Part 1 The issues of plant science and food security

Introduction

DAVID BAULCOMBE

The underpinning fundamental challenge of food security is to match supply and demand. In a simple world this challenge would be met by straightforward technology that balances these two market forces. However, we do not live in a simple world. Innovations to save labour in production, for example, would be damaging if they eliminate the only source of personal income for farmworkers. In other settings the same innovation could release time for people to participate in education or business activities and lead to growth of the local economy. Any new technology should, therefore, be appropriate to the environment and society in which it is to be applied.

However, even setting aside the context, the balance of supply with demand is a complex topic. The crop technology which is fundamental to all aspects of food security needs to address more than simple accumulation of calorie reserves for consumption by animals and people – although yield is important. It needs to address sustainability through reduced greenhouse gas emissions and carbon sequestration. Soil erosion, aquifer depletion and impact on other ecosystem services including biodiversity should all be minimised and there should be a net benefit of the new technology on farm income through a combination of direct and indirect effects.

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The following chapters set out the background to the food security challenge and they describe appropriate and diverse technologies based on progress in plant science. These technologies aid sustainable production, improve the nutritional quality of the product and they help reduce the level of waste that would otherwise occur through pre- and post-harvest deterioration. The writers of these chapters are all proponents of biotechnology at least to some extent but, reflecting the complexity of the challenge, the writers do not advocate a GM single solution. They describe a range of solutions in which biotechnologies of various types are an important component.

Conway and Wilson categorise crop technologies as being ‘traditional’, ‘intermediate’, ‘conventional’ and ‘new platform’ and they point out that innovation at all levels has a place in the global effort to achieve food security. They refer, for example, to a traditional *Zai* system in Burkino Faso and adjacent countries. The method involves crops being planted in manure-filled pits in which termites make porous tunnels that store water. Similarly I describe an intermediate companion cropping approach in which crops are fertilised and protected from insect and parasitic weeds by legumes and forage grasses that are cultivated either between or around the main crop.

An illustration of innovation in the ‘conventional’ category is the development of New Rices for Africa (NERICAs) through tissue-culture-assisted hybridisation of a traditional African species with Asian rice (Conway and Wilson) and by a new generation of agrochemicals that enhance endogenous plant defence pathways rather than having components of the pathogen as their direct target (Baulcombe).

Many of the innovations in the ‘new platform’ category are dependent on DNA sequence data. These advances are in a continuing state of flux because there is a continuing revolution in DNA sequencing technology. As a result it is now easy to link genomic DNA sequences with traits (Graham, Baulcombe). This capacity is new because, until recently, a state-of-the-art research laboratory could identify the DNA sequence affecting defined traits only in model plant species rather than crops. It would take years of work for each trait. Now, as a result of these new technologies, gene identification is relatively routine in crops as well as model species.

The consequence of this new capacity is more precise breeding of improved major crops. Similarly, breeding minor or orphan crops including *Artemisia* and *Jatropha* (Graham), for example, can be accelerated and there is the opportunity to diversify global agriculture due to the application of this new technology. Powell and Barsby describe the principles of conventional plant breeding and how they vary depending on the system of propagation – vegetative, inbreeding or outbreeding – and how the approaches are influenced by genomics. A particularly exciting opportunity is derived from genome sequencing in which genome-wide panels of genetic markers are used to predict performance and estimated breeding value of the new variety. This new approach will allow more precise breeding of complex traits affected by multiple loci.

The new sequencing technology also facilitates molecular isolation of genes associated with traits so that they can be transferred between varieties by GM. It is likely, therefore, that many of the GM varieties to be developed in the near future will involve the transfer of plant genes to plants. In contrast, the first generation of GM crops were improved with bacterial or viral genes.

It has been suggested that the use of plant rather than alien genes in GM crops should be described as cis- rather than trans-genesis (Schouten *et al.*, 2006). However, the non-plant genes are similar to plant genes in that they have the same nucleotide composition and use the same genetic code. There is, therefore, no rational reason why genes of plant or non-plant origin should be differentiated or subject to distinct regulation or risk assessment. In both instances there should be appropriate safeguards for the farmer, the consumer and the environment but they may not need to be as restrictive as those in the European Union (Dunwell). Brookes describes how the transfer of non-plant genes can have both direct and indirect benefits for the farmer and the environment. In this light the differentiation of cis- and trans-genesis should perhaps be discouraged because it implies wrongly that there is a hazard associated with a useful technology.

Biotechnology is often presented as being inevitably linked to multinational corporations and as being inconsistent with the interests of small farmers and less developed countries. However, these chapters illustrate the diversity of the opportunities from modern biotechnology. Such diversity may be inconsistent with the business priority of large companies in which the scale of operation requires focus on large targets that can be applied over large areas in many regions. Ironically it may be that biotechnology and GM is most useful when linked with traditional and intermediate technology. Once we have identified a framework to support this linkage we will be well on the way towards sufficiency of food supply in a sustainable manner over the peak of global population and as we feel the first major effects of anthropogenic climate change. We will have achieved a doubly Green Revolution (Conway and Wilson).

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DAVID BAULCOMBE

1

Reaping the benefits of plant science for food security

Global food security can be achieved by reducing demand for food and by increasing sustainable crop production. Both approaches are necessary. To increase sustainable production it will be necessary to harness recent developments in plant science for both genetic improvement of crops and their agronomy. The technological innovations will be most effective if they can be developed as integrated components of agricultural systems. This chapter presents four case histories to illustrate the potential of new developments in plant science. It illustrates how new technology can help improve existing crop production systems and, through grand challenge projects, produce radical innovations.

FOOD SECURITY AND CROP PRODUCTION

The recent upheaval of global economies illustrates how quickly the illusion of sufficiency can translate into a catastrophe. At the start of 2008 most financial commentators were optimistic although there were some indications that global economies were not sustainable. The general view was that 'fundamentals' were sound and that there could be growth in many stockmarkets during the year (Barber, 2008). Unfortunately the optimism was not justified and the subsequent market collapse and squeeze on credit will affect us all in the Western world for some time to come.

The economy in the recent past could well serve as a lesson for global food supplies over the next generation because, as with the economy before 2008, there is an illusion that the fundamental systems

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for production are sound. However, as with the economy in 2008, there are indications from various studies and reports that warn of insufficient capacity to meet demand for food over a 30–50-year period (IAASTD, 2009; Royal Society, 2009; Foresight, 2011).

The proposed solutions to food security place emphasis to differing degrees on production or demand. Those addressing demand involve control of population growth, distribution mechanisms and reduced consumption of grain-fed animals or on minimising the massive waste of food.

Of course crop production would be much less of a challenge than it seems now if these approaches to reduce demand could be successful. Unfortunately we cannot be confident that the global community will succeed if the emphasis is only on demand. If the Millennium Development Goals aiming to free people from extreme poverty and multiple deprivations are a guide then we should not be optimistic. The goal of halving the number of undernourished people between 1990 and 2015 is a long way behind schedule and the trend may even be in the wrong direction (United Nations, 2010).

Failure to meet demand for food would have catastrophic humanitarian and political consequences and it would be irresponsible to rely on any single solution. Population growth, elimination of waste and moderated consumption should all be addressed. However a prudent strategy requires that we look not only to solutions aimed at reducing demand but that we also attempt to increase supply via improvements in crop production.

SUSTAINABILITY AND YIELD

Current crop production is not always based on sustainable practice (Foley *et al.*, 2011). Croplands cover 12% of the available land and they have a massive environmental impact. Natural resources are depleted, ecosystem services are degraded and there may be pollution of groundwater with pesticide and fertiliser residues or the atmosphere with nitrous oxide which is a potent greenhouse gas. Future climate change may also make it difficult to sustain high levels of crop production in regions where rainfall is reduced or crops are subject to high temperature stress at critical stages in their life history. The prudent strategies for improved crop production will, therefore, have to generate an increase in yield but using more sustainable production methods than those in present use. Unfortunately there are very few regions where additional land is available for cultivation without adverse environmental impacts

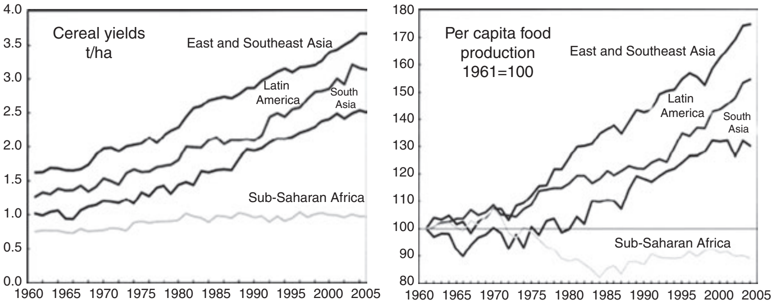

Figure 1.1 For the past four decades, cereal yields in sub-Saharan Africa have been stagnant and per capita food production has declined. The right-hand panel shows the percentage increase or decrease from 1961 which was assigned 100. (From Toenniessen *et al.*, 2008)

(Tilman *et al.*, 2011). Sustainable and productive agriculture needs to operate to a large extent on existing agricultural land.

The strategies will need to be tailored to different regions. This need is illustrated clearly by the variation in yield growth in different continents over the last 50 years (Toenniessen *et al.*, 2008) (Figure 1.1).

In regions with industrialised crop production the yields can be greater than 10 tonnes per hectare and the future focus will need to be on sustainability and environmental impact as much as yield. In the parts of Central and South America and much of Asia that benefited from the first Green Revolution there may be scope for further yield increase although sustainability is an important consideration. However, in sub-Saharan Africa, there has been no overall yield increase (Figure 1.1) and future strategies will need to focus on both yield and sustainability. Clearly an increase of only 1 or 2 tonnes per hectare provides a large proportional increase in African productivity and would add greatly to global supplies

CROP PRODUCTION AND THE ROLE OF PLANT SCIENCE

Improvements in crop production can be achieved in various ways including those that do not involve new technology. Yield increases in Malawi, for example, were achieved by farmer subsidy so that fertilisers and pesticides could be purchased (Denning *et al.*, 2009): no new technology was required. Agri-environment schemes have been used in the UK to encourage farmer practice that promotes environmental sustainability (Stevens and Bradbury, 2006) and again new technology was not required. However these and other examples are not evidence

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that technology advances are irrelevant. A balance of measures is required and, in connection with production, the balance will involve social and economic structures and appropriate technology as well as new science-based technology.

Discussion over technical innovation and crops is often focused on genetics (Tester and Langridge, 2010). In part this emphasis is because some of the most spectacular progress in basic science has been in molecular biology leading to new powerful methods for crop improvement through conventional breeding and genetic manipulation. However crop production can also be improved through innovation in the ways that crop plants are grown or the chemicals that are applied to them (Royal Society, 2009). These agronomic advances have an advantage over genetic improvements in that they can be applied to existing varieties of crop and, once developed, applied much more rapidly than genetic improvements that normally take many years.

Plant science is the key to improvements in crop genetics and agronomy and, as with many other areas of biology, it is in the throes of a revolution. The emerging methods in plant science differ from the traditional approaches in that they involve a much larger component of computing and the use of very large datasets. Imaging of cellular structure, for example, is no longer with a simple microscope but it may be linked to confocal or two-photon systems enabling much deeper tissue penetration and computational analysis of the data. Combined with immunodetection of different proteins it is now possible to monitor the changes to the subcellular structures that are well below the limits of detection of normal light microscopy.

Chemical analysis of plant extracts is similarly more sophisticated than in the last century. Complex extracts can be characterised using mass spectrometry so that previously uncharacterised proteins or small-molecule components of cells can be monitored during cellular transitions during development or associated with responses to external stimuli (Kopka *et al.*, 2005). Computing again features prominently in these chemical analyses.

New methods for sequencing of DNA or RNA also illustrate the increased power of new technology (Lister *et al.*, 2009). We can generate sequence data for an entire genome, the organism’s genetic information, or transcriptome, all the different types of RNA molecules in its cells, for relatively low cost and very quickly. The challenge therefore is in the computational analysis rather than the generation of the data. This ‘next-generation’ sequencing is useful for large projects involving the characterisation of new species’ genomes. It is also useful for more specific projects in which a mutant or genetic variant is identified or in which differentially expressed genes are characterised (Lister *et al.*, 2009).

The following sections illustrate how recent progress in plant science either has or will generate technologies for improved crop production. In selecting these examples the aim is to illustrate how new science could enhance many different approaches to crop production and, in particular, how new science links not only with biotechnology including genetic modification (GM): it also links with approaches that are classically associated with organic or other low-input approaches. There is no contradiction in these examples because the aim of biotechnology and low-input agriculture is the same: to achieve the highest possible yield of the crop with the lowest possible impact and the greatest sustainability.

CASE HISTORY I: 'PUSH–PULL' SYSTEMS AND COMPANION CROPPING

Many crops are damaged by insects either directly by feeding or because the insect is a vector for virus disease. Control of these pests in industrial agriculture is typically by application of systemic insecticides or resistant varieties of crops. However, the insecticides may target insects other than the pest or even the farmer and for that reason are subject to increasingly stringent control regulation. Resistant varieties of crop are not always available or may take a long time to develop.

An alternative strategy is a component of integrated pest management strategies in low-input agricultural systems and is based on the production of chemicals by plants that can affect the behaviour of insect pests. These chemicals are referred to as semiochemicals – *semeion* is signal in Greek – and they influence the mating behaviour or feeding of insects and can be either attractants or repellents. One of the best-known strategies to exploit semiochemicals is known as 'push–pull' and it is used, for example, in the control of stem-borer moths on maize in East Africa (Cook *et al.*, 2007) (Figure 1.2). The term push–pull is used because the strategy uses a push plant grown between the maize that produces a volatile repellent and a trap crop (the pull) on the outside of the plots that produces a volatile attractant of the stem-borer moth. The approach is also referred to as companion cropping. Under field conditions in East Africa, push–pull has increased maize yields by 100% or more without additional inputs (Khan *et al.*, 2008).

There are many advantages to push–pull as an alternative to the use of insecticides. The push plant used as the intercrop is a

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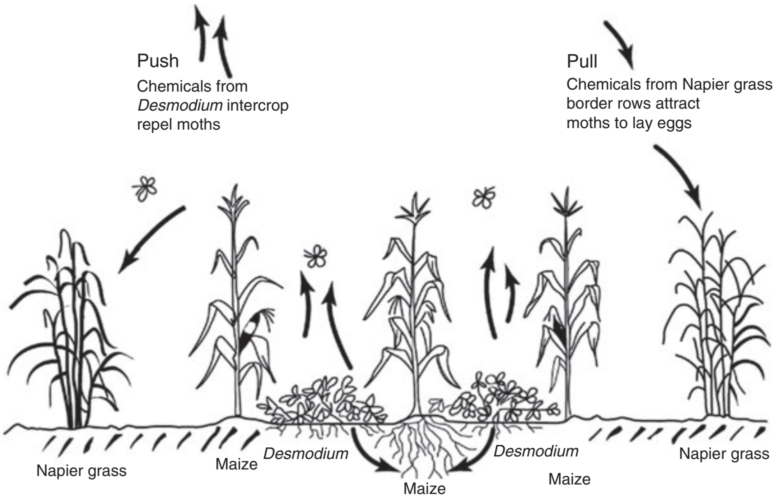

Figure 1.2 Push–pull in maize cultivation. The maize field is surrounded by a border of the forage grass *Pennisetum purpureum* (Napier grass). Napier grass is more attractive to the moths than maize for laying their eggs (the ‘pull’ aspect). The Napier grass produces a gum-like substance which kills 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’ aspect). *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* (witchweed), so has an additional crop protection benefit. (*Source*: The Gatsby Charitable Foundation, *The Quiet Revolution: Push–Pull Technology and the African Farmer*)

legume (*Desmodium* species) that fixes nitrogen and so fertilises the main maize crop. It produces a diffusible compound in the soil that benefits the maize crop. This compound suppresses the African witchweed that parasitises maize and causes major reductions in yield. Finally, the ground cover provided by *Desmodium* helps with soil and water conservation. The pull crop may also promote parasites of the stem-borer moth and be a forage grass for livestock.

An insect pest in industrial agriculture is often under strong selection pressure to develop resistance to an insecticide. In contrast, in push–pull the pest is not eliminated and the selection pressure is minimised. This example of integrated pest management is,