Journal of Agricultural Science (2011), **149**, 1–7. © *Cambridge University Press* 2011
doi:10.1017/S0021859611000074

FORESIGHT PROJECT ON GLOBAL FOOD AND FARMING FUTURES

Editorial
Improving the productivity and sustainability of terrestrial and aquatic food production systems: future perspectives

I. R. CRUTE[1]* AND J. F. MUIR[2]

[1] *Agriculture and Horticulture Development Board, Stoneleigh Park, Kenilworth, Warwickshire, CV8 2TL, UK*
[2] *Institute of Aquaculture, University of Stirling, Stirling, Stirlingshire, FK9 4LA, UK*

(*Revised MS received 6 January 2011; Accepted 6 January 2011; First published online 21 January 2011*)

SUMMARY

To meet the increasing global demand for food that is predicted over the coming decades it will be necessary to increase productivity and to do this in a way that is sustainable and efficient in its use of resources. Productivity is currently determined by the intrinsic genetic potential of the domestic plants and animals on which mankind is dependent as well as by components of the biophysical environment (temperature, water availability and quality, soil fertility, parasites, pathogens, weeds) from which terrestrial or aquatic food production is derived. Within certain limits, it is possible to manipulate plant and animal genotypes, the production environment, and the inevitable interaction between these factors, to relax constraints on productivity and potential output. Looking to the future, increased scientific understanding will undoubtedly permit this manipulation to be achieved more effectively, thus enabling the scale of production to be elevated predictably while reducing reliance on non-renewable inputs and limiting the use of more forest, grassland, wetland or coastal margin. The present paper introduces a collection of reviews that were commissioned as part of the UK's Government Office of Science Foresight Project on *Global Food and Farming Futures* which reports early in 2011. The reviews explore opportunities for advances in science and technology to impact in coming decades on the sustainable productivity of terrestrial and aquatic food production systems. Collectively, they describe many of the approaches currently being considered to define, remove or relax the different genetic or environmental constraints limiting sustainable food production. These include: potential impacts of climate change on aquatic systems, the application of biotechnology, genetics and the development of systems to improve livestock, fish and crop production; approaches to the management of parasites and pathogens; weed control in crops; management of soil fertility; approaches to countering problems of water shortage; reducing post-harvest wastage; the role of advanced engineering and the potential for increasing food production in urban environments.

INTRODUCTION

The ready global availability of food, and therefore its relatively low price, over the last 3 decades has meant that investment in the improvement of plant and animal productivity has not been accorded as high a priority for governments and other organizations as had earlier been the case when shortage and unpredictability of supply was more common (Piesse & Thirtle 2010). However, there is a growing realization, particularly provoked by recent volatility in the price

* To whom all correspondence should be addressed. E-mail: ian.crute@ahdb.org.uk

of many internationally traded food commodities, that global food supplies may not affordably meet increased demand in the years ahead unless actions are taken now to enable greater and more efficient production (Cicera & Masset 2010). This increase in demand is inextricably linked to the projected growth in the global population from *c*. 6.8 billion at the end of 2010, peaking at *c*. 9 billion soon after 2050 (Lutz & Samir 2010). Not only will populations be larger but on average they will be wealthier, which is associated with a change in diet and, in particular, an increase in demand for animal protein (Kearney 2010).

Food production demands land for crop production and livestock rearing as well as healthy and productive marine and fresh-water environments for aquatic products (Strzepek & Boehlert 2010; Smith *et al*. 2010). In addition to fertile soils and good quality water, food production systems also demand a range of other renewable and non-renewable natural resources. Inputs include energy and synthetic chemicals derived from fossil fuels and mined minerals for use in fertilizers (primarily phosphate, potassium and sulphur) (Woods *et al*. 2010). The sustainable production of food requires that resources are not utilized at rates that exceed the capacity to replenish them and it is clear that the current dependency on fossil fuels, in particular, is not sustainable. In addition, two other forces are at work which impact on sustainability and the ability to produce the quantities of food that will be demanded over the coming decades.

The first of these relates to the powerful force of evolution and the ability of weed species, pathogenic microorganisms and viruses, as well as invertebrate parasites and pests to adapt to the range of chemical or genetic measures which are used to reduce or completely inhibit their growth and reproduction to protect crop yield, fish or livestock performance. This genetic adaptation frequently results in the selection of populations of organisms such that effects of particular control measures are much reduced or completely negated.

The second constraining force for achieving food system sustainability is environmental change and in particular climate change. How fast these changes occur, their magnitude and variation between geographical locations will all impact on sustainable food production and on how readily it will be possible to adapt and adjust both terrestrial and aquatic production systems to previously unencountered and as yet undefinable biotic and abiotic stresses (Gornall *et al*. 2010; Jaggard *et al*. 2010; Thornton 2010).

Stimulated by the issues outlined above, the UK Government's Office for Science initiated a project in 2009 on *Global Food and Farming Futures* which reports early in 2011. The main drivers for change in the global food system over the coming decades have been critically examined in a series of recently published papers (Godfray *et al*. 2010) covering consumption and production in terrestrial and aquatic environments. A further set of commissioned reviews are collected together in this Supplement to *The Journal of Agricultural Science, Cambridge* (volume 149 Supplement 1 2011). The authors were asked to identify those areas of science and technology which would have the greatest impacts on the potential to increase productivity sustainably using resources most efficiently; or, in other words, accommodate recognizable change to contribute significantly to sustainable intensification. Here it is not enough just to consider increases in yield alone (such as tonnes of grain, litres of milk or kg of meat or fish) but also to define appropriate measures of resource and environmental impact (such as kg CO_2 equivalent emissions, litres of water required or hectares of land cultivated). Defining and applying informative and exchangeable metrics of yield and environmental externalities will be critical to measuring progress over time towards increasing sustainability.

The present paper introduces the subject matter and primary conclusions of these 'state of science' reviews examining possible approaches in both terrestrial and aquatic production systems to removing or relaxing existing constraints on productivity in ways that ensure increased resource use efficiency.

CONSTRAINTS ON CROP PRODUCTION

Increasing the magnitude, predictability and sustainability of yields of high quality crops will be essential to address major global challenges in food security. An important approach will be to increase the genetic potential of the crop in terms of traits which result in:

- greater biomass production;
- altered partitioning of photosynthate to edible parts (seeds, fruits, tubers etc.);
- improved resource use efficiency (water, nutrients etc.);
- resistance to or tolerance of abiotic stresses (high or low temperature, drought or waterlogging etc.);
- resistance to or tolerance of biotic stresses such as pests and diseases;
- tolerance of herbicides which enable the use of wide-spectrum herbicides for weed control;
- elevated nutritional or processing quality.

Dunwell (2010), Lucas (2010) and Davies *et al*. (2010) all discuss how this may be achieved through advances in crop genomics: the future availability of full genome sequences for most crops will allow the efficient selection of combinations of genes, or regions of crop genomes, which are identified as controlling complex traits such as drought tolerance or photosynthetic efficiency. Dunwell (2010) discusses likely advances in crop performance that will be made through the exploitation of biotechnology and highlights recent progress that has occurred with transgenic maize and barley exhibiting increased water use efficiency. This theme is also taken up by Davies *et al*. (2010), who appear less persuaded by the prospect of manipulating single transgenes to achieve drought tolerance, drawing attention to the complexity of the ways crops respond to, and cope with, restricted water availability. Davies *et al*. (2010) point to the inherent physiological trade-off between maintaining biomass accumulation and restricting water loss to avoiding stress which they think may frustrate major progress.

Both Dunwell (2010) and Lucas (2010) identify the numerous approaches and opportunities that exist genetically to increase the resistance of crops to pests and diseases. These include RNA interference, manipulation of plant volatile profiles to attract the predators or parasitoids of pest insects, as well as the production of combinations of specific resistance gene that are likely to prove inherently difficult or even impossible for organisms to counter by an evolutionary response. The need to deliver durability is a theme that is developed by Gressel (2010) in his review of increasingly intractable weed control problems. He describes opportunities that exist to tackle these issues through the use of new herbicide tolerance traits, engineering new leaf morphologies to elevate crop competitiveness with weeds and, in the case of plant-parasitic weeds, exploitation of RNA interference technology.

In addition to identifying approaches to countering biotic and abiotic stresses in crops, Dunwell (2010) points to several opportunities for yield increases based on more radical re-engineering of the crop's physiology. These include better understanding of heterosis to capitalise on the advantages of hybrid vigour; engineering increased photosynthetic efficiency; modifications to plant architecture; and control of developmental processes such as flowering time. Dunwell also points out that methods for targeted and directed gene mutation in plants are advancing rapidly and the possibility now exists to achieve certain desired phenotypes without recourse to transgenic technology.

A second set of approaches is directed towards increasing sustainable yields through improved soil, water and crop management and creating an agri-environment where pests, pathogens and weeds are unable to establish or thrive. Such approaches can be particular important when yields are low because the biophysical environment is sub-optimal.

An environment hostile to diseases, pests and weeds is conventionally created by the use of fungicides, insecticides and herbicides which will undoubtedly remain a mainstay for effective crop protection well into the future despite the widespread problems encountered with evolution of resistance. Lucas (2010; pests and pathogens) and Gressel (2010; weeds) point to the way in which advances in genomics will reveal new specific targets for intervention and the identification of novel bioactive molecules. Both authors also identify new opportunities for biological control and, in the case of pests and pathogens, a raft of novel approaches is becoming feasible based on an increased understanding of plant defence mechanisms including pathogen perception and signal transduction. In the context of optimizing chemical or biological intervention, Lucas describes progress on diagnostic technologies, remote sensing and the development of information networks which can provide early warning of pest or disease incidence.

Biosensors and other sensing devices, advanced data acquisition, hyperspectral imaging and associated analytical tools will find application in areas beyond those referred to above. Day (2010) discusses the major role that advances in engineering such as precision interventions supported by mathematical modelling will play in the better management and design of agricultural production systems. This is particularly evident in soil management where the need to avoid both soil degradation and excessive emissions of greenhouse gases from agricultural practices on grassland and cropped land will become increasingly critical. Precision approaches based on appropriate engineering leading to integrated and sustainable soil management is further developed in the review by Killham (2010), who makes the close connection between soil as a substrate supporting crop growth and a medium capable of regulating water pollution and gaseous emissions.

Maintaining the biological functions of soil with respect to nutrient cycling and fertility are fundamental to sustainable food production but Killham also draws attention to the way in which integrated approaches to management of soils and the soil biota can impact on the biocontrol of pests and diseases (cf. Lucas 2010) as well as enabling integrated weed management practices to be pursued effectively based on minimum tillage practices (cf. Gressel 2010). Soil management practices are particularly critical in water-limited regions and two papers (Davies *et al.* 2010; Carberry *et al.* 2010) deal specifically with scientific innovations for increasing resource use efficiency and maintaining crop production when water is severely limited.

Novel mulching technologies, intercropping, deficit irrigation, partial root-zone drying and use of microbial root inocula are all techniques which are effective and in limited practical use but undergoing further refinement as described by Davis *et al.* (2010). Under the specific conditions of Australian dry-land agriculture (including crop and livestock production), Carberry *et al.* (2010) relate the success that has been achieved in elevating production over the last 30 years by encouraging mixed livestock and crop production enterprises along with the widespread adoption of soil management and tillage practices that build organic matter content and improve water-holding capacity. They go on to describe the sorts of technology adoption that they anticipate in the next 20 years including improved irrigation practices, expansion of precision agriculture (including automation and robotics), introduction of dual-purpose crops and investment in breeding and biotechnology to deliver crops specifically adapted to a water-limited production regime.

The case-studies described by Carberry *et al.* (2010) and Davis *et al.* (2010) are good illustrations of the need for fully integrated approaches to reducing constraints on crop production by exploiting a range of approaches to crop genetic improvement in concert with a focus on management practices that result in a high degree of resource use efficiency when whole production systems are considered.

As has been alluded to above, much potential crop production can be lost to pests, diseases and other causes, such as adverse weather, prior to harvest. However, very significant post-harvest crop losses and food waste can be experienced in both developed and less developed countries. In their review of this subject Hodges *et al.* (2010) draw attention to the contrasting situations that exist between countries such as the USA and UK on the one hand and countries in Sub-Saharan Africa on the other. In the former, the largest losses are experienced beyond the farm gate in the retail and food service sectors, and in the home (in the USA, the figure quoted for grain products is 0·30); they suggest that this waste could be reduced by campaigns to bring about behaviour change or by targeted taxation. For low-income countries, the scale of wastage is harder to quantify but it occurs predominantly before crop products leave the farm due to poor post-harvest processing facilities and connectivity to markets. In this case, farmer education and investment in infrastructure are among the suggested solutions of the Foresight Project.

CONSTRAINTS ON LIVESTOCK PRODUCTION

As with crop production, there are constraints on livestock production that can be addressed by improving the genetic potential of the animal. Examples include:

- feed conversion efficiency;
- female fertility and fecundity;
- influencing sex ratios;
- resistance to parasites and pathogens; and
- quality attributes such as nutritional content and meat texture.

In addition to livestock health considerations, it is also possible for some aspects of animal welfare to be improved through the selection criteria adopted during breeding.

Hume *et al.* (2011) explore approaches to improving the productivity and sustainability of animal production against the background of an increasing global demand for animal protein and building on the major productivity gains over the last few decades particularly in the case of dairy cattle, pigs and poultry.

With the completion of the genome sequences of all livestock species Hume *et al.* point out that predicting the breeding value of high genetic merit males will become increasingly efficient as the availability of very large numbers of genetic markers distributed throughout the genome is coupled with sophisticated progeny testing.

Livestock husbandry and in particular optimizing nutrition and controlling disease is fundamental to increasing productivity and production efficiency (both measured per unit input and per unit of pollutant released into the environment). Progress with dietary supplements and therapeutic treatments will provide important opportunities here. In their review of new opportunities for livestock disease control, Shirley *et al.* (2010) cite the example of Rinderpest eradication as a fine example of the combined impact of reliable diagnostics, successful application of an effective vaccine and excellent knowledge of disease epidemiology. Shirley *et al.* (2010) provide other examples of novel approaches to the combined use of modern diagnostic technologies with development of vaccines, both for metazoan parasitic infections as well as disease caused by viruses and bacteria. They also point to advances in the genomic analysis of pathogens which will assist the development of refined diagnostic tests, including those that might be suitable for field use in low-income counties. In addition to the deployment of ever more effective vaccines, Hume *et al.* (2011) discuss the contribution that insights into the genetic mechanisms of disease resistance in livestock is likely to have on conventional breeding and the exploitation of transgenesis to reduce losses due to endemic and newly introduced pathogens.

Hume *et al.* (2011) explore efficient energy utilization in the generation of animal protein and point to the prospect of using genomics to generate 'purpose-built' breeds adapted to particular feeding regimes and environments. They discuss the role of feed additives and the selection or modification of the rumen microbiota to reduce the amount of methane emitted by ruminant animals. They also stress the importance of an integrated approach to minimizing the environmental impact of livestock production in terms of both inputs and outputs. Hence, the combined impact of effective waste reduction (including that resulting from disease and poor welfare), increasing feed conversion efficiency and greater reproductive output has the potential to be very considerable in future years. They envisage entirely new production systems located in multi-storey buildings within urban environments ('vertical farms') a vision of the future that mirrors that of de Zeeuw *et al.* (2011) in their review on the future role of urban agriculture.

de Zeeuw *et al.* (2011) argue that food production within the urban environment in low-income countries is important because it improves nutrition and increases access to affordable food, particularly at times of high food prices. They provide examples of cities that have embraced the concept of urban agriculture as one component of dealing collectively with food security, social exclusion and environmental enhancement.

CONSTRAINTS ON AQUATIC PRODUCTION

Many of the issues and approaches outlined in the terrestrial reviews have equivalent implications and applications in the aquatic sector. Managed interactions between genotype and environment, efficient resource use and effective technology application have equal place in fisheries and aquaculture. The former has particular characteristics however, in that the production and resource management strategies have much greater dependence on externally derived ecosystem conditions and the ways in which they respond to different exploitation strategies. As already set out in reviews by Cochrane *et al.* (2009) and others, climate change will have significant effect on aquatic environments and on capture fisheries in particular, as well as wider implications for aquaculture and for post-harvest activities, markets and global trade. Although aquaculture is likely to contribute to a greater share in future aquatic food supply, capture fisheries still provide around 0·50 of current supply and though subject to significant fishing pressure have major importance for food security, livelihoods and economic opportunity. The potential implications of climate change on fisheries resources and ecosystems, as reviewed by Perry (2010) are therefore critical in defining the future potential of this major food system, and in providing effective frameworks for ecosystem assessment, resource status and management.

The strategic aspects of science and technology application in aquaculture are addressed by Bostock (2010), exploring in particular the ways that the sector has evolved, improved its output and resource use efficiency, and developed structurally over a period of unprecedented expansion, diversification and geographical spread. The processes of scientific development and application in reproduction and genetics, seed supply, nutrition and feeds, water management and disease control, and their uptake and use at public and private sector level are particularly vital in this rapidly developing sector. Related to this, the emergence of major 'aqua-industrial' groups capable of harnessing newer technologies, overcoming production constraints, systematising efficient production to meet and drive modern supply chain needs is now an increasingly significant feature. The challenge of applying management skills competitively to expand output, hold real term prices amidst rising resource costs, and meet wider market demands will be a key issue for these groups as well as for the organization of smallholder producers to retain an effective role in future supply.

Focusing more specifically on the highly important impact and potential of genetic and genomic sciences and their application in aquatic systems, McAndrew & Napier (2010) provide an overview of current and emerging approaches in the breeding and selection of aquatic animals and the potential development of novel plant-based feedstocks to reduce the needs for fishmeal and oil in aquaculture diets. In addition to the development of desirable characteristics for aquaculture, including the possibility of using genetically modified stocks, and the more routine targeting of improved growth, environmental tolerance and disease resistance, genetic selection for restocking and fisheries enhancement is also important and could have notable biodiversity implications. Although work on genetic modification of plant materials for feeds is in early stages, it has significant implications for future growth in aquaculture production and its de-coupling from capture fisheries resources. A key aspect of this review is the substantial gap between the potential power of emerging techniques in genetic sciences, and the means of developing systematised practical approaches for larger scale gains across the aquaculture sector, and for developing associated strategies for sustaining and building aquatic biodiversity. These will represent major practical challenges in 'sustainable intensification' in the aquatic sector.

CONCLUSIONS

One message that emerges from all the reviews in this Supplement to *The Journal of Agricultural Science, Cambridge* (volume 149 Supplement 1 2011) is that there is no simple overarching solution to the challenge of delivering increased productivity from terrestrial or aquatic food production systems, particularly when overlaid by the absolute necessity simultaneously to deliver improved efficiency in terms of resource use and environmental impact.

It is clear that in crops, livestock and fish species, information derived from knowledge of genome structure and function as well as full genome sequence data will have an enormously beneficial impact on the efficiency with which it will be possible to select novel combinations of genes and genomic segments. At the same time advances in animal cloning technologies will also be an important adjunct to conventional breeding, as will the exploitation of transgenesis where it is necessary to access genes for novel traits not available within a species' own genepool or in the case of purely vegetatively propagated crops or in perennial species where conventional breeding is very slow.

https://doi.org/10.1017/S0021859611000074 Published online by Cambridge University Press

Nevertheless, while heavy reliance on genetic and genomic sciences will be necessary for future progress it will not be sufficient. It is critical to understand the interaction between the genotype and environment and to provide an environment which maximizes sustainable yield. Hence, a range of novel approaches to the diagnosis and durable management of biotic stresses (pests, parasites, pathogens and weeds) will need to be introduced. Reduction of losses from these stresses is a key component of maximizing the efficiency with which inputs such as land, water, energy, animal feed and plant nutrients are used. Similar efficiency gains are to be achieved from improved soil management aided by the better spatial and temporal precision of water and nutrient inputs that can be delivered through advanced engineering and control solutions. Finally, public and private sector linkages to deliver, apply and scale up these approaches will be critical, as will effective supply chain systems to generate benefits to producers and consumers alike.

In short, the reviews in this Supplement to *The Journal of Agricultural Science, Cambridge* (volume 149 Supplement 1 2011) illustrate that though the challenges are great, the opportunities to meet them are many and that with continued investment in scientific insight as well as targeted approaches to applications there is cause for optimism that many constraints on productivity that currently exist can be significantly relaxed or even eliminated.

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