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The Role of Plant Breeding and Biotechnology in Meeting the Challenge of Global Warming

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1. Introduction

The availability of water is already a major limitation for plant production in many parts of the world and shortages of water are recognised as major threats to food security. Drought is often, although not always, accompanied by high temperatures and although these two stresses provoke different responses in plants the dividing line is often blurred as one stress exacerbates the effects of the other. While both drought and heat stress are already problems, the range over which they impact seriously on crop yields and the frequency with which they do it are both predicted to increase as a result of global warming. Plants will also have to cope with a steeply rising atmospheric CO₂ concentration.

If the predictions of climate change are correct, global warming will cause changes in temperature at a rate unmatched by any temperature change over the last 50 million years. For example, the temperature changes that happened between ice ages and warm interglacial periods as a result of the glacial cycles of the past million years were of 4 to 7 °C (Solomon et al., 2007). Although these changes in temperature were large, they occurred relatively gradually, with the global warming at the end of each ice age taking approximately 5,000 years (Solomon et al., 2007). The current rate of global climate change is much more rapid. The upper end of the range predicted by Global Climate Models in the International Panel for Climate Change (IPCC) 4th Assessment Report is a 5°C increase in global mean temperature by the end of the century. As well as the mean increase in temperature, there is predicted to be an increase in the frequency and severity of extreme weather events.

The potential consequences of such events for food production can be seen in the effects of the severe Australian drought of the last decade, which reached crisis point in 2007-2008, and the Russian drought of 2010. Both Australia and Russia are major wheat exporters in normal years, but in 2007-2008 exports of wheat from Australia fell to 1.7 million tonnes, compared with 7.5 million tonnes in 2005-2006, while in July 2010 the Russian government banned wheat exports altogether to protect domestic supply. The price of wheat grain on the London International Financial Futures & Options Exchange (LIFFE) rose in 2008 to 198 pounds (GBP) per tonne. It fell back to below 100 GBP per tonne in 2009 but rose to a new record of 200 GBP per tonne in December 2010. At the time of writing it is at 198 GBP per tonne for July 2011.

In both the Australian and Russian droughts, lack of rain was accompanied by high temperature and both stresses would likely have affected grain yield. Drought stress can be

devastating at any time during wheat development, while increased temperature shortens the growing period, reducing yield. Heat stress at flowering is especially damaging, resulting in much lower grain number and substantial yield losses. During the hot summer in northern Europe in 2003, for example, with maximum temperatures up to 38 °C in the UK and 40 °C in France, wheat production fell by about 20 %.

There is another angle to the issue of global warming for agriculture in that agriculture is a major contributor to greenhouse gas emissions and will be expected to contribute to efforts to cut emissions in order to avoid the worst case scenario predictions of global temperature increases. In the UK, for example, farming is responsible for about 7.4 % of total greenhouse gas emissions and the Climate Change Act (2008) commits the country to an 80 % reduction in emissions by 2050 across all sectors of the economy. Much of the greenhouse gas emissions from agriculture come from the methane that is produced from microbial breakdown of animal waste. The technology to capture this methane through anaerobic fermentation is being developed and there is an embryonic industry growing to provide it to farmers. It is not yet cost-effective for most farms but cost may not be the deciding factor if governments interfere in the market as they have done with other biofuels. As far as crops are concerned, the major 'carbon footprint' comes from the use of fossil fuels to produce fertilisers, herbicides and pesticides. Intensive agriculture is and will be required in order to meet the demand for food and fuel, but its dependency on fossil fuels is not sustainable and will have to be addressed.

Concerns about climate change are also driving the use of crops to produce biofuels. Peak oil, the point when the maximum rate of global petroleum extraction is reached, after which the rate of production enters terminal decline, may be imminent, but bioethanol from sugar and starch crops, biodiesel from oil crops and biomass for electricity production would still struggle to compete with fossil fuels in open competition. However, governments in many countries have intervened in the market to promote the use of biofuels. In Europe, for example, the Directive on the Promotion of the Use of Biofuels and Other Renewable Fuels for Transport, 2003/30/EC (also known as the Biofuels Directive), stipulated that measures had to be taken across the EU to replace 5.75 % of all transport fossil fuels with biofuels by 2010. The Renewable Energy Directive/Fuel Quality Directive of 2009 then imposed targets of 20 % of all energy and 10 % of transport fuel to come from renewable sources by 2020. These directives effectively created a protected market for biofuels in Europe.

The problems brought on by or in response to climate change add to a long list of issues facing agriculture. World population passed six billion in 1999. In 2011 it will pass seven billion and it is predicted to peak at nine billion around the middle of this century before starting to decline slowly. In addition, greater prosperity in highly populated, economically rapidly emerging countries such as China and India is leading, understandably, to a demand for a better diet, in particular a demand for more meat. There are also increasing problems of fresh water supply, competition for land use, the need for wildlife conservation, soil erosion, salination and pollution. Arguably, the era of crop surpluses and cheap food is over and we have entered one where food security is at the top of political and scientific agendas.

Plant breeders face the challenge of developing new crop varieties that will meet the increasing demand for food and biofuels in a rapidly changing and unpredictable environment. New varieties will be required with a set of physiological traits suited for the conditions that are likely to prevail ten to twenty years ahead. Here, modelling will play an important part.

This chapter reviews the role that plant breeding and agriculture will play in meeting the exceptional challenges of climate change, and the progress that has been made in developing the genetic tools that plant breeders will require. It describes the role of modelling and systems biology, current knowledge on plant responses to drought, heat and high CO₂, the often ignored issue of the effect of stress on crop quality and food safety, and the use of established and novel crops for biofuel production.

2. The role of modelling

The fact that plant breeders will have to develop new varieties for climatic conditions that do not currently prevail makes crop simulation modelling particularly important (reviewed by Semenov and Halford, 2009). Crop simulation modelling, sometimes referred to as an application of systems biology, has been used increasingly as a guide to experimentation. The aim is to enable a broad understanding of complex processes that would not be possible by studying single or small groups of genes responding, for example, to one particular environmental stimulus. Mathematical equations are developed from the analysis of large datasets from transcriptomic, proteomic and metabolomic analyses of plants subjected to a range of environmental conditions. Experiments are then carried out to test hypotheses derived from the model and the results of these experiments are used to refine the model. In the case of climate change, crop simulation modelling is used in conjunction with modelling of future climates.

There are several examples of the use of crop simulation models in assessing the impact of climate change. Carbone and co-workers (Carbone et al., 2003), for example, used modelling to predict the response of soybean and sorghum to varying climate change scenarios in the south-eastern USA. The study predicted yield decreases of up to 69 % in soybean and 51 % in sorghum in response to higher temperatures and reduced rainfall, although these decreases could be mitigated considerably by changing sowing date and variety, and if increased atmospheric CO₂ concentrations were considered.

Ewert and co-workers (2002) used crop simulation models to predict the effects of elevated CO₂ concentration on wheat yield, using data from free-air CO₂ enrichment (FACE) in Arizona, USA, and open-top chamber experiments in Germany. The authors concluded that crop simulation models could be used to predict wheat growth and yield for different CO₂ and drought treatments in a field environment, but that there was still uncertainty about the combined effects of CO₂ concentration and drought that required further testing and enhancement of the model.

Jamieson and co-workers (2000) also tested three crop simulation models against data from FACE wheat experiments in Arizona, but in this case included results of experiments in which the amount of applied nitrogen as well as atmospheric CO₂ concentration was varied. The models all predicted yield trends in terms of green area index, biomass accumulation and yield. The study showed that changes in CO₂ concentration affected light use efficiency, whereas nitrogen application affected the green area index.

Oleson and co-workers (2007) predicted some positive consequences of climate change for European agriculture when the impact of increased CO₂ concentration was included, but with considerable uncertainty arising from emission scenarios, the climate and crop simulation models that were used, and local soil and climatic conditions. The study predicted that the area where temperature was sufficient for maize cultivation in Europe would expand 30–50 % by the end of the century, and that there would be increases of 35–54

% in net primary productivity in northern Europe as a result of a longer growing season and higher CO₂ concentrations. It showed large increases in yield of winter wheat for northern Europe, but smaller increases or even decreases in southern Europe.

Richter and Semenov (2005) used the *Sirius* crop simulation model to evaluate the impact of climate change on drought indicators and yield of winter wheat in the United Kingdom. Climate scenarios were constructed using a stochastic weather generator for the 2020s and 2050s and compared with a 1960–1990 baseline. The study predicted that soil moisture deficit and potential yield loss due to drought would increase in the future, especially on shallow soils. However, this would be offset by a CO₂-related increase in radiation use efficiency, so that average wheat yields would be likely to increase by 15–23 % by the 2050s. Semenov et al. (2009) used *Sirius* to predict the effects of temperature and drought on UK wheat yield. Some researchers had suggested that the impact of drought on UK wheat yield would increase with climate change (Foulkes et al., 2007; Witcombe et al., 2008) and emphasised the importance of breeding for drought-tolerant varieties. The potential effects of an increase in temperature had been considered to be of secondary importance. However, Mitchell and co-workers (1993) had reported that a temperature of 27 °C or higher half-way through anthesis resulted in a high number of sterile grains and potentially high yield losses and this was followed by a series of studies predicting severe effects of temperature increases on wheat yield (Wheeler et al., 1996; 2000; Ferris et al., 1998).

Climate scenarios constructed by using the LARS-WG stochastic weather generator (Semenov, 2007) predict warmer, drier summers for the UK by 2050, but wetter winters, compared with the baseline of 1960–90. The predicted increases in maximum temperature for the 2050 high emissions scenario are between 2 and 4 °C and the probability of maximum temperature exceeding 27 °C around flowering would be affected significantly by such large increases in temperature mean. However, the crop simulation model predicts that this would be offset somewhat because of wheat phenology; that is the fact that wheat development is driven by thermal time (in other words the rate of wheat growth and development is temperature-dependent), so flowering would occur earlier in the season, before the summer temperature peak. This would also mitigate the effect of summer drought because the crop would avoid the most severe summer drought stress by maturing earlier. Indeed, the model actually predicted that the impact of drought stress on wheat in the UK would decrease with climate change, despite the drier and warmer summers, and that an increase in the frequency of heat stress around flowering represented a greater risk for sustainable wheat production (Semenov et al., 2009; Semenov and Halford, 2009). Challinor et al. (2010), on the other hand, used crop simulations to show wheat crop failure rates increasing under climate change in Northeast China due to increasing extremes of both heat and water stress. The predictions in all of these studies are based on a number of assumptions and in my view it would be premature, for example, to discount the potential yield losses from drought for wheat in the UK in the mid to late part of the century. However, breeding for heat stress tolerance is clearly an important target.

In conclusion, not all of the predicted effects of climate change on yield are negative. Effects vary from one location to another and are also variety-dependent. However, the predicted yield losses for some crops in some areas are spectacular, demonstrating clearly that the impact of climate change on agriculture needs to be addressed urgently. The other main conclusion is that crop simulation modelling can sometimes predict surprising and counter-intuitive effects on crops, and identify traits that had been considered to be of secondary importance but which should be given top priority.

3. Drought and heat tolerance

Plants adopt several strategies to avoid the effects of drought. For example, if drought is most likely to occur in late summer (typical of the UK and northern Europe) they may avoid it by growing, flowering and setting seed before this time. Other 'avoidance' strategies include the development of deeper and more extensive root systems, allowing the plant to obtain more water from the soil to survive dry periods. Plants have also evolved responses that enable them to survive even if they do become short of water. These are referred to as tolerance traits and they differ from species to species and between different varieties, developmental stages, organs and tissue types. The plant hormone, abscisic acid (ABA), plays a key role, initiating a network of signalling pathways involving multiple protein kinases (enzymes that attach a phosphate group to another protein, affecting its activity) and transcription factors (proteins that regulate the expression of genes).

Transcription factors involved in drought stress responses include ABA response element binding proteins (AREBPs), members of the zinc finger homeodomain (ZFHD)-1, myeloblastosis (MYB) and myelocytomatosis (MYC) families, dehydration-responsive element binding protein (DREB)-1 and -2, and the NAC family (reviewed by Semenov and Halford, 2009). Over-expression of another transcription factor, plant nuclear factor-Y (NF-Y), has been shown to improve drought tolerance in maize.

Some of the signalling pathways that respond to drought are also activated when heat stress is applied. In some cases this may be misleading because elevated temperatures will cause water stress unless ambient humidity is adjusted to prevent it, and this sometimes obscures the fact that heat stress presents a plant with its own specific problems. As described in the previous section, high temperature causes wheat and other cereals to develop and mature more quickly; it also brings about an increase in respiration and an inhibition of photosynthesis. This is caused by a reduction in the activity of ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) and the efficiency of photosystem II. The reduction in Rubisco activity occurs because the enzyme responsible for maintaining its activity, Rubisco activase, is unstable at even moderately high temperatures. This makes the genetic manipulation of Rubisco activase to improve its stability at high temperatures a potentially important target.

Transcription factors that are specifically associated with heat stress include heat shock factors (HSFs) (reviewed by Semenov and Halford, 2009) and over-expression experiments with HSFs have resulted in increased thermo-tolerance in transgenic plants. Heat stress can cause RNA, proteins and other molecules to fold incorrectly, affecting their assembly, translocation, turnover and activity. So-called molecular 'chaperones', such as heat-shock proteins (HSPs), that keep proteins and RNA in their correct conformation, are expressed to mitigate this problem and these have therefore also attracted much attention.

It is not clear yet whether the manipulation of any of these genes would provide a consistent improvement in drought and/or heat tolerance under field as opposed to laboratory conditions. At present there are no transgenic crop varieties being marketed on the basis of improved drought or heat tolerance, but all of the major plant biotechnology companies have such varieties in development.

4. Plant responses to high CO₂

Atmospheric CO₂ concentration 500 million years ago was approximately twenty times what it is today. Its long-term decline reflects the loss of carbon from the biosphere as it is

incorporated into rocks occurring at a faster rate than the release of carbon into the atmosphere through volcanic activity. In the very long term this loss of carbon from the biosphere is a threat to life on Earth because CO₂ concentration will eventually fall below the point where plants can photosynthesise efficiently. There have been blips in this decline in the past, probably as a result of periods of unusual volcanic activity, such as during the so-called 'mid-Cretaceous superplume'. Currently we are on the up-curve of another blip, this time resulting from human activity, and it is the effect of this blip over the coming decades and centuries that is the more immediate threat. The atmospheric CO₂ concentration has risen from a pre-industrial level of 270 parts per million (ppm) to 390 ppm and is rising at 1-2 ppm per year, taking it to levels not seen for 20 million years.

How crop plants respond to rapidly rising CO₂ levels will be key to food security over the coming decades; in particular, will elevated CO₂ levels have beneficial effects on plant growth and crop yield that will offset the negative effects of increased temperature and drought stress? A substantial amount of research has been carried out over the last twenty years or so on the long-term acclimation of crop plants to elevated CO₂ using free-air CO₂ enrichment (FACE). In these experiments, CO₂-enriched air is passed over the plants in an experimental plot from a system of pipes, with the flow controlled in response to the data fed back from sensors in the plot. The reader is referred to the catalogue of publications arising from these experiments from Steve Long, Don Ort, Andrew Leakey, Elizabeth Ainsworth and colleagues at the University of Illinois, and to a detailed review by Leakey et al (2009), which lists the following major conclusions: Elevated CO₂ stimulates photosynthetic carbon gain and net primary production, but Rubisco activity is down-regulated; nitrogen use efficiency is improved; water use is decreased; dark respiration is stimulated through transcriptional reprogramming of metabolism; carbon gain in C₄ plants is stimulated under drought stress, although photosynthesis is unaffected; yield is increased but by less than might be expected.

A key finding of the FACE experiments and a significant potential problem in meeting the challenges of climate change is that photosynthesis of crop plants does not increase as much as predicted in response to elevated CO₂ concentrations (Long et al., 2006); in addition, a decreased proportion of photosynthate is partitioned to the harvested organs. Understanding why this is and how it can be remedied is an important challenge. Part of the explanation may be that exposure to elevated CO₂ causes an increase in sugar levels in leaves and a decrease in expression of Rubisco genes (Cheng et al., 1998). Feedback regulation of photosynthetic gene expression in response to sugars was first demonstrated by Jen Sheen in 1990 (Sheen, 1990), using photosynthetic gene promoter/reporter gene fusions to show repression by glucose or sucrose in a maize protoplast system. The expression of the Rubisco small subunit (*RbcS*) and other genes encoding proteins involved in photosynthesis have also been shown to be reduced by glucose in cell suspensions of *Chenopodium rubrum* and by sucrose in oilseed rape cell cultures.

Sugars also affect the expression of genes encoding isocitrate lyase and malate synthase, the two key enzymes involved in the glyoxylate cycle, as well as α - and β -amylase. These experiments, which were performed by several research groups, were reviewed by Sheen (1994). Subsequently, micro-array experiments showed that 444 *Arabidopsis* genes are up-regulated by glucose (Price et al., 2004), including those involved in biotic and abiotic responses, carbohydrate metabolism, N metabolism, lipid metabolism, inositol metabolism, secondary metabolism, nucleic acid related activities, protein synthesis and degradation, transport, signal transduction, hormone synthesis and cell growth or structure. A similar number (534) are down-regulated. Clearly, changes in carbohydrate metabolism and sugar

concentration as a result of increases in CO₂ levels could have profound effects on gene expression and metabolism. However, a systems analysis of photosynthetic metabolism under elevated CO₂ suggested that 'dynamic reprogramming' and 'co-operativity' of the chloroplast network made the system more robust in the face of abnormal conditions, minimising large and possibly damaging fluctuations in metabolites (Luo et al., 2009).

Increased atmospheric CO₂ concentration has other effects on plant leaves. For example, it causes changes in stomatal density (Woodward, 1987) in a response that involves detection by mature leaves and the initiation of a systemic signal that brings about changes in developing leaves even if those leaves are not experiencing elevated CO₂ levels themselves (Lake et al., 2001; Coupe et al., 2006). Teng et al. (2006) found that elevated CO₂ not only reduced the stomatal density of *Arabidopsis* leaves, but also stomatal conductance and transpiration rate. It also increased chloroplast number and size, the latter possibly due to an increase in starch grain size and number. In another study, Bloom et al. (2010) showed that elevated CO₂ inhibited the assimilation of nitrate into organic nitrogen compounds and suggested that this, rather than feedback inhibition by sugars, was largely responsible for lower than expected photosynthetic rates in plants exposed to high CO₂ concentrations.

To date, while many studies have investigated the effects of high CO₂ concentration on plants, few have reported attempts to improve plant performance at high CO₂. Clearly, the mechanisms of feedback inhibition of photosynthesis and the inhibition of nitrogen assimilation by high CO₂ are potential targets for elucidation and manipulation.

5. Potential effects on crop quality and food safety

An often ignored aspect of global warming is the effect it will have on crop quality and food safety, as opposed to yield. For example, temperatures greater than 35 °C during wheat grain development cause changes in the expression of different groups of seed storage proteins, with consequent effects on dough quality (Blumenthal et al. 1993; Irmak et al., 2008). Heat stress is also likely to affect the concentrations of free amino acids and sugars, with potentially profound effects on processing properties. Free asparagine and proline, for example, accumulate in many plant species in response to stress (Lea et al., 2007; Lea and Azevedo, 2007). On the other hand, moderate increases in summer temperature in the UK may actually reduce the levels of free asparagine and other amino acids in wheat (Curtis et al., 2009).

Temperature during cultivation is a major factor in determining sugar concentrations in potatoes because the processes of photosynthesis, transpiration, translocation of carbohydrates and respiration are all temperature-dependent. The optimum temperature range for most varieties is quite narrow, between 15 °C and 20 °C (Kumar *et al.*, 2004). High temperatures during grain filling also cause an increase in sucrose, reducing sugars and sugar phosphates, and a reduction in starch in wheat (Jenner, 1991; Gooding et al., 2003).

Drought causes an increase in sugar content in wheat and its close relatives, barley and rye, although rye is generally more tolerant of stresses than wheat or barley, and there are considerable inter-varietal differences, with tolerant varieties accumulating higher concentrations of sugars than intolerant varieties (reviewed by Halford et al., 2011). Drought also causes an accumulation of sugars in the leaf sheath of rice (Cabuslay *et al.*, 2002) and affects enzymes involved in the conversion of sucrose to starch, with a concomitant effect on grain filling (Yang *et al.*, 2003). Sucrose synthase activity, for example, has been shown to be substantially enhanced by mild drought stress and to correlate with starch accumulation in the grain (Yang *et al.*, 2003). High temperature and drought stress also cause sugar accumulation in maize.

Drought imposes an osmotic stress on plants and plants respond by changing the partitioning between soluble and insoluble carbohydrates to maintain osmoregulation. Fructan accumulation, for example, plays a role in dehydration tolerance in cereals, and has been shown to improve rye liposome stability during drying and rehydration (Hinch *et al.*, 2007). Simple sugars and long chain carbohydrate polymers, including fructan, also improve heat shock tolerance (Fu *et al.*, 1998). Interestingly, the capacity for osmotic adjustment in plants is enhanced by elevated CO₂, possibly because of the energy requirement of the process (Pérez-López *et al.*, 2010).

Changes in sugar and amino acid concentrations in potato tubers, cereal grain and other crop products are important because they have a major impact on processing properties through the participation of these metabolites in the Maillard reaction. This reaction, which was named after the French chemist, Louis Camille Maillard, who first described it in 1912, comprises a series of non-enzymatic reactions between reducing sugars, such as glucose, fructose or maltose (although sucrose can participate after high temperature breakdown) and amino groups, principally those of amino acids. The Maillard reaction only occurs during high temperature cooking and processing, mainly in foods prepared by frying, baking and roasting. Its products include melanoidin pigments, which are complex polymers that are responsible for the brown colour in fried, baked and roasted foods. The reaction also provides complex mixtures of compounds that impart flavour and aroma. (Mottram, 2007; Halford *et al.*, 2011). The particular compounds formed give different cooked foods their characteristic aroma, and depend on the amino acid and sugar composition of the food as well as the processing conditions. Unfortunately, some of the products of the Maillard reaction are undesirable. One of these is acrylamide, which is neurotoxic, carcinogenic and genotoxic in rodents and has been classified as a probable human carcinogen by the World Health Organisation. Acrylamide forms when the amino acid that participates in the later stages of the Maillard reaction is asparagine. The reduction of acrylamide levels in food is now recognized as a difficult and important problem for the agricultural and food industries and anything that increased the acrylamide forming potential of crop products would be a serious problem.

6. Energy crops

A potentially major contribution that agriculture can make in the mitigation of climate change is through the development of energy crops; that is crops from which biomass is obtained for burning to produce electricity, or crops from which bioethanol or biodiesel is produced for use in liquid fuels. Simplistically, the benefit in terms of reducing CO₂ emissions is that the CO₂ that is released when the biomass or fuel is burnt is first acquired from the atmosphere as the crop grows. In reality, many crops require a considerable input of fossil fuels for their cultivation, for example in the production of agrochemicals and fertilisers, the oil and diesel that is used to power farm machinery and vehicles, transport, storage and processing. The carbon equation for different crops and production systems varies, and how it is calculated is a controversial issue. Some scientists question the ethics and usefulness of biofuels altogether (Walker, 2010).

The use of plant material for fuel is nothing new, of course. Humans are believed to have started using fire in a controlled way for warmth and cooking some three quarters of a million years ago. The dependence on plant products for fuel, however, has declined as

human civilisations have developed and alternative sources of energy have been discovered. One of the consequences of this is that fuel and food production from agriculture have never previously been in conflict. That is not the case now, however, with agriculture expected to meet the challenge of providing food security for an expanding world population while also helping to meet the demand for fuel as the approach of peak oil and the need to reduce CO₂ emissions forces the development of alternatives to fossil fuels.

The prospect of using biomass crops for electricity production, either for co-firing with fossil fuels or for burning on their own, has led to considerable research on the possible development of non-food crops specifically for this market (Halford and Karp, 2011). These include fast-growing trees such as willow and poplar, 'giant' grasses, such as *Miscanthus*, as well as reeds switchgrass and algae. The potential market is obviously huge, but so far these novel crops have not been adopted on a large scale, possibly because the burning of plant biomass is one of many possible 'renewable' alternatives to fossil fuels for heat and power generation, such as wind, hydro-electric and solar energy. In contrast, there are few alternatives to replace transport fuels, unless radical changes occur, such as the widespread adoption of battery or hydrogen-powered vehicles. The number of vehicles on the roads is continually rising and unless CO₂ emissions from the transport sector can be curbed, they will counter any reductions achieved elsewhere. There is also a political aspect to this, with some countries wishing to reduce their reliance on a few major producers for their fuel needs. As a result, the last decade has seen a massive increase in the production and use of bioethanol and biodiesel from plants.

Bioethanol is produced from sugars and the major sugar crops, sugar cane and sugar beet, are potential sources of feedstock. Indeed, production of ethanol from sugar cane has been an established industry in Brazil for several decades. Sugars can also be produced from starch through enzymatic digestion, which means that cereal grain is another potential feedstock. This industry is more recent but it too is now well-established, particularly in the USA, where the annual growth rate in bioethanol production, almost entirely from maize starch, was 25 % in the second half of the last decade, resulting in bioethanol production taking a third of the US maize crop in 2010. In Europe, the major starch crop is wheat, and a plant designed to produce bioethanol, operated by Ensus on Teeside in the UK, is expected to take 1.2 million tonnes of grain per year (about 8 % of the total UK wheat crop in a good year) when fully operational, and produce 400 million litres of ethanol, 350 thousand tonnes of animal feed and 300 thousand tonnes of carbon dioxide for use in the manufacture of soft drinks. A similarly-sized plant will come on line in the UK in 2011, operated by Viverno, a joint venture between British Sugar, BP and DuPont. With a number of smaller plants in the pipeline, one fifth of the UK's wheat harvest could be used for fuel rather than food production by 2015. Such a massive change in grain use will undoubtedly affect the market and there is likely to be some controversy and conflict if food prices rise as a result. However, production at the Ensus plant has stalled due to a fall in demand arising from slow implementation of EU Biofuel Directives and competition from imported bioethanol. While production is expected to re-commence later in 2011, there are clearly uncertainties in the market.

Sugars from starchy grains are, of course, used in the production of alcoholic drinks by malting, fermenting and distilling. However, the traditional malting process has been considered too complex for bioethanol production for fuel and a 'dry-grind' process has been favoured in which the entire kernel is ground into a coarse flour, then slurried with water. The resulting mash is then cooked, treated with enzymes, fermented and distilled. The first enzyme to be added is α -amylase, an endoamylase that acts at random locations

along the starch chain to yield shorter glucan chains. Ultimately its products are maltotriose, maltose and limit dextrin (a mixture of branched and unbranched glucans) and the process is known as gelatinisation and liquefaction. Gluco-amylases are then added to produce smaller sugars that can be fermented; this process is known as saccharification.

The drivers for plant breeding and biotechnology in the biofuel market are starch content and fermentability, and the quality and value of the co-product of fuel production, which is a protein-rich animal feed. Syngenta, for example, have produced a GM maize variety with a highly thermostable α -amylase gene, *amy797E*, from the thermophilic bacterium, *Thermococcales*. This variety is claimed to give a better yield of ethanol in the dry-grind process. Monsanto, on the other hand, have targeted the nutritional value of the animal feed co-product and, together with Cargill in a joint venture called Renessen, has developed a variety of maize (Mavera) that has been genetically modified to increase its lysine content. Lysine is an essential amino acid and cereal grains are generally too low in it to provide a balanced diet on their own. This means that animal feed must contain other sources of lysine, for example soybean or oilseed rape meal. The high lysine trait is imparted by a bacterial gene encoding a lysine-insensitive dihydrodipicolinate synthase. Dihydrodipicolinate synthase is an enzyme in the pathway for lysine synthesis which is feedback-inhibited by lysine, thereby providing the major regulatory control for flux through the pathway. The bacterial enzyme is not affected by lysine, allowing the amino acid to accumulate to levels beyond what it would in an unmodified plant. Maveria maize is being grown entirely for US domestic bioethanol production with high-lysine animal feed as a valuable co-product.

Biodiesel is derived from plant oils, usually after the fatty acids have been esterified with methanol to create fatty acid methyl esters (FAMEs). Biodiesel production is now an important and rapidly-growing industry in Europe. All of the major oil crops are potential sources, including oilseed rape (canola), soybean, sunflower and palm oil (Halford and Karp, 2011, and chapters therein). Less well-known, non-food crops, may also enter this market, including *Jatropha*, *Pongamia* and algae (Halford and Karp, 2011). *Jatropha* is the name given to a large group of succulent trees and shrubs, sometimes given the common name physic nut, within the Euphorbiaceae family. *Jatropha* oil is toxic (it is commonly called vomit or purge oil), but that does not affect its use for biofuel production, and *Jatropha* could be cultivated in sub-tropical and tropical countries on land that is currently considered too poor for food production. *Pongamia* is another medium-sized tree, suitable for tropical and sub-tropical cultivation, which produces large, oil-rich seeds. The attraction of algae as a source of oil for biofuel is its enormous potential yield (ten times that of oil palm, per hectare) and very low cost (less than a hundredth that of crude oil). Despite the potential of these novel, non-food crops, however, it is oil from well-established crops that is currently being diverted into biodiesel production.

As with the use of grains for ethanol, the impact of the use of plant oils for fuel on food prices is likely to provoke conflict, and the economic and ethical pros and cons are already controversial issues. This is exemplified in oilseed rape. Ironically, oilseed rape was first grown on a large scale in Europe during World War II to produce oil for industrial uses. At that time, erucic acid made up about half of oilseed rape oil. This particular fatty acid can be used to make transmission oils, oil paints, emulsions for photographic film and paper, healthcare products and plastics (in the form of its derivative, erucamide), as well as biodiesel. Erucic acid is still used for these purposes, but erucic acid is toxic, so oilseed rape varieties being grown for industrial oil have to be separated from varieties grown for food and feed. Edible varieties were produced through intensive plant breeding in the thirty

years following World War II to reduce the levels of erucic acid and other toxins to the point considered acceptable for human consumption. The first low erucic acid varieties were grown in Canada in 1968. Nevertheless, oilseed rape did not get its seal of approval for human consumption (Generally Recognized as Safe) from the Food and Drug Administration of the USA until 1985. Canadian producers then came up with the name Canola (**Can**adian **oil** low erucic **acid**) for edible oilseed rape oil. This name was adopted all over North America not only for the edible oil but also for the crop itself. The oil of these varieties is made up mainly of oleic acid (60 %), linoleic acid (20 %) and α -linolenic acid (10 %). The prevalence of these varieties means that they are the main source of oil for the new market in biodiesel. However, the rapidly increasing demand for biodiesel may lead to more cultivation of high erucic acid varieties and conflicting demands on plant breeders and growers for varieties with different oil profiles suitable for different end uses.

The debate on the use of plants to produce energy and fuel is a complex one, but energy crops do have the potential to provide a source of renewable energy which can reduce CO₂ and other greenhouse gas emissions and mitigate global warming. Competition for land, water, fertiliser and other inputs, and the conflicting demands of food and fuel security, make the issue a difficult one, with many shades of grey. Biomass/biofuel production was originally envisaged as being centred on dedicated non-food crops with the potential to produce high biomass yields with relatively low fertiliser inputs, such as willow, poplar and some perennial grasses. However, it is the use of sugar cane and starchy grain crops such as wheat and maize to produce bioethanol and oil crops for biodiesel that has taken off. These crops are, obviously, also used for food, and they require high fertiliser and other chemical inputs, which means that the carbon saving that they offer is much reduced. Nevertheless, as long as the market remains, the technology will move on. One possibility is that cell wall polysaccharides in the straw from crops such as wheat and maize will provide fuel feedstock in the future, complementing rather than competing with the production of food. These polysaccharides are currently much less amenable than starch to digestion and breakdown to simple sugars for fermentation, but solutions to that will be found through either modification of the plants or the discovery and development of microbial enzymes that will break these polysaccharides down.

7. Conclusion

I have reviewed the current state of knowledge on plant responses to drought, heat and high CO₂, the effect of stress on crop quality and food safety, and the use of crops for biofuel production, all in the context of global warming and climate change. The review emphasises the important role of modelling and systems biology in enabling plant scientists and breeders to produce varieties that will cope with extremes of drought, temperature and CO₂ concentrations in future climates.

Food prices have risen sharply in recent years as a result of increasing demand from a growing world population, increased prosperity in countries such as India, China and Brazil, all with huge populations aspiring to eat a better diet, the rapidly expanding use of biofuels from food crops, competition for land and water, and a series of extreme weather events, notably in Australia and Russia. These weather events may or may not be linked to global warming, but climate models predict that global warming will cause not only a rise in temperature at a rate not seen in the last 50 million years, but also an increase in the frequency and severity of extreme weather events. These events will impact severely on crop yield. The charitable organisation, Oxfam, released a report in May 2011 predicting that

food prices will continue to increase and that the cost of staple foods will double in 20 years unless world leaders take action to reform the global food system, with climate change accounting for half of the increase. Minimising food price increases and ensuring food security for all will be a major challenge in the coming decades and will require improved varieties and the wide adoption of agronomic best practice. Plant breeding and agriculture are, therefore, two of the key areas that will decide how we cope with climate change and how mankind emerges from the 21st century. There is an urgent need for investment in crop science, as well as knowledge transfer to ensure that advances in our understanding of plant responses to heat, drought and CO₂ feed through into improved varieties.

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.

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