching	Mixed habitats reduce pest incidence Increase in carbon sequestration in soil (if added as green manure)
Pheromones for pest reproduction disruption and inundative biological control	Likely to be minimal if highly host-specific although there may be insect dispersal to remote areas	Reduced pesticide use (if replaced) Increased incidence of parasitoids and predators
Precision agriculture for pesticides and fertilisers	Likely to be lower side effects than for conventional applications	Reduced losses to ground and surface water
Push-pull system for IPM and weed control	Likely to be low	Reduced use of pesticides Damage to viability of *Striga* Increased resilience of system

Soil and water conservation, contour farming, mulches and cover crops	Losses of nitrogen to groundwater	Reduction in soil erosion Increased infiltration and recharge of aquifers Increased carbon sequestration if plant material added to soil
Water conservation and harvesting	Retention of water in watersheds through reductions in surface run-off	Reduction in soil erosion
Recessional rainfed agriculture		Increased infiltration and recharge of aquifers
Zero-tillage or conservation tillage	Losses of N_2O to atmosphere from fertilisers Leaching of herbicides to groundwater	Increased carbon sequestration in organic matter in the soil Reduced soil erosion Reduced water run-off Cleaner waterways

(a) Analysis of nano-particles in the environment is available in Royal Society (2004).

(b) There are potential *indirect* environmental side effects if conventional, high-yield agriculture is replaced by systems that use IPM and produce lower yields, requiring, on average, an expansion of agricultural land.

Case study 4.1. Water use in the Shiyang River Basin

The negative impacts of over-use of water in agriculture combined with the influence of a changing climate are well illustrated in the Shiyang River Basin, an inland river basin in Gansu Province in northwest China. Shiyang has a large human population with very significant exploitation of its water resources. In consequence, water shortage constrains its social and economic development and results in some of the worst ecological and environmental deterioration in China. With an increasing population (by 159% in 50 years), the amount of cultivated land in the basin has expanded greatly (by 51%). Large-scale irrigation has been introduced in the middle reach of the basin. The introduction of leakage-free canals and more extensive exploitation of underground water have further expanded the irrigated area. Water usage due to human activities has exceeded the carrying capacity of the water resources in the basin, leading to a dramatic shift of water allocation between the upper and lower reaches and a rapid reduction in the water table in lower reaches (the Minqin oasis). Much of what was once a lake and which had become productive agricultural land is now a desert. The oasis is shrinking in area, natural vegetation relying on underground water is disappearing, and desertification is accelerating (see Kang *et al.* 2008).

In this region, the dropping water table makes it very difficult to sustain productive agriculture, resulting in the abandonment of villages and population emigration. Agricultural practices are changing with more protected cropping introduced to increase water use efficiency. In the oasis, a research station established jointly by China Agricultural University and Wuwei City (Gansu Province) is helping the region's farmers introduce 'water saving agriculture techniques'. These biological and engineering solutions allow the production of 'more crop per drop' of water available. The hope is that these practices will sustain food production, restore the water table with positive ecological consequences, and allow small quantities of water to be used to establish drought-resistant plants at the southern limit of the desert to prevent further desertification. If this programme is not successful then the consequences for the local population will be serious. The loss of vegetation from the area, which is surrounded by massive deserts, would also contribute to global warming.

4.1.2 Biodiversity in agricultural systems

Taking the UK as a well documented case, there is evidence for widespread changes in biodiversity in agricultural landscapes. Farmland weeds declined by about 90% over the last century (Robinson & Sutherland 2002) and there have been dramatic losses in recent decades of much of the flower-rich farmland habitat, such as hay meadows (Wilson 1992). Many farmland specialist species have declined in recent decades including around half of the relevant plants, a third of insects and four-fifths of bird species (Robinson & Sutherland 2002). The intensification of agriculture in the UK has been identified as contributing to declines in threatened farmland bird species (BirdLife International 2008b). The greatest declines in Europe over the last 25 years of farmland ecosystem birds have been in the more intensively farmed areas of north-western Europe and least in eastern Europe, where the largest bird populations remain (Donald *et al.* 2001). In North America many bird species characteristic of farmland or grassland habitats have declined over recent decades (Peterjohn & Sauer 1999).

In Europe, significant impacts of agriculture on biodiversity in agroecosystems have arisen from the development of

Box 4.1 Ecosystem services

Climate regulation (global). Ecosystems play a key role in absorbing and managing levels of GHGs in the atmosphere.

Climate regulation (regional). Changes in land cover have affected regional and local climates, both positively and negatively, with a preponderance of negative impacts such as reduced local rainfall near tropical deforestation.

Air quality regulation. The ability of the atmosphere to cleanse itself of pollutants has declined slightly since pre-industrial times but probably not by more than 10%.

Water regulation. The effect of ecosystem change on the timing and magnitude of runoff, flooding and aquifer recharge depends on the ecosystem involved.

Erosion regulation. Land use and crop/soil management practices have exacerbated soil degradation and erosion.

Water purification and waste treatment. Globally, water quality is declining, although in most industrial countries pathogen and organic pollution of surface waters has decreased over the last 20 years.

Disease regulation. Ecosystem modifications associated with development have often increased the local incidence of infectious diseases, although major changes in habitats can both increase or decrease the risk of particular infectious diseases.

Pest regulation. In many agricultural areas, pest control provided by natural enemies has been replaced by the use of pesticides. Such pesticide use has itself degraded the capacity of agroecosystems to provide pest control.

Pollination. There is established but incomplete evidence of a global decline in the quantity of pollinators. Declines in abundance of pollinators have rarely resulted in complete failure to produce seed or fruit, but have more frequently resulted in fewer seeds or in fruit of reduced viability or quantity.

Natural hazard regulation. People are increasingly occupying regions and localities that are exposed to extreme events, thereby exacerbating human vulnerability to natural hazards.

Source: Millennium Ecosystem Assessment (2005)

more effective herbicides and pesticides, increased drainage, larger fields, greater mechanisation, the rapid shifts to winter cereals (and the consequent loss of over-winter stubbles), the move away from hay making to silage (Potts & Vickerman 1974; Chamberlain *et al.* 2000) and the increase in the area of land farmed (see Section 4.5).

The impact of agriculture on biodiversity can be associated with reduced efficiency of crop production. This point is illustrated by research in the 1980s in southeast Asia in which it was found that pest attacks on rice increased when pesticides were used. Insecticides were eliminating the natural enemies of insect pests such as spiders and beetles (Kogan 1998), so the pests were able to multiply very rapidly.

However, the careful use of science-based technology in agriculture need not lead inevitably to the deterioration of biodiversity. In the southeast Asian example referred to above, the introduction of integrated pest management (IPM) resulted in remarkable achievements in human and social development and was associated with more effective agriculture. Farmer field schools are now being deployed in many parts of the world to introduce IPM: by 2005, more than 4 million farmers had been trained in 175,000 field schools in 78 countries. Indonesia has the largest number of trained farmers with 1.1 million, while there are significant numbers in other countries such as Vietnam (930,000), Bangladesh (650,000), Philippines (500,000), India (255,000), Egypt (210,000), China (130,000), Thailand (75,000), Nepal (57,000), Kenya (46,000) and Sri Lanka (45,000) (Eveleens *et al.* 1996; Braun *et al.* 2005).

Similarly, in Europe it has been established that the ecological and environmental importance of farmland can often be enhanced at little cost. There has been considerable research into the habitat requirements of a range of declining bird species and the means of restoring their populations (Newton 2004). The practicalities of such solutions have been assessed by the Royal Society for the Protection of Birds at their trial farm, which has markedly increased the densities of a range of farmland species while increasing profits. A similar farm-scale scheme run by the Game Conservancy Trust has demonstrated the potential to use agriculture to provide food and habitats for farmland birds (Stoate *et al.* 2004).

Agri-environment schemes are a favoured solution for maintaining or enhancing wildlife in farms. Their impact has been variable (Kleijn & Sutherland 2003), but with greatest success when carefully targeted (Ausden & Hirons 2002; Evans & Green 2007). In one example, a well researched and focused agri-environment scheme was introduced in southwest England with the objective of restoring the cirl bunting (Peach *et al.* 2001); the population increased 5-fold between 1989 and 2003 (Wooton *et al.* 2004).

However, although the effects of agriculture on biodiversity can be minimised with careful management, as described above, these effects cannot be eliminated totally if agricultural production is increased. It is inevitable that any move to intensify agriculture or to increase the area of cultivated land will present challenges for biodiversity and ecosystem services.

4.1.3 Gene flow

It has been known for many years that genes can flow from a crop into related crops or weedy relatives by pollen transfer (Dunwell 2008). Conner *et al.* (2003) refer to Charles Darwin's experience with cabbage seed stocks that were contaminated by pollen from purple kale grown more than half a mile away to produce what he called 'purple bastards'. They also review other examples of gene flow between crops and weeds. Historically, the effect of such gene flow has not been perceived as an agricultural or environmental problem, but routine measures are taken to minimise genetic contamination of seed supplies and testing is carried out to maintain purity. The recent introduction of GM crops has highlighted this issue, although there is no evidence that transgenes and endogenous genes differ in their ability to move into or out of a crop. Since absolute genetic containment of crops is impossible (Dunwell & Ford 2005), the current regulation of GM crops addresses both the likelihood and potential consequences of such gene transfer. The frequency of gene-flow is substantially dependent on the breeding system of the crop (inbreeding or outbreeding) and the relative magnitude of the source of pollen relative to the density of recipient plants.

Genes for disease resistance and other traits have been bred into many crops for nearly a century by crossing between crop varieties or by crossing between a crop and related species. Spread of the conventionally bred genes into sexually compatible relatives will have occurred but there is no indication of harm even when crops are grown in centres of natural biodiversity for the crop. There is no good evidence that these crops have resulted in environmental or other damage.

GM techniques may be used to transfer genes that could otherwise have been transferred from plant to plant by conventional breeding. This *cisgenic*, as opposed to *transgenic*, approach (see Section 3.2.1.3) has the potential advantage that it accelerates the cycle of crop improvement and allows the introduction of new useful traits without other less useful traits ('linkage drag'—see Section 3.2.1.2) (Jacobsen & Schouten 2007; Porteus 2009). However, there are no such products on the market at present, and it should be noted that they would be covered by current environmental assessment procedures required for GM crops. Existing European and UK legislation and procedures for risk assessment are currently effective as a means for assessing the impact of pollen flow and other potential risks of GM crops. GM crops have been grown in several European countries and there are no reports of environmental damage to date (Brookes 2008).

Most existing GM crops (ie glyphosate herbicide resistance and *Bt* insect resistance) utilise non-plant genes. Various hypothetical scenarios could be envisaged in which these and any other transgenes would have environmental impacts and it is an integral part of existing regulation that all theoretical risks are assessed before the release of any GM plant into the environment is permitted. Specific examples in which environmental impact issues may arise include the following (Dunwell & Ford 2005):

1. Herbicide resistance. The flow of herbicide resistance genes from transgenic or non-transgenic plants to weeds may complicate weed control (Section 3.3.3.1).
2. Insect resistance. The possible effects of the insecticidal protein on non-target organisms are considered in environmental risk assessments (Marvier *et al.* 2007; Duan *et al.* 2008; Wolfenbarger *et al.* 2008). Transfer of resistance genes may provide a selective advantage to a wild relative and therefore alter its competitive ability (Section 3.3.3.2).
3. Stress tolerance. The transfer of a gene conferring tolerance to abiotic stress may theoretically alter the competitive ability of a wild relative (Section 3.3.2).
4. Viral genes. Concern has been expressed that virus resistance genes may recombine with viruses or that viral gene products may be used by and give new properties to viruses. However, virus-resistant transgenes have been used in the field to protect papaya plants against viruses in the USA (Hawaii) and there are no indications of damage. The consequence, on the contrary, has been the restoration of papaya cultivation to areas in which it was being eliminated by papaya ringspot virus (Fuchs & Gonsalves 2007) (Section 3.3.3.2).
5. Genes affecting pollen production. There are several examples in which it has been suggested that transgenes would be useful if they blocked pollen production. Such genes could be used to prevent gene flow. They could also be used to generate male sterile parents for use in hybrid seed production or as part of a strategy by which biotechnology companies could prevent use of the plants without having a proprietary chemical to release the block on pollen (Lemaux 2009). However, there are no commercial programmes to use this type of technology at present.

4.2 Human health

Food has an obvious link with health. Health is promoted by sufficient food of good quality and variety, and damaged by either too much or too little with an unbalanced nutrient content. Any intervention in food crops and their production has the potential to affect human health through nutritional content or potentially harmful components.

There is concern that certain novel crops may introduce health hazards if the product is eaten. A previous Royal Society report (2002) and the Government's GM Science Review (2003/2004) assessed the possibilities of health impacts from GM crops and found no evidence of harm. Since then no significant new evidence has appeared. There is therefore no reason to suspect that the process of genetic modification of crops should *per se* present new allergic or toxic reactions.

Crop plants have begun to be modified to produce biopharmaceuticals (Spök *et al.* 2008). Plant-produced insulin, for example, has recently entered clinical trials.[9] Inevitably there has been contamination of food crops by the biopharmaceutical and we consider it likely that future contaminations will occur. As biopharmaceuticals begin to be engineered into plants it seems most sensible that, to avoid possible risks, the target plants should not be food crops.

4.3 Social and economic systems

The introduction of new agricultural technologies can have complex social and economic consequences both for people in the immediate farming area and more distant groups through markets for land, labour and physical inputs and outputs. Beneficial technologies and techniques can take time to filter through to farmers and to expand into widespread practice. If new technologies are introduced without consideration of infrastructure, institutions, markets, cultures and practices, success can be short-lived or there can be serious unintended consequences. New technologies typically offer greater or lesser benefits depending on scale, and often benefit larger-scale farmers more than smallholders.

In parts of the developing world, when harvests are good, prices then fall as local markets become oversupplied. Investment in increased productivity therefore needs to go hand in hand with investment in better market channels and transport infrastructure. Farmers need to be able to recoup increased production costs, which is difficult if prices are falling, as well as to invest in their own farms. Increasing production without consideration of underlying economic conditions can amplify rather than reduce income inequities. The approaches of organisations such as the Gates' Foundation and the Alliance for a Green Revolution in Africa now recognise that productivity increases alone will not solve the problems of hunger and farmer livelihoods. Investment is also required in physical and institutional channels for getting inputs to farmers and crops to market.

New technologies change the productivity of different factors (particularly land and labour) and hence the value of different resources. For example, some new techniques may reduce the amount of labour required, restricting opportunities for employment in agriculture. New crop varieties may increase the yields on irrigated land, pushing up rental prices and increasing competition for water. It is often difficult to predict in advance the multiple consequences that flow from a change in the productivity of land and labour, since subsequent changes in price produce further shifts in behaviour, investment and re-allocation of land and labour. New technologies may cause a loss of income to agricultural labourers no longer needed in the fields, but this may be compensated for by the generation of jobs in crop harvesting and processing.

In all agricultural systems, there are producers of various sizes and incomes, with different levels of knowledge. New technologies are often taken up first by those farmers with access to sufficient money and information to be able to take a risk by trying something new. These early adopters may then benefit from productivity gains or lower costs, putting pressure on their poorer competitors, who risk being forced out of farming and becoming landless. Technologies can therefore widen the gap between rich and poor farmers.

Farmers' knowledge is a vital asset that needs to be brought into the process of designing more productive farming systems. Farmers have their own understanding of soils, climate and the use of different agricultural practices in their geographic location (Reij *et al.* 1996; Scoones 2001; Scoones & Thomson 2009). These need to be part of the search for solutions for improved crop productivity and more resilient agroecological systems. Decades of work has gone into the development of farmer participatory methods, for crop breeding, insect/pest control, soil conservation and fertility management (Pretty 1995). Working through farmer organisations is often the best way to gain this effective collaboration between formal science and local understandings (Pretty 2003). Maximising yield may not be the primary motivation for many farmers. Given the uncertainties of climate and markets, they may choose instead to reduce uncertainties, boosting their resilience by diversifying their output. Farmers must also serve the complex needs of consumers, who will be interested in how crops keep, how they taste and how they cook.

Seed markets, formal and informal, are vitally important. In developing countries, some farmers prefer purchased seed despite its cost because it is disease free and higher quality than saved seed.[10] The use of purchased seed also allows the farmer to benefit from the hybrid vigour of F1 seed in some species (Section 3.3.1). Some farmers will experiment with new seed but also retain their own varieties, which contain a broad spectrum of desirable characteristics. But many farmers, particularly subsistence farmers, never buy seeds, relying instead on informal systems of saving, swapping and bartering. New technologies used to develop traits that may be useful for these farmers therefore need to

9 Press Release: 'SemBioSys Genetics Inc. announces clinical results with plant-produced Insulin, SBS-1000 shown to be bioequivalent to Humulin(R) R (recombinant human insulin)', 19 March 2009; see also Aviezer et al. 2009.

10 Oral evidence from Professor Michael Lipton.

be linked to appropriate trading systems and not compromise the use of farmer-saved seed.

In Africa, innovation needs to appreciate the high density of small rural farms operating at or near subsistence level. Technologies that offer benefits only to larger farms, or force the creation of larger farms and the subsequent displacement of smallholders, may exacerbate current problems rather than alleviate poverty (Adesina 2009). If research is to focus on addressing the needs of the small-scale producers, their needs and constraints must be considered in the design of new systems.

4.3.1 Intellectual property

Many examples of new crop technology—especially GM crops—are protected by patents. The use of patents has mixed consequences (Murray & Stern 2007). In some instances—with high value crops in industrialised countries—this strategy has stimulated the commercial development of products and their application. However, intellectual property restrictions have major impacts on the access to new technologies, especially for the poor (Glover & Yamin 2003; Lea 2008). The potential for patent protection has engendered mistrust of the technology because it may restrict the options of farmers or force those with no other options into restrictive and expensive commercial relationships. For these types of application it makes sense to review alternative strategies to patenting. These alternatives include open-source strategies akin to those in the computer software industry,[11] plant variety rights (PVR) and public ownership of patents. As with other sectors, there is a clear need for the public sector, private companies and farmers to increase their capacity to design and build credible and cost-effective IPR systems that meet the needs of each country. The International Treaty on Plant Genetic Resources for Food and Agriculture recognises the connections between intellectual property regimes, biodiversity and poverty alleviation. Breeders' rights and patents need to be balanced against the diversity and availability of germplasm for agriculture and research.

We have highlighted in the previous chapter the importance of agronomy, and improvements to crop management, including mixtures and agroecological methods that reduce inputs into crop systems. These improvements to crop management are often not linked to a specific product that can be marketed or intellectual property that can be secured and may be of little interest to private R&D. Where this type of research will have environmental benefits or advantages for poor people, it will need to be supported by the public sector or other non-commercial agencies.

11 See, for example, the BIOS project at CAMBIA in Australia, available online at: http://www.bios.net.

4.4 Extension and technology transfer

Extension and technology transfer systems have always been important to agricultural development. These encapsulate a range of education, advice and consultancy activities designed to spread new research and techniques into agriculture. Many extension services around the world have been cut back and privatised over the last two decades. They are often severely underfunded despite the critical links they provide between research scientists and farmers and the vital role that they play in ensuring a return on investment in research by translating new knowledge into innovative practices. They also help to form social capital, often a necessary factor in the adoption and adaptation of new technologies. In many farming systems, extension systems tend to focus on male farmers and ignore the very significant role played by women in assuring the family's food production (World Bank 2008). Cultural factors may prevent women from being able to access advice from usually male extension staff. Hence, where women are the principal food producers, the design of research and extension systems needs to take this into account (Doss & Morris 2001).

England and Wales no longer have a public agricultural extension service. This limits the ability of UK farmers to make the most of science, or scientists to learn from agricultural experience, and reduces channels of communication between farmers about improved practices. It also limits the ability to assess technologies in their contexts. One result has been a sharp decline of confidence amongst UK farmers in government (Hall & Pretty 2008). This reduction in social capital limits the possibility of the emergence of novel and sustainable food production systems. UK farmers need ways to act collectively to maintain collective ecosystem services.

Knowledge transfer models often assume a linear model of innovation—a one-way flow from scientific discovery, through technological application, to implementation and productivity benefit. Such a model works for new seed varieties and other inputs supplied by the private sector, but tends not to address the complexity of extending changes in practice and agronomy, which require voluntary and sustained behaviour change. In many countries, attempts at knowledge exchange have attempted to make up for reductions in publicly funded applied research, demonstration and extension. New possibilities offered by ICT and mobile phones may allow information about markets, weather, new products and processes to be transmitted more effectively, and might be a way forward in many countries. Innovation in agriculture happens within basic research, within farming practice and everywhere in between. It is enabled through the links between different parts of the system.

Any approach to agricultural improvement has to recognise the distinctive contributions of public, private and charity sectors. Policy makers need to be aware of the advantages, interests and limitations of each and balance them accordingly. Large global organisations, such as the Gates, Rockefeller and Ford Foundations, the CGIAR research institutes, or multinational food and agricultural companies, all play a valuable role in generating and delivering new technologies widely. Research-based companies will inevitably focus on those areas where they will be able to capture a return on their research investments. Their targets are therefore likely to be improved products (seeds and other agricultural inputs) which can be sold. Where public sector research results in improved crops, public–private partnerships may be involved in getting improved seed to farmers.[12] But where the focus is on improved practices, investment is likely to be led by the public or charity sectors.

Market mechanisms alone are unlikely to deliver improved crops and practices that address the problems of poor people, and the solutions offered only by the private sector may bring increased productivity at too high a social and environmental cost. Public sector funding should therefore emphasise those crops or countries where the private sector does not have sufficient financial incentive to make investments for long-term return, nor address the needs of poorer farmers.

4.5 Innovating towards sustainable intensification

There will be, at least in the short term, few easy answers to the question of how to increase yields sustainably. There are likely to be trade-offs between economic gain from increased production and external impacts. The impacts of agriculture on the natural environment, societies and economies need to be understood and managed. Agricultural change is often presented as a choice between unsustainable intensification of agriculture and extensive systems with fewer negative impacts. Our conclusion is that we must aim for sustainable intensification—the production of more food on a sustainable basis with minimal use of additional land. Here, we define intensive agriculture as being knowledge-, technology-, natural capital- and land-intensive. The intensity of use of non-renewable inputs must in the long term decrease. This is particularly true for nitrogenous fertilisers that will in future need to be manufactured using renewable sources of energy and hydrogen. Finding ways of reducing the processes of denitrification will also impact positively on GHG emissions and the sustainability of agricultural systems (regardless of the source of nitrogen inputs).

Historical increases in food production have been linked to the amount of land used. There has been a 6-fold increase in the land area devoted to agriculture over the last 300 years from under 6% in 1700 to about 32% today (Klein 2001). Over half of the agriculturally usable land has been converted into land for growing crops or raising stock (Green *et al.* 2005) with commodity crops such as soya bean and oil palm accounting for large increases in recent decades, with consequences for tropical forests (Donald 2004). This rate of increase clearly cannot continue as indicated by Waggoner's calculation (1995) that the area of cropland would have to be almost doubled by 2050 in order to maintain per capita food production. However, not all current farmland would be needed if global yields per hectare achieved the level achieved in Europe and North America (Balmford *et al.* 2005; Green *et al.* 2005). Cross-country comparisons have shown lower deforestation rates in countries with higher agricultural yields (Barbier & Burgess 1997) while the expansion of the agricultural area was lower in those countries with greater increases in yield (Southgate 1994).

Cultivating any additional land is likely to require considerable investment and incur social and environmental costs which will outweigh the advantages of the extra food produced, while constraints of soil quality and climate will mean that lower than average yields will be produced as a result of this extra cultivation (FAO & OECD 2009). Ploughing additional land will also increase GHG emissions (Ovando & Caparrós 2009).

The general approach in the EU has been for widespread low-intensity agri-environment schemes, which have had limited success. The alternative and preferable approach involves greater targeting with more intensive agri-environment schemes, often involving habitat restoration, in areas of particular importance to society. The focus should be on the restoration of habitats that are most important for flood protection, carbon sequestration, critical biodiversity or enhancing the health and quality of life of local people (Sutherland 2004), linked inevitably with greater intensification in other areas. Understanding how to manage landscapes to provide these multiple benefits is a major challenge that, among other factors, will require careful and sensitive application of the technologies described in Chapter 3.

The negative impacts of past agricultural change reinforce the need proactively to assess the broader impacts of new technologies and practices, and to monitor these over time (ACRE 2007). They also provide a strong rationale for future technologies and practices that will contribute to the sustainable intensification of agricultural systems. Science is a vital part of any approach to improving agriculture. Ensuring it makes a positive difference requires analysis and management of possible negative side effects—intended and unintended—and an awareness of how scientific innovation sits in a wider context. Managing the role of science therefore requires a multi-faceted approach to policymaking, recognising the range of choices faced. The next chapter contains some recommendations to help policymakers realise the potential of science to make a positive difference to people's lives across the world.

12 See, for example, the partnership between CIMMYT, the Kenya Agricultural Research Institute, BASF (a private producer of agrochemicals), the Forum for Organic Resource Management and Agricultural Technologies, seed companies and NGOs attempts to make the Striga-killing maize-herbicide technology (de Groote et al. 2008) available to smallholders in Kenya.

5 Conclusions and recommendations

5.1 Meeting the challenge of global food security

From now until 2050, changes in population, climate and consumption patterns will put added pressure on a world food system already unable to feed its population. Food demand will increase substantially. We endorse the conclusions in several previous studies (Section 1.7) that this demand can only be satisfied if there is also a substantial increase—by between 50 and 100%—over today's levels of production of all major food crops. This increase demands urgent action, with clear short-, medium- and long-term goals.

This growth in production must be achieved for the most part without the cultivation of additional land (Section 1.3). There is insufficient water to support an increase in the cultivated area (Section 2.2) and the environmental consequences of increasing cultivated areas are undesirable (Section 1.3). Additional production will have to take place without further damage to essential ecosystem services or excessive use of non-renewable resources. We need a large-scale 'sustainable intensification' of global agriculture in which yield is assessed not just per hectare, but also per unit of non-renewable inputs and impacts upon ecosystem services. Given the expense and environmental impact of energy production, we will need agricultural systems that achieve the necessary levels of production with substantially lower reliance on fossil fuels (Section 1.5).

Sustainable intensification of global agriculture requires systems that are resilient in the face of changing climates across diverse economic, social and political conditions. It is likely that there will be trade-offs between intensification and biodiversity (Section 4.1) but the long-term goal should be to increase global food production without damage to societies or the environment.

Some organisations have concluded that the problem is one of distribution rather than production—the world currently appears to produce enough food, but the people who need it do not have access to it. Others argue that production must indeed increase, but current knowledge is sufficient—the challenge is to extend best practice into those areas that have not yet benefited from yield increases. There is also a range of views that emphasise measures to slow population growth, to reduce waste in the food chain, to discourage meat eating, and to develop the infrastructure of countries with food shortages.

The assumption of the UK government has often been that domestic food supplies can be secured through a combination of national production and global trade with diverse other sources (DEFRA 2006). We are clear in this report that the issue of food security is global. Demand for food by rich countries will divert supplies away from poorer nations and international markets alone will not equitably and sustainably address global food insecurity.

We endorse the importance of distribution, making more of existing knowledge and measures to reduce demand for certain foods. We also recognise that increases in production alone will not solve problems of poverty or hunger. The complexity of the food security challenge means that our report needs to be read in the context of others looking at different aspects of food security (Section 1.7). However, the task of increasing food availability through production on a constant area of land with reduced inputs is such an enormous challenge that no useful approach or technology can be ignored. Countries must maintain and build their capacity to innovate. Science and, in particular, the biology of crop plants and their management, is a necessary part of addressing this challenge.

Underlying our conclusions and recommendations is a sense of urgency. Even in a conventional plant breeding programme, the production of a new variety can take more than 10 years. Other innovations in crop science and related topics (such as those described in Chapter 3) have a longer cycle. Given that there could be a crisis in global food production much sooner than the 40-year horizon of this study, it is crucial therefore that the relevant research, the capacity for this research and the systems for its translation are reinforced as soon as possible.

There is a clear need for policy action and publicly funded science. The UK has a responsibility and the capacity to take a leading role in creating scientific solutions to mitigate potential food shortages. At the Rome Food Summit in June 2008, the UK led calls to create a Global Partnership for Agriculture and Food, with a commitment to double investment in agricultural research. A global initiative for the sustainable intensification of food crop production, in which biological sciences play a prominent role, is vital. We welcome government efforts, led by DEFRA, to set a clear strategy for UK food security with sustainability criteria at its heart. The next iterations of this strategy should recognise the need to look globally, in partnership with DFID (UK Department for International Development). The UK should seek to lead global food security research efforts.

Primary recommendation

1. Research Councils UK (RCUK) should develop a cross-council 'grand challenge' on global food crop security as a priority. This needs to secure at least £2 billion over 10 years to make a substantial difference. We believe this will require between £50 and £100 million per year of new government money in addition to existing research spending. This long-term UK programme should bring together all research councils, the Technology Strategy Board and key central government research funders (DFID and DEFRA) and be aligned

with comparable international activities in this area. It should be informed by dialogue with farmers, other stakeholders and members of the public. The following recommendations justify allocation of these funds to excellent and relevant research, research training and technology transfer.

5.2 Scientific targets

Past debates about agricultural technology have tended to involve different parties arguing for either advanced biotechnology including GM, improved conventional agricultural practice or low-input methods. We do not consider that these approaches are mutually exclusive: improvements to all systems require high-quality science. Global food insecurity is the product of a set of interrelated local problems of food production and consumption. The diversity of these problems needs to be reflected in the diversity of scientific approaches used to tackle them. Rather than focusing on particular scientific tools and techniques, the approaches should be evaluated in terms of their outcomes.

Recent progress in science means that yield increases can be achieved by both crop genetics (using conventional breeding and molecular GM) and crop management practices (using agronomic and agroecological methods) (Chapter 3). Advances in these two areas are interdependent. The opportunity for progress in both areas would be greatly facilitated if genome sequence data were available for multiple varieties of many different crops. We also acknowledge that developments in areas outside the remit of this study (such as chemistry, engineering and social science) will bring considerable and complementary benefits.

We stress the need for scientific developments in agronomy and agroecological practices in particular, to ensure that an ecosystem-based approach is taken in which the full consequences of changes to production systems are understood and the full range of opportunities for yield enhancement exploited. These approaches offer opportunities for relatively rapid improvements in crop management and yield increases, particularly in developing countries. New crop and soil management strategies can be introduced widely and applied to many different cultivars without the need for lengthy breeding cycles for each variety of crop (see Sections 3.3.2.1 and 3.3.3.1). An example is the push-pull approach to controlling parasitic weeds and insect pests (Section 3.3.3.1.1 and Case study 3.4). Other successful crop management approaches include integrated pest and nutrient management, soil and water conservation, conservation tillage, water harvesting, and integration of agroforestry into crop systems. However, many of the developments in crop management until now (Chapter 3) do not exploit advanced technology and developments in research. Our view is that there is great untapped potential to develop novel crop management strategies based on the type of research developments described in Chapter 3.

Future research programmes should be structured to optimise the use of plants, microbes, genomes and chemicals in agricultural systems so that this untapped potential is realised.

Our enthusiasm for agronomy and agroecological approaches does not imply that genetic improvement is less important than in the past. Both genetic improvement and better crop management are vital and both should be resourced in parallel. Amongst the targets for genetic improvement of crops are some major challenges with potentially enormous benefits in food crop production that could be achieved within 20 years. There are also areas in which science could benefit food crop production in the shorter term.

The major long-term targets include modification of the metabolism of crops in order to increase the efficiency of solar energy conversion and storage or so that crops can fix nitrogen. It may also be possible to remodel the architecture of plants with radical effects on photosynthetic efficiency or by roots that more efficiently acquire mineral nutrients (Section 3.3.4.2). It may even be possible to convert annual production systems to those based on perennial types (Section 3.3.5.1). The reproductive biology of plants could also be modified with major effects on the availability and production of seed of high-yielding varieties (Section 3.3.1). These major challenges will most likely require a combination of GM and conventional breeding.

The shorter term targets of genetic improvement include production, quality and post-harvest traits. Traits affecting the ability of crops to yield well in conditions of water or temperature stress or to resist pests and diseases are particularly important for sustainable intensification. However, there is a multitude of other improved traits with significant benefit either to the producer of food or the consumer that are achievable within a 10 year period. These shorter term targets could also be achieved with a combination of GM and conventional breeding, using knowledge acquired in recent years based on work with model plants rather than crops. In the medium term it is likely that the research focus will be directly on crops and that the cycle of crop improvement can be accelerated.

Both improved crop genetics and altered crop management strategies will benefit hugely from recent advances in research methods and tools, such as genomic sequencing (Section 3.2.1.1) and high throughput analysis of small molecules (Section 3.2.2.2). These technologies make it possible to identify genes and patterns of gene expression that are associated with particular traits or with good performance of crop plants. It is then possible to target strategies for the improvement of crops or crop management strategies more precisely than at present.

The emphasis of much of the work on plants conducted over the last two decades has been on model species—Arabidopsis, tobacco and other plants that are easy to use for experimentation. Molecular genetics research has been highly successful because it focused, at least initially, on model species. However, high throughput methods can now be applied to crops as well as model species. Research applied directly to crops will generate benefits that appear more rapidly and that are more easily translatable than at present. Crop genome sequence information is a necessary foundation for the use of high throughput analysis methods and computational approaches. The cost of genome sequencing is reducing rapidly and it is therefore an achievable target to have the genome sequences from several varieties of all significant crops including those used in developing countries.

Crop improvement based on conventional breeding will continue to be important. Conventional breeding strategies are often enhanced by the recruitment of additional genetic diversity from wild crop relatives. Many cycles of crossing and backcrossing (pre-breeding) are required to detect and map useful traits from wild relatives prior to normal breeding. Pre-breeding is long term and it is a lower priority for private breeders because the payoff is slow, although it can be accelerated through the use of genome sequence data and marker assisted selection (Section 3.2). This enrichment of genetic diversity in the breeding pool is crucial to prospects for continued yield increases. Pre-breeding programmes with the major crops need to be established as soon as possible and maintained. These pre-breeding activities are most appropriately carried out in the public sector so that the resources generated are widely available, to ensure long-term commitment to germplasm enrichment, and to train the next generation of plant breeders.

Specific research recommendations

2. UK research funders should support public sector crop breeding and genomics programmes to understand, preserve and enhance the germplasm of priority crops and train the next generation of plant breeders. International programmes in collaboration with Consultative Group on International Agricultural Research (CGIAR) centres and others in Africa and India should include millet, sorghum and rice. The top UK priority should be wheat, followed by barley, oil seed rape, potato, vegetable brassicas and other horticultural crops. Public sector support for breeding needs to emphasise longer term strategic approaches than can be expected from the private sector and develop traits from public sector research.
3. RCUK should increase support for ecosystem-based approaches, agronomy and the related sciences that underpin improved crop and soil management.
4. RCUK, and BBSRC in particular, should support long-term high-risk approaches to high-return targets in genetic improvement of crops. These targets include GM crops with improved photosynthetic efficiency or nitrogen fixation. High risk approaches might also produce GM or conventionally bred crops with reduced environmental impact because they need lower fertiliser input or could be grown as perennials. Research into conventional breeding and GM approaches to increased yield and resistance to stress and disease should also continue to be funded.

5.3 The capacity to innovate

Development of new technologies for agriculture requires a cross-disciplinary approach in which mathematics, physics, chemistry, ecology and the crop sciences (including genetics, pathology, entomology and soil science) are integrated. The outcome of research in these subjects can be used to develop predictive understanding and robust options that, when linked with social and economic science, can be used for the required sustainable intensification of agriculture.

Unfortunately many universities have closed down or reduced their teaching and research in agriculture and crop science. There is a shortage of expertise in important topics, often in subjects that are closer to the farmer, where UK scientists and agronomists have traditionally played a leading role. Several key subjects are particularly vulnerable, including plant breeding, various aspects of pathology including mycology and virology, whole plant and crop physiology, agricultural entomology, nematology and soil science. There is a danger that valuable skills will be lost as researchers and teachers retire. In the few universities where relevant subjects are taught there is no evidence that students are attracted in large numbers to the few courses in these science areas, indicating that the existing courses may not be appropriately structured or presented. We welcome the BBSRC's interest in addressing skill gaps in this area. We recommend that universities should review their strategies for attracting students to the disciplines that are relevant to developments in food crop science and that they aim to retain expertise and the potential for cross-disciplinary approaches in science related to agriculture and its application. In particular, there is scope for enhancement of the plant science component in the A level Biology syllabus.

This shift away from the traditional subjects in agriculture has been accompanied by a move towards molecular biology (Tatchell 2005). Genomics and genetics, especially in model plant species, have been well supported in recent years in the UK and the rest of Europe. We welcome this support that has resulted in rapid progress towards understanding long-standing problems such as disease resistance mechanisms, developmental control, epigenetics, hormone action and plant physiology. The revival of other subjects should not be at the expense of the effort in molecular biology and genomics because, as discussed in Section 5.2, they are fundamental to necessary developments in all aspects of genetic improvement and new approaches in the management of crops.

Industry and public sector research institutes are also important in maintaining the capacity to innovate. Industry has considerable expertise, particularly in seeds, breeding and molecular GM. Research institutes have the opportunity to preserve neglected key subjects independently of the enthusiasm of students for the subject and they have the infrastructure that allows long-term challenges to be tackled. They can also focus on aspects of food crops that might benefit the environment or poor countries but would be insufficiently profitable for private sector investment.

Building on efforts by DFID and the Agriculture and Horticulture Development Board (AHDB), training and development of UK crop scientists should be broadened to include, where possible, aspects of translation and extension. Universities, research funders and institutes should look to internationalise their training through placements in developing countries. We also welcome, as a model for future strategic research, the Sustainable Agriculture Research for International Development (SARID) initiative supported by BBSRC and DFID.

Research capacity recommendations

5. Universities should work with funding bodies to reverse the decline in subjects relevant to a sustainable intensification of food crop production, such as agronomy, plant physiology, pathology and general botany, soil science, environmental microbiology, weed science and entomology. We recommend that attempts by universities and funding bodies to address this skills gap look globally. Studentships and postdoctoral research positions should provide targeted subsidies to scientists in developing countries to visit the UK and work with UK researchers.
6. In order to sustain research capacity and maximise the potential for research to be utilised, crop science research funded by BBSRC, DFID and others, together or separately, should have regular calls for proposals rather than one-off grant rounds. Grants awarded in phases will allow researchers to pursue successful ideas in the field or in new countries.
7. DFID should work with the CGIAR institutes to develop new mechanisms for international research collaborations with emerging scientific bases such as in China, Brazil, India and South Africa. Through its support for CGIAR, DFID should work with research funders and UK scientists to strengthen collaborations with international researchers. The UK should work with other partner countries to prioritise global agricultural research within the forthcoming European Commission Eighth Framework Programme.

5.4 Making science make a difference

5.4.1 Translation and extension

Unless policy heeds the specific needs of the poorest people, they are less likely to benefit from technologies to improve crop production and more likely to suffer from poor management and regulation of such new technologies. Global equity—the need to narrow the gap between rich and poor—is an essential goal in policies aimed at improving food production. Scientific research needs to understand and focus on the specific needs of farmers in the poorest countries, many of whom are women (Section 4.4). Policies for science and innovation, including extension services and intellectual property regimes, need to be aligned to ensure that the benefits of research are shared.

Relevant expertise exists within the public, private and charities sectors. There is an opportunity for research in all sectors to help achieve sustainable intensification of global agriculture. Strong public sector engagement is essential to ensure long-term programmes are implemented that the private sector would neglect because of insufficient short-term profitability. Market mechanisms alone are unlikely to deliver improved crops and practices that address the problems of poor people. Carrying out basic research in the public sector should also reduce the likelihood of intellectual property constraints preventing the widespread use of the technology in developing countries or for environmental benefit. However, the engagement of the private sector is essential for effective translation of the developments in publically funded science into agricultural applications, especially in industrialised countries.

To ensure that food crop science research is appropriately targeted there needs to be good communication between researchers, farmers and industry in both industrialised and developing countries. In that spirit we welcome the 'food strategy task force' created by the UK government to coordinate policy. It oversees a research strand, under the Government Chief Scientific Adviser, and a 'vision' strand, run by DEFRA. We welcome moves towards such a joined-up approach, but the unavoidably global vision for food security must also have the involvement and commitment of other government departments including DFID, BIS and DECC, at its core.

Agricultural extension services should be a key component of any strategy to ensure that science developments are appropriately developed and targeted. These services provide a mechanism for informing farmers about new technological developments, as well as providing a route for feedback from farmers to the research base. They could also help inform the research community so that technological innovation is appropriately targeted. Extension services also help farmers work together for the benefits of food output and the environment. We support the Technology Strategy Board's plans to create a new innovation platform on the sustainable agri-food chain, with a

UK focus. We have identified a major need to review the support for and provision of extension services in the UK and more widely, particularly in developing countries (Section 4.4).

Translation and extension recommendations

8. Research that links UK science with developing countries, funded by DFID, BBSRC and others, should work with farmers and extension services in target countries to make sure that benefits are captured and made accessible to poor farmers.
9. As part of the RCUK grand challenge there should be support for joint initiatives between the public sector and industry in which the explicit aim is the translation and application of previously executed basic research.
10. The UK department for Business, Innovation and Skills should review relevant intellectual property systems to ensure that patenting or varietal protection of new seed varieties does not work against poverty alleviation, farmer-led innovation or publicly funded research efforts.

5.4.2 Governance

We have highlighted various social and environmental consequences of conventionally intensive agriculture (Chapter 4). These past experiences are a lesson for the future sustainable intensification of agriculture and should inform the governance of new approaches to food crop production.

The IAASTD (2008a) concluded that the assessment of new technologies for agriculture lags behind their development: 'uncertainty about possible benefits and damage is unavoidable'. Existing regulations and guidelines in agriculture seek to protect against damage to the environment, but they should also involve an assessment of *benefits* alongside an appreciation of the risks and uncertainties. The Comparative Sustainability Assessment conducted by the Advisory Committee on Releases to the Environment (ACRE 2007) provides a useful guide in this area. Assessment of benefits, risks and uncertainties should be seen broadly, and include the wider impacts of new technologies and practices on economies and societies. Stakeholders and members of the public need to be engaged in dialogue about new research and technology options. This dialogue should start with the problem that needs to be addressed, ie food security, rather than presupposing any particular solutions.

We hesitate to recommend additional regulation of new crops or to support more widespread regulation of science-based technologies in agriculture. However, we agree with the Royal Commission for Environmental Pollution (RCEP) that governance of new technologies should be informed, transparent, prospective and adaptive (RCEP 2008). We believe that regulation needs to be built on some key principles. Regulation should:

- be science-based, acknowledging areas of uncertainty alongside the assessments of risk and benefit of different approaches;
- be proactive, drawing on a wide range of expertise (scientific and social scientific) to horizon scan for potential developments in technology and practice and their intended and unintended consequences;
- be built on a shared vision of the future of agricultural sustainability, informed by dialogue with farmers, NGOs, the public and scientists;
- aim to steer research of public benefit towards addressing human needs;
- be proportionate; large-scale agricultural applications should require greater regulation than research;
- reflect public values, informed by a joined-up process of continual intelligence gathering; and
- acknowledge wider social and economic uncertainties.

We consider that continuous horizon scanning to identify future issues, combined with reviews when appropriate, models and experiments, should improve our capacity to make decisions when the evidence is available. This would reduce the risk of repeating some of the problems of biofuels, where the policy decisions were made with little information on the social and environmental consequences (Danielsen *et al.* 2009). We believe that DEFRA and DFID need to have access to independent scientific, social scientific and other stakeholder expertise (including representatives from NGOs) to evaluate new technological possibilities for global agriculture and offer advice for strategic research and extension.

Governance recommendations

11. UK government should work with EU partner countries over the next five to ten years to develop a system of regulation for new agricultural processes and products, based on shared principles.
12. DFID and DEFRA should build on the work of the Food Research Partnership to establish an independent food security advisory function. This would work openly with stakeholders to help the government put future technological options into a broad social and economic context and appraise their benefits and uncertainties alongside alternatives. It would feed into and stimulate similar international efforts at CGIAR and UN level.

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7 Annexes

7.1 Project terms of reference

There are significant and growing concerns about the long-term security and sufficiency of global food-crop production due to the potential impact of many factors including climate change, population growth and changing consumption patterns, increasing urbanisation and prosperity, and competing demands for land. This study will assess the extent to which the biological and related sciences can contribute to enhancing global food-crop production over the next 30 years within the context of changing global and regional demand during this period. The study will be aimed primarily at policy makers, including those in UK Government, EU and further afield (for example, developing countries where appropriate). This work should also be of interest to other stakeholders, for example non-governmental organisations with interests in agriculture and food-crop production and it is anticipated that it will help inform the media about the contribution of science to food-crop production.

The study aims to:

- Identify and assess challenges to food-crop production in the developed and developing world.
- Evaluate targets and mechanisms for potential improvement of food-crop production including through increasing yields, enhancing nutritional value, minimising waste, increasing resource-use efficiency and reducing reliance on non-renewable inputs.
- Identify and assess biological approaches towards enhancing food-crop production. These may include biotechnological approaches to the optimisation of the genetic make-up of crops and other biological and agroecological methods such as biocontrol.
- Consider possible positive and negative impacts of crop production technologies and practices on, for example, the environment, human health and economies.
- Identify and assess any barriers to the effective introduction and use of biological approaches for enhancing food-crop production. Such limitations may include regulatory hurdles, the adequacy of the skills base and research infrastructure, knowledge and technology transfer and intellectual property rights.

Within this project, use of the term ‘food-crop’ covers annual and perennial crops grown for both human and animal consumption. Horticultural crop production methods and technologies are included in the scope of this project. The study will not directly consider non-food crops (such as biofuels) or dairy, livestock and fish production.

7.2 Call for evidence

7.2.1 Written evidence

The following organisations and individuals provided written submissions in response to the call for evidence. Organisations or individuals who have asked for their evidence not to be published have been omitted. Copies of the submissions can be obtained from the Royal Society website (http://royalsociety.org/reapingthebenefits).

Professor Bill Adams, University of Cambridge, UK.

Agricultural Biotechnology Council (abc), UK.

Dr Pedro Arraes, Embrapa, Brazil.

Professor Howard Atkinson, University of Leeds, UK.

Professor Jeff Bale, University of Birmingham, UK.

Sir John Beringer CBE.

Dr John Bingham CBE FRS.

British Society of Animal Science, UK.

British Society of Plant Breeders Ltd, UK.

Dr Stuart Bunting, University of Essex, UK.

Ayub Chege.

Professor Edward Cocking FRS, University of Nottingham, UK.

Cornell International Institute for Food, Agriculture and Development, USA.

Crop and Soil Systems Research Group, Scottish Agricultural College, UK.

CropLife International, Belgium.

DEFRA, UK.

Department of Plant Sciences, University of Oxford, UK.

Departments of Animal and Plant Sciences and Molecular Biology and Biotechnology, University of Sheffield, UK.

DG Research, EU.

Dr Amadou Makhtar Diop, Rodale Institute, USA.

Professor Thomas Dobbs, South Dakota State University, USA.

Donald Danforth Plant Science Center, USA.

Professor Tim Dyson, London School of Economics, UK.

European Plant Science Organisation, Belgium.

ESRC Innogen Centre, UK.

European Technology Platform ‘Plants for the Future’, Belgium.

Faculty of Life Science, University of Reading, UK.

Professor Alastair Fitter FRS, University of York, UK.

Dr Richard Flavell CBE FRS, Ceres Inc, USA.

Food Ethics Council, UK.

Dr Susan Gallagher, Scottish Government, UK.

Genewatch UK.

Sir Ben Gill, Hawkhills Consultancy Ltd, UK.

Global Crop Diversity Trust, Italy.

Global Environmental Change and Food Systems, UK.

GM Freeze, UK.

Dr Duncan Greenwood CBE FRS, Warwick HRI, UK.

Professor Perry Gustafson, Agricultural Research Service, USDA, USA.

Dr Dimah Habash, Rothamsted Research, UK.

HGCA, UK.

Institute of Biological and Environmental Sciences, University of Aberdeen, UK.

Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University, UK.

John Innes Centre, UK.

KWS UK Ltd, UK.

Professor Roger Leakey.

Professor Chris Leaver FRS.

Dr Jill Lenne.

Professor Keith Lindsey, Durham University, UK.

Jeff McNeely, International Union for Conservation of Nature, Switzerland.

Professor Graham Moore, John Innes Centre, UK.

Professor Donal Murphy-Bokern, Murphy-Bokern Konzepte, Germany.

Professor Nagib Nassar, Universidade de Brasilia, Brazil.

National Farmers’ Union, UK.

National Institute of Agricultural Botany, UK.

Natural England, UK.

Nickerson UK Ltd, UK.

David Njubi, National Council for Science and Technology, Kenya.

Nuffield Council on Bioethics, UK.

Dr Rodomiro Ortiz, CIMMYT, Mexico.

Oxitec Ltd, UK.

Professor Guy Poppy, University of Southampton, UK.

Professor John Postgate.

Practical Action, UK.

Professor Arpad Pusztai.

Professor Rudy Rabbinge, Wageningen University, The Netherlands.

Dr Elibio Rech, Embrapa, Brazil.

Dr Ian Robertson, University of Zimbabwe.

Niels Roling and Jannice Jiggins, Wageningen University, The Netherlands.

Royal Society of Chemistry and Institute of Chemical Engineering, UK.

Science Council of Japan.

Scottish Crop Research Institute, UK.

Professor Toni Slabas, Durham University, UK.

The Soil Association, UK.

Sir Edwin Southern FRS.

Dr David Steane.

Syngenta, UK.

Professor Anthony Trewavas FRS, University of Edinburgh, UK.

Tropical Agriculture Association, UK.

University of Leeds, UK.

University of Nottingham, UK.

Professor Richard Visser, Wageningen University, The Netherlands.

Professor Bryan Walker.

Dr Steve Wilcockson, Newcastle University, UK.

Dr David Wood.

Yara (Prosyn) Ltd, UK.

Zurich-Basel Plant Science Center, Switzerland.

7.2.2 Oral evidence

We are grateful to the following for presenting oral evidence at a meeting of the working group:

Dr Bruce Lankford and Dr Shawn McGuire, School of Development Studies, University of East Anglia, UK.

Professor Michael Lipton, Poverty Research Unit, University of Sussex, UK.

In October 2008, the Royal Society and others held a two-day, multilateral workshop on food-crop production at the National Institute for Plant Genome Research, Delhi, India. Several working group members attended this meeting, and the discussion which took place at the workshop contributed to the evidence for the study. A report on this workshop can be found on the Royal Society's website at: http://royalsociety.org/document.asp?tip=0&id=8434.

The following individuals attended a workshop for non-governmental organisations, held at the Royal Society on 8 May 2009:

Lea Borkenhagen, Oxfam, UK.

Sue Davies, Which?, UK.

Mark Driscoll, WWF, UK.

Patrick Mulvany, Practical Action, UK.

Tom Oliver, Campaign to Protect Rural England, UK.

8 Glossary

Abiotic stresses	Constraints derived from non-living factors—heat, water etc.
ACRE	Advisory Committee on Releases to the Environment.
Aerenchyma	An airy tissue found in the roots of plants.
Agroecology	The science of sustainable agriculture, studying interactions between plants, animals, humans and the environment within agricultural systems.
Agroforestry	The combination of agricultural and forestry technologies.
Agronomy	The science of soil management and crop production.
AHDB	Agriculture and Horticulture Development Board.
Allele	One of several DNA sequences that can be found at the same physical gene locus.
Allelopathy	The phenomenon whereby one organism produces biochemicals that influence the growth and development of other organisms.
Aluminosilicate	Minerals composed of aluminium, silicon and oxygen.
Apomixis	Asexual seed production.
Aquifer	Underground layer of permeable material from which groundwater can be extracted.
Arabidopsis	A small flowering plant that is widely used as a model organism in plant biology.
Arthropod	An invertebrate animal with jointed legs and a segmented body with a horny or chitinous casing (exoskeleton), which is shed periodically and replaced as the animal grows.
BBSRC	UK Biotechnology and Biological Sciences Research Council.
Biocontrol	Biological control of pests and diseases.
Biodiversity	The variability among all living organisms from all sources (from the Convention on Biological Diversity).
Biofortification	Breeding crops to increase their nutritional value.
Biomass	The mass of living biological organisms in a given area or ecosystem at a given time.
Biopharmaceuticals	Drugs produced using biotechnology.
Biosensor	An analytical device combining a biological component with a physicochemical component.
Biotic stresses	Constraints derived from living factors—pests, diseases, etc.
Brassicas	Plants in the mustard family.
Carbon sequestration	The deliberate removal or storage of carbon in a place (a sink) where it will remain.
CGIAR	Consultative Group on International Agricultural Research.
CIMMYT	International Maize and Wheat Improvement Centre.
Cisgenic modification	A type of genetic modification where the genes inserted are from the same species as the modified plant.
Coir	A course fibre extracted from the outer shell of a coconut.
Cultivar	A plant cultivated for distinct characteristics.
DEFRA	UK Department for Environment, Food and Rural Affairs.
Denitrification	A microbial process which transforms nitrate compounds into nitrogen gas.

Desertification	The degradation of land in dry areas.
DFID	UK Department for International Development.
Ecosystem	A system of living organisms interacting with each other and with their physical environment.
Endoparasites	A parasite which feeds from inside the host.
Entomology	The study of insects.
Epigenetics	The study of how genes produce their effect on the phenotype.
Eutrophication	The concentration of chemical nutrients in an ecosystem.
Extension services	Services which connect farmers with new innovations.
F1 hybrid	First generation offspring of different parents.
FAO	Food and Agricultural Organisation (of the United Nations).
Friable	Easily crumbled.
GEF	Global Environment Facility.
Genetic improvement	The changing of a genome through breeding or genetic modification to introduce desirable traits.
Genetic modification	The direct introduction of novel genes into an organism's DNA.
Genomics	The analysis of genome sequences.
Genotype	The combination of genes which determines a particular characteristic.
Germplasm	The collection of genetic resources for a particular organism.
GHG	Greenhouse gases.
Glyphosate	A broad spectrum herbicide.
GM	Genetically modified.
Green revolution	The crop varietal development which took place in the 1950s–1960s.
Heterosis	Hybrid vigour.
High-throughput analysis	A technique which allows the fast analysis of large numbers of molecules in parallel.
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development.
Intensification	An increase in the productivity of existing land and water resources.
Intercropping	The practice of cultivating two or more crops in the same place at the same time.
IPCC	International Panel on Climate Change.
IPR	Intellectual property rights.
IRRI	International Rice Research Institute.
ISAAA	International Service for the Acquisition of Agri-biotech Applications.
Lepidoptera	Order of insects including moths and butterflies.
Linkage drag	The genetic linking of desired traits to undesired traits.
MAS	Marker-assisted selection. The use of DNA markers to select plants for a breeding programme.
Mass spectrometry	An analytical technique used to determine the chemical structure of molecules.
Metabolites	The intermediates and products of metabolism.
Micronutrients	Nutrients essential to plant health, required in small quantities.

Millenium Ecosystem Assessment	A United Nations programme which assessed the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being.
Molecular genetics	The study of structure and function of genes at a molecular level.
Monocarpic	A term used to describe plants which die after seeding.
Monoculture	The practice of growing a single crop over a large area.
Multifunctionality	The interconnectedness of agriculture with societies, economies and the environment.
Mycology	The study of fungi.
Mycorrhiza	Symbiotic relationship between a fungus and the roots of a plant.
Nematology	The study of nematodes (roundworms).
NGO	Non-governmental organisation.
Nitrogen fixation	The biological process by which nitrogen in the atmosphere is converted into ammonia.
NRC	National Research Council.
Nutrient cycling	The movement of nutrients through an ecosystem.
OECD	Organisation for Economic Co-operation and Development.
Orphan crops	Minor crops.
Parasitism	A relationship between two different species where one (the parasite) benefits at the expense of the other (the host).
Perennial	A plant that lives for more than 2 years.
Phenotype	The observable properties of an organism.
Photosynthesis	A process which converts carbon dioxide into organic compounds using energy from sunlight.
Phytoplankton	Photosynthetic plankton.
Phytoplasma	Bacteria which are obligate parasites of plant tissue and insect vectors.
Phytoremediation	The treatment of environmental problems through the use of plants.
Prebreeding	Cycles of crossing and backcrossing used to select desired traits in plants.
Predation	The hunting of one organism by another.
PVR	Plant variety rights.
Quantitative trait loci (QTL)	Stretches of DNA strongly associated with the gene for a particular trait.
RCEP	Royal Commission for Environmental Pollution.
Refugia	Areas which provide shelter from environmental change.
Resilience	The ability of a system to recover from, or adjust to, change.
Rhizobia	Soil bacteria which fix nitrogen after becoming established in the roots of legumes.
Rhizosphere	The soil region immediately surrounding plant roots.
SARID	Sustainable Agriculture Research for International Development programme run by DFID.
Semiochemical	A chemical substance that carries a message.
Spores	Reproductive structures which can be dispersed and survive for a long time in unfavourable conditions.

Stem Rust	A fungal disease of cereal crops.
Stomatal conductance	The rate at which water evaporates from the stomata of a plant.
Striga	A parasitic weed.
Stylet	A hardened mouthpart of some invertebrates.
Sustainable system	A system which incorporates the principles of persistence (the capacity to continue to deliver desired outputs over long periods of time thus conferring predictability); resilience (the capacity to absorb, utilise or even benefit from perturbations, and so persist without qualitative changes in structure); autarchy (the capacity to deliver desired outputs from inputs and resources acquired from within key system boundaries); and benevolence (the capacity to produce desired outputs while sustaining the functioning of ecosystem services and not causing depletion of natural capital).
Symbiotic	Describes a close interaction between different species.
Transgenic modification	A type of genetic modification where the genes inserted are from a different species to the modified plant.
Transgressive segregation	The formation of extreme phenotypes in hybrid populations compared to parental lines.
Transpiration	The evaporation of water from plants.
UNDP	United Nations Development Programme.
UNEP	United Nations Environment Programme.
UNESCO	United Nations Educational Scientific and Cultural Organisation.
Virology	The study of viruses.
Water Footprint	How much water an activity requires in a year (Gm^3/yr).
WDR	World Development Report.
WHO	World Health Organisation.
WUE	Water use efficiency.

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