Australian Government
Bureau of Rural Sciences

Australia's crops and pastures in a changing climate – can biotechnology help?

Julie Glover, Hilary Johnson, Jacqueline Lizzio, Varsha Wesley, Paul Hattersley and Catherine Knight

ISBN: 1 921192 291

Postal address:
Bureau of Rural Sciences
GPO Box 858
Canberra, ACT 2601

Copies available from:
BRS Publication Sales
GPO Box 858
Canberra ACT 2601

Ph: 1800 020 157
Fax: 02 6272 2330
Email: salesbrs@brs.gov.au
Internet: http://www.brs.gov.au

Preferred way to cite this document:

Glover J, Johnson H, Lizzio J, Wesley V, Hattersley P and Knight C 2008, *Australia's crops and pastures in a changing climate – can biotechnology help?* Australian Government Bureau of Rural Sciences, Canberra.

Foreword

The global climate has changed over the past century and is predicted to continue changing throughout the 21st century. While Australian agriculture has demonstrated a capacity to adapt to the challenges of a variable climate, the predicted changes in climate have the potential to expose farming systems to conditions and extremes not experienced before.

Climate change impacts are likely to vary across geographical regions and between different agricultural sectors. Some of the changes in climate could have positive impacts while others will be detrimental. Taking advantage of these opportunities and minimising detrimental impacts will require the use of a variety of tools including biotechnology.

This report summarises the impacts that predicted changes in climate may have on cropping and pastoral industries in Australia. It then describes the potential role of biotechnology, such as using genetic modification and molecular markers to develop new plant varieties, to help farmers adapt to climate change. It also describes ways in which biotechnology may help reduce greenhouse gas emissions from agricultural areas.

The report's findings were informed by a desktop literature review and the outcomes of a one-day workshop held by the Bureau of Rural Sciences to discuss agricultural biotechnology and climate change. The workshop brought together experts in a variety of scientific fields (including climatology, biotechnology, plant physiology, plant pests and disease, modelling and agronomy) and highlighted the broad applications of this technology for agriculture when faced with the uncertainty of climate change.

K Schneider

Karen Schneider
Executive Director
Bureau of Rural Sciences

Executive Summary

This report explores the potential role of biotechnology in helping Australian cropping and pastoral industries meet the challenges of climate change.

This report reviews modern biotechnology tools that could help farmers adapt to the predicted impacts of climate change, as well as assist in mitigation strategies to reduce greenhouse gas emissions. It focuses on the Australian broadacre cropping and pastoral sectors.

The Earth's climate is currently warming, most likely due to increases in atmospheric greenhouse gases.

According to the 2007 report by the Intergovernmental Panel on Climate Change (IPCC), warming of the Earth's climate system is unequivocal. Humans, through the release of greenhouse gases such as carbon dioxide, are very likely to be the cause of most of the warming that has been experienced since 1950. Continued increases in atmospheric greenhouse gas concentrations are predicted to lead to further changes in the global climate system well into the future.

Australia's climate is likely to be different in 2030.

Changes in the climate will not be uniform. In Australia, the best estimate of annual warming by 2030 relative to 1990 is about 1.0ºC. Rainfall is also likely to change, although projections are more uncertain, with increases and decreases predicted for different parts of Australia. The future precipitation regime for much of Australia is predicted to involve longer dry spells interrupted by heavier rainfall events.

Changes in climate will impact significantly on agriculture.

Predicted changes in climate present challenges to all sectors to adapt to them and help mitigate any further human-induced climate change. Agriculture will be particularly vulnerable as the sector is heavily reliant on natural resources, which are influenced by climatic conditions. Climate change impacts are likely to vary geographically and between agricultural sectors, with the potential for both positive and negative impacts.

For crops and pastures, climate change could lead to the plants facing heat stress, both extremes of water stress (i.e. drought and waterlogging) and changes in the distribution, abundance and severity of insect pests, pathogens and weeds. Whilst increases in atmospheric carbon dioxide concentrations could lead to an increase in biomass, it could also decrease the nutritional quality of crops and pastures.

The agricultural sector is a net emitter of greenhouse gases, and is the major contributing source of nitrous oxide and methane.

The agricultural sector accounts for 16–18 per cent of Australia's net greenhouse gas emissions, which includes nitrous oxide (primarily from fertiliser applications), methane (primarily from livestock) and carbon dioxide. As a net emitter, agriculture needs to take steps to reduce emissions and/or to increase carbon storage. This is a particular challenge for intensive cropping. Agricultural soils can act as a sink for carbon storage, and stored carbon can be increased by growing trees, changing cultivation and other cropping practices.

Climate change risks to crops and pastures need to be managed through a range of measures, including biotechnology.

Australia's cropping and pastoral industries will need to apply a range of measures to help them meet the challenges of climate change. Three main approaches which will help farmers adapt to climate change as well as mitigate greenhouse gas emissions are the development of new crop varieties, changing farm management practices, and using alternative crops or pastures. Biotechnology has an important role in each of these approaches.

Modern biotechnology includes the use of enhanced genetic mapping technologies, such as molecular markers, in plant breeding and in development of genetically modified (GM) varieties.

Modern biotechnology will help in developing new crop and pasture varieties adapted to changing climates…

Modern biotechnology is increasingly playing an important role in the development of new crop and pasture varieties that will continue to produce a competitive yield under the stresses of climate change. Tools such as molecular markers can provide greater accuracy and speed in conventional crop and pasture breeding programs. Genetic modification techniques provide access to a greatly increased diversity of genes for developing plant varieties with traits relevant to climate change adaptation and mitigation.

There are a number of plant traits likely to be important for adapting to climate change. These include heat tolerance, water-use efficiency, nitrogen-use efficiency, early vigour, waterlogging tolerance, frost resistance, pest and disease resistance, and reduced dependence on low temperatures to trigger flowering or seed germination. Research is being conducted into developing molecular markers or GM varieties for these traits.

…as well as providing greater options for changing farm management practices…

Modern biotechnology can help in developing plant varieties which can assist in the adoption of farm management practices that are likely to be beneficial under climate change. Practices such as no-till farming and dry sowing have been found to be beneficial for growing crops in water-limited environments. Weed control becomes a problem when dry sowing or when tillage is reduced, but GM crops tolerant to broad spectrum herbicides have enabled farmers to adopt these practices and will enable farmers to meet new weed management issues in a changing climate.

…and for managing new and emerging pests and diseases.

Biotechnology tools are also used in many diagnostic tests and in surveillance for plant pests and pathogens. Laboratory-based techniques such as Enzyme-Linked Immunosorbent Assay (ELISA) and Polymerase Chain Reaction (PCR) will be important to detect and identify any new and emerging pathogens which have become established, become more abundant, or spread into new areas under changed climatic conditions.

Breeding new crop and pastures species through biotechnology can provide farmers with alternative land use options and hence greater flexibility in the face of climate change.

Biotechnology may also assist the adaptation to climate change by breeding crop and pasture varieties for alternative land uses. For example, plants used for biofuels could provide alternative sources of income for farmers whose land had become more marginal due to climate change.

Plants can also be genetically modified to produce novel pharmaceutical and industrial products which could provide opportunities to diversify from traditional food and feed markets into new markets. Growing such alternative crops could maintain or increase the profitability of farms in a scenario where a changed climate makes traditionally grown crops unprofitable or results in unacceptably frequent crop failure.

Biotechnology has a role to play in reducing agricultural greenhouse gas emissions…

In addition to helping farmers adapt to climate change, biotechnology can assist in reducing greenhouse gas emissions generated by agriculture and in increasing the amount of carbon sequestered in agricultural soils.

Current insect-resistant GM crop varieties have resulted in reductions in on-farm fossil fuel use due to the decrease in the number of insecticide applications required. Herbicide-tolerant crops have promoted the adoption of no-till practices that require less tillage and therefore reduce fuel use. Future developments of pasture grasses and grains with improved digestibility could assist in reducing methane emissions from ruminants and nitrous oxide emissions from animal excreta. Crops and pastures with improved nitrogen-use efficiency would reduce nitrous oxide emissions through reducing the amount of nitrogenous fertiliser applications required.

…and in increasing carbon sinks.

Increasing carbon sequestration in agricultural soils to reduce atmospheric carbon dioxide can be achieved by maximising the amount of carbon delivered to the soil and then increasing the time that the carbon stays in the soil. Strategies for achieving this include breeding plant varieties through biotechnology that have increased photosynthetic efficiency, increased lignin content, improved pest and disease resistance, deeper roots, and improved water use and nutrient efficiency. The adoption of no-till farming practices also helps increase carbon sequestration.

In assessing the value of biotechnology, traits need to be considered for their technical feasibility, financial viability and community acceptance.

This report identifies a number of traits which may directly or indirectly (through encouraging the adoption of beneficial farm management practices) help farmers adapt to the impacts of climate change and reduce agricultural greenhouse gas emissions. Some of these traits are more immediately attainable than others.

For example, traits for which there is a single gene solution will be more easily attained. In this regard, insect-resistant and herbicide-tolerant varieties have already been successfully developed and commercially grown. For future developments, disease resistance is a very realistic goal for biotechnology while varieties with stacked (combined) traits of multiple insect-resistant and herbicide-tolerant genes are also becoming available.

In the short term, conventional breeding techniques, with the aid of molecular marker technologies, are perhaps more likely than genetic modification to result in significant yield improvement under environmental stress due to the complex nature of the genetic pathways involved. This is likely to be the case for most traits which can be affected by a changing climate, such as nitrogen-use efficiency, frost resistance, waterlogging tolerance and control of the timing of flowering. However, discoveries of single genes which control complex traits could speed up the time to commercialisation. While an analysis of financial viability is beyond the scope of this study, this aspect must be noted as a key determinant when assessing the value of biotechnology.

It is unlikely that any of the new crops for alternative land use options identified in this study will be technically feasible and/or financially viable in the near future. Commercialisation in Australia of broadacre GM crops producing industrial and pharmaceutical products is still a long way off. Similarly, the climate change adaptation and mitigation opportunities provided by biofuels are likely to be limited in the short term.

In developing GM crops and pastures, consideration must also be given to the community acceptability of particular traits. Despite being technically feasible and financially viable, there has been community resistance to some GM herbicide-tolerant crops. A study on attitudes in Australia towards GM crops showed that a high percentage of the community rated traits that provided drought and pest resistance as very valuable (69 per cent and 52 per cent respectively), while only 29 per cent of those surveyed rated GM herbicide-tolerant crops as very valuable.

Conclusion

The use of modern biotechnology is one of many strategies which could be applied to help farmers adapt to and mitigate climate change. Biotechnology offers a broad range of options for the development of new crop and pasture varieties that are better adapted to a changed climate. It also has a role to play in reducing greenhouse gas emissions from agriculture and in increasing soil carbon.

The traits described in this report are being investigated or developed in Australia or overseas, but some traits will be more achievable and desirable than others. It is important to identify the traits that are most achievable, most needed and would have the greatest impact for adapting to or mitigating climate change. A collaborative approach between farmers, industry, scientists and government to identify those traits and associated farm management practices is needed.

Adoption of enabling technologies such as biotechnology for the agriculture sector needs to be further encouraged and adequately funded. A comparative analysis of the relative benefits and impacts, in a range of agriculture sectors (crops, pastures, horticulture and forestry) of the applications scoped in this study, would help identify priorities for biotechnology research and development relevant to climate change.

Contents

Part 1 – Australian crops and pastures in a changing climate

Chapter 1 – Introduction

1.1 Background and scope of study

This report is the result of a study funded by the Department of Agriculture, Fisheries and Forestry (DAFF) using funds provided under the National Biotechnology Strategy. The study investigated modern biotechnology tools that could help farmers adapt to the predicted impacts of anthropogenic (human-induced) climate change, as well as assist in mitigation strategies to reduce greenhouse gas emissions.

The study comprised a desktop literature review and was also informed by a workshop held by the Bureau of Rural Sciences (BRS) in June 2007 on 'Agricultural Biotechnology and Climate Change'. The scope of the workshop was limited to broadacre plant varieties and focused on climate change scenarios predicted for the year 2030.

There were 23 attendees at the workshop, with expertise in a variety of scientific fields including climatology, biotechnology, plant physiology, plant pests and disease, modelling and agronomy. Attendees at the workshop discussed issues including biotechnology as a tool and its effects or potential effects on:

- crop development
- biological components of the agricultural system (insect pests/plant diseases/weeds)
- farm management practices
- the understanding of interactions between genetics/environment/management.

Where information from the workshop is referred to in the report, it is cited as 'BRS Workshop 2007'.

The scope of this study was restricted to modern biotechnology which includes molecular marker, genomic, genetic modification, and deoxyribonucleic acid (DNA) and immuno-diagnostic techniques.

It should be noted that this report is not a comprehensive list of every biotechnology development or crop that may assist in adapting to and mitigating climate change. Rather, this report identifies a selection of opportunities where biotechnology is likely to provide important tools for farming in Australia under a changing climate. The prioritising of various developments or crop traits has not been made, although some commentary is provided on how attainable these goals might be in the immediate future.

1.2 Climate change in Australia in 2030

Throughout Earth's history, climate[1] has changed on all time-scales from months to millions of years and longer (IPCC 2007). The changes in the climate can be caused by processes internal to the Earth, as well as external forces ("forcings") such as variations in light energy input, and, more recently, human-induced changes in atmospheric composition.

[1] Climate is the statistical aggregate of weather conditions such as temperature, precipitation, wind, cloudiness, and storms over a period of time. Climate "normals" such as means, extremes and frequencies of occurrence are set over 30-year periods. Climate variability is defined as the variations (ups and downs) in climatic conditions on time-scales of months, years, decades, centuries, and millennia.

Warming of the Earth's climate system is now unequivocal, with the Intergovernmental Panel on Climate Change (IPCC 2007) stating that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Greenhouse gases absorb and re-radiate infra-red radiation that is emitted by the Earth, and are responsible for maintaining the Earth's surface temperature. An increase in greenhouse gas concentrations in the atmosphere leads to further absorption of infra-red radiation and hence more heat is trapped. The greenhouse gases of most concern are carbon dioxide, methane and nitrous oxide. The main anthropogenic sources of carbon dioxide are fossil fuel use and land use change; whilst agriculture is the predominant anthropogenic source for both methane and nitrous oxide.

The resulting changes in climate are not uniform at global, continental or regional levels. For example, projected changes in temperature and precipitation can vary significantly at fine spatial scales, particularly in coastal and mountainous areas. For Australia, climate change projections have been developed by CSIRO and the Bureau of Meteorology (2007). The best estimate[2] of annual warming for Australia is a 1°C increase by 2030 relative to 1990 levels, with an uncertainty range between 0.6 – 1.5°C. For coastal areas the warming is likely to be around 0.7–0.9°C and 1–1.2°C for inland Australia. It is also likely there will be a substantial increase in the frequency of days over 35°C and a moderate decrease in frosts.

Rainfall projections are more complex and uncertain, with climate models showing increases and decreases for many locations. Best estimates of annual rainfall for 2030 relative to 1990 levels indicate little change for the far north and a decrease of 2 to 5 per cent everywhere else. This includes a decrease of 5 per cent in winter and spring, particularly the south-west where projected rainfall decreases reach 10 per cent. Decreases are smaller over summer and autumn, with a slight increase in New South Wales in summer. The uncertainty with these predictions is large, with rainfall change ranging from -10 per cent to +5 per cent in northern areas, and from -10 per cent to little change in southern areas. Winter and spring changes are predicted to be between -10 per cent to little change in southern areas of south-east Australia, -15 per cent to little change in the south-west and -15 per cent to +5 per cent in eastern areas. In summer and autumn, the range is typically -15 per cent to +10 per cent. Decadal-scale natural variability in rainfall could mask or significantly enhance the greenhouse-forced changes. Increases in daily precipitation intensity (rainfall per rain day) and the number of dry days have also been predicted, suggesting that the future precipitation regime will have longer dry spells interrupted by heavier precipitation events (CSIRO and BOM 2007).

Annual potential evapotranspiration (the amount of evaporation and transpiration that will occur if there is no deficiency of water) is projected to increase across Australia. Largest increases are in the north and east with the best estimate being a 2 per cent increase by 2030, with an uncertainty range of little change to a 6 per cent increase. Models suggest an increase in drought occurrence across Australia, particularly in south-western Australia, with up to 20 per cent more agricultural drought[3] months over most of Australia by 2030 (CSIRO and BOM 2007).

Other climatic changes have also been identified in the CSIRO and Bureau of Meteorology (2007) projections. Average wind speed is expected to increase in most coastal areas, and extreme wind speed is also likely to increase. Small decreases in relative humidity are projected over most of Australia. Fire weather risk is likely to increase substantially at most sites in south-eastern Australia.

---

[2] Best estimate is the 50th percentile of projected climate changes for 2030 relative to 1990 and based on a mid-range greenhouse gas emission scenario (A1B scenario).

[3] Agricultural drought refers to changes in the seasonal temperatures and/or the distribution or amount of rainfall that constrain agricultural production and it was defined in the report as a period of extremely low soil moisture (CSIRO and BOM 2007).

A crucial issue is whether climate change will occur gradually via small changes in underlying climate component averages, or whether a series of abrupt, stepped changes will occur. An abrupt change can be described technically as a change which is determined by the internal dynamics of the climate system, triggered by the system being forced to cross some threshold or tipping point. By contrast, a gradual change is one where the climate system change is controlled by the time-scale of the forcing cause or event (such as variation in sunlight) (Meehl et al. 2007). A gradual change in the climatic system is regarded as having less adverse outcomes for human societies and thought to be more favourable, as abrupt changes are unpredictable and so cannot be planned for, and may push some industries beyond operational thresholds (Steffen et al. 2006). It is not certain whether abrupt or gradual climate changes are more likely to occur.

1.3 The challenge of climate change for Australian agriculture

These predicted climate changes present challenges to all sectors both to adapt to the changes and to help mitigate any further human-induced impacts. They present a particular challenge to the diverse agricultural industry because this sector is heavily reliant on natural resources and ecosystem services, which are influenced by climatic conditions. Although the magnitude of these changes is uncertain, particularly at a regional level, the threat is very real.

Australia already has a highly variable climate, with significant spatial and temporal variations in climate across the continent and over time. Precipitation in particular varies significantly from year-to-year and decade-to-decade. Broadly, Australia has a number of distinct climatic zones: the summer-rainfall-dominant subtropics and tropics to the north; the Mediterranean climates to the south-west and mid-south; the arid and semi-arid regions in most of the inner continent; and temperate areas of high to medium rainfall on most coastal fringes and in the ranges of the east of mainland Australia and Tasmania (BRS 2007).

It is under this variable climate that Australia's diverse agricultural sector has evolved. Australian producers have developed land management and farming systems that are adapted to these climate regimes and to some extent respond to previously experienced climate variability. Despite this adaptive capacity, Australian agriculture is still susceptible to the extreme vagaries of climate, as highlighted by recent droughts (2002–2003; 2006–2007). Climate change is likely to lead to an increase in variability and in the occurrence of extreme events such as exposure to prolonged high temperatures, severe storms and dry conditions. Climate change impacts will vary between regions—some impacts may pose threats to the viability of agriculture in some regions, while in other regions changes in climate may improve viability or create new opportunities. In response to climate change, farmers will be required to develop new approaches to manage climate related risks.

Chapter 2 – Predicted climate change impacts on Australian crops and pastures

2.1 Cropping and pasture systems in Australia

For crops and pastures, climate change could lead to plants facing heat stress, both extremes of water stress (drought or waterlogging) and changes to the distribution and abundance of insect pests, pathogens and weeds. Impact assessments to date suggest a wide range in the magnitude and direction of climate change impacts and also highlight regional variability. In addition to biophysical factors, the projected changes are likely to be further influenced by a range of social trends and economic forces, which add further dimensions of complexity to climate predictions. The report focuses on three farming sectors—winter dryland cropping, cotton and pastures—to highlight some of the impacts of climate change on Australian agriculture and examine the potential role for biotechnology in these systems. Some agricultural sectors, such as cotton, already grow genetically modified (GM) varieties and provide a useful demonstration of how biotechnology can help Australian crops in a changing climate. The information was compiled through a literature review and is not intended to represent definitive scenarios or risks. Maps illustrating the three farming sectors are included in the Appendix to the report.

2.1.1 Australian winter dryland cropping sector

Australia's winter dryland cropping sector produces wheat—Australia's most important crop in terms of economic value, volume and area—as well as other crops such as barley, oats, canola, lupins and peas. Wheat is grown in temperate regions (see Appendix) and the sector is highly sensitive to climatic influences as it tends to be grown in areas which experience relatively low rainfall (200–300mm in winter and spring) and high potential evaporation values. Dryland cropping relies solely on rainfall (as opposed to irrigation water) for the provision of soil moisture, and this makes the sector even more vulnerable to climate change.

2.1.2 Australia's cotton growing sector

Australia's cotton sector is one of Australia's largest rural export earners, generating approximately $825 million in export revenue in the year 2006–07 (ABARE 2007). The sector is heavily dependant upon irrigation water for production, with irrigation used on around 86 per cent of Australian cotton farms in 2005–06 (ABS 2007). Cotton is a summer crop, and most of it is grown in northern New South Wales and southern and central Queensland (see Appendix). The crop prefers hot summers with low humidity and a maximum amount of sunshine when water is adequately supplied. In general, cotton grows faster as the average temperature rises, and the longer and hotter the season the greater the yield provided water is supplied (Cotton Australia 2006). Over the past ten years, average yields have been increasing, largely as a result of rising use of GM cotton varieties, other technological improvements and improved crop management (ABARE and MAF 2006). However, it was predicted that continued dry conditions in most catchments and low water storages will lead to a decline in the area of cotton grown in 2007–08 (ABARE 2007) and this proved to be the case.

2.1.3 Pastures

Pastures are the primary resource for many farm industries and are the basis for the production of meat, wool, milk and fodder in Australia. They are diverse in terms of the different farming enterprises they support, geographical distribution and species composition. Pastures comprise both native and exotic annual and perennial grasses, legumes, herbs and shrubs. Native pastures for grazing are predominantly located in the Australian rangelands (northern, central and the more inland areas of Australia) and occupy 55 per cent of the continent (see Appendix) (Lesslie et al. 2006). Introduced species, sown pastures and irrigated pastures are more commonly located in the wheat belt and the high rainfall zone of coastal and southern Australia. Irrigated pastures currently use about 35 per cent of total irrigation water used in Australia.

2.2 Direct impacts on crop and pasture plants

Plants require carbon dioxide, sunlight, water, a given temperature range, and nutrients to germinate, grow and reproduce. These are non-biological (abiotic) environmental factors or inputs. Unlike animals, plants can make their own ‘food’ from carbon dioxide and water, using the sun’s energy (light). This process is known as photosynthesis.

Of these five primary abiotic environmental factors that are critical for plants, four are related to climate: carbon dioxide, light, temperature and water. They vary not only spatially, diurnally, and seasonally but also, in the climate change context, over longer time periods. These four factors that affect crop or pasture growth and productivity in current climates are discussed in turn:

- atmospheric carbon dioxide concentration in open-environment situations for crops and pastures is ‘constant’ and reliable from a farmer’s seasonal perspective. It is not regarded by farmers as a factor limiting growth and productivity. Although higher carbon dioxide concentrations could increase the productivity of many crops and pastures, it is uneconomical for farmers to provide extra carbon dioxide inputs to their crop or pasture
- light energy input varies diurnally (and with amount of cloud cover), with latitude, and with the season (because day-length varies seasonally). Light energy input to a crop or pasture is also more or less reliable from a farmer’s perspective (in open-environment situations for crops and pastures) and is generally not a limiting factor or risk (though an exception is when plants are water-stressed). Farmers cannot, and do not attempt to, manage the light inputs to their crop or pasture, except through choice of which crop they can grow in a given climate (because of, for example, different day-length requirements of different crops) and the density at which they sow a crop
- temperature varies diurnally, with latitude and with season, and also with altitude. Average temperature ranges and fluctuations have been more or less predictable, but unseasonal variations can have drastic effects on a crop (for example, a late frost can destroy or severely set back a crop). In open-environment situations for crops and pastures, farmers have control over temperature in the sense that they plant or sow a given crop or pasture in the appropriate season and at a time in the season to which the crop or pasture species is adapted
- water supply through rainfall varies daily, over regions, and between years and the variations are significant. In dryland farming, crops and pastures are especially impacted by these variations, and consequently there is an inherent risk in relying on rainfall for water supplies and water availability is a critically limiting input in farming. Hence, water inputs are often managed intensively, with many crops and pastures under furrow, drip or boom irrigation.

During evolution, plants have adapted in a range of ways to varied climatic regimes. Hence, different species have different optimal ranges for the abiotic inputs for successfully growing and completing their life cycles. Plants also have different upper and/or lower threshold levels for these factors, beyond which individuals die or their growth is severely retarded. All plants have their particular limits and tolerances when exposed to drought stress, waterlogging, very high temperature or very low temperature (i.e. frost tolerance). Plants can also be stressed by high light energy input; for example, when they are water-stressed. Crops, but relatively few pasture species, have been adapted to particular growing situations through plant breeding (human-directed ‘selection’).

A given crop or pasture species’ (or variety’s) functional (physiological) response to changing climatic inputs are critical to understanding the performance of any crop or pasture in a changed climate. However, responses will be very diverse, depending on the species, variety and, in a given place, whether or not the crop is already being grown in areas where the climate is already marginally suitable.

The responses of a given crop or pastures species to variations in carbon dioxide, light and water are not only specific to that type of plant (variety or species), but also complex. Specific species/varieties are uniquely programmed, as already noted. Further, responses to changes in one variable will be interdependent with the changes in another variable. For example, an increase in atmospheric carbon dioxide has the potential to increase photosynthetic rates and increase growth, but only if there is sufficient water and nutrients to sustain that increased growth (and therefore increase yield). Increases in temperature generally increase metabolic rates, again with the potential for increased growth and yield, but only if there is adequate water and the maximum temperature threshold for that species is not exceeded. An increase in rainfall would clearly help plants grow faster, but not if:

- temperatures and light energy input (dense cloud cover) are suboptimal
- there is so much water, that plants become waterlogged
- the increased rainfall is associated with more frequent storms which damage crops.

Predicting the precise impacts of climate change on a crop or pasture growing across all current areas of distribution would be very complex and perhaps not even possible, given the lack of sufficient detail of plant physiological responses to climatic variations and their interactions. It would be further compounded by the lack of certainly about the precise climate changes for given regions and localities. Nevertheless, impacts can be predicted in general terms and, where there has been some detailed research, specific cases and predictions can be described.

Of the four abiotic environmental factors critical for plants mentioned above, three are mainly relevant to considering the impacts a particular climate change scenario will have on crops and pastures: carbon dioxide concentration, temperature and water. Light energy input is not included because any changes in a climate change scenario would be unlikely to be a major factor limiting plant growth.

The following sections summarise some of the predictions based on known plant physiological responses for these three abiotic inputs for plant growth and performance. Understanding the likely responses of plants to carbon dioxide concentration, temperature and water is fundamental to understanding how biotechnology could be applied to ameliorate adverse effects on plants through adaptation.

2.2.1 Impacts of increased atmospheric carbon dioxide concentration

Increases in atmospheric carbon dioxide concentrations (similar to concentration levels predicted for 2030) are expected to:

- increase the rate of photosynthesis in C_3 plants[4] (Tubiello et al. 2007)
- increase the transpiration efficiency of the leaf (in both C_3 and C_4 plants); that is, decrease the amount of water lost through transpiration per unit of sugar produced (Steffen and Canadell 2005). Transpiration efficiency refers to the rate of biomass production of a plant relative to the amount of water lost from leaves, so greater efficiency results in a decrease

[4] Plants can be classified based on how they fix carbon from atmospheric carbon dioxide into plant carbohydrates, with the two main types being C_3 or C_4 plants. An estimated 95 per cent of plant species are C_3 plants, and include wheat, barley and rice. C_3 photosynthesis is more efficient than C_4 photosynthesis under cool and moist conditions, and normal light levels. C_4 plants include sugarcane, corn (maize), sorghum, and other grasses such as kangaroo grass and Mitchell grass. C_4 photosynthesis occurs faster and more efficiently under high temperature and light, and conserves more water in comparison to the more common C_3 photosynthesis. Consequently, C_4 plants are most prevalent in hot arid, tropical and subtropical climates, although C_3 plants still usually dominate vegetation in all regions.

in the amount of water lost through transpiration per unit of sugar produced (Steffen and Canadell 2005).

The overall effect would be an increase in yield for crops and the carrying capacity of pastures, provided all other factors and conditions remain the same. This effect is known as carbon dioxide fertilisation. The percentage increase in yield would be greatest in water-limited environments. Any increases in yield due to increased carbon dioxide concentrations may be offset by yield losses due to decreases in precipitation, increases in temperature and changes in the pest, disease and weed regimes as predicted under climate change (Chakraborty et al. 2002).

Elevated atmospheric carbon dioxide concentration is predicted to increase yields for winter dryland cropping (Amthor 2001; van Ittersum et al. 2003; Steffen and Canadell 2005) and increase above-ground plant productivity for pastures (Howden et al. 2004). For cotton, an increase in atmospheric carbon dioxide may lead to an increased rate of photosynthesis, and greater transpiration efficiency resulting in increased biomass, fruit weight and lint yield (Hunsaker et al. 1994; Reddy et al. 1995; Reddy et al. 2000; Zhao et al. 2004).

Elevated atmospheric carbon dioxide concentrations could possibly lead to a decrease in the nutritional quality of crops and pastures due to reduced protein and nitrogen content in grains and leaves (Amthor 2001; Pittock 2003; Ludwig and Asseng 2006). Much of the protein in leaves is involved in assimilating carbon dioxide into sugars. Thus, when elevated carbon dioxide levels are present this process becomes much easier, so plants require less protein, which in turn reduces nitrogen needs (Stafford 2007). A doubling of current carbon dioxide concentrations has been found to reduce grain nitrogen content by 4–14 per cent in a simulation (assuming no management adaptation) (Howden et al. 1999), which represents a loss of up to $70/tonne based on prices over the ten years prior to 2002 (Pittock 2003). Increasing nitrogen fertiliser applications may negate this reduction in protein (Kimball et al. 2001).

In pastures, the concentration of soluble carbohydrates in the leaves goes up with increasing carbon dioxide concentrations. This improves the digestibility of forage crops and hence the access to forage nitrogen (Steffen and Canadell 2005). In high nitrogen forage (e.g. temperate pasture) elevated carbon dioxide is likely to increase energy availability, thus increasing nitrogen processing in the rumen and enhancing productivity (Howden et al. 2004). However, in nitrogen-deficient forage (many rangelands for part of the year) the effect may exacerbate nutrient deficiencies (Howden et al. 2004).

2.2.2 Impacts of increased temperatures

Increased temperatures may affect phenological development in some cropping areas (Fuhrer 2003; Pittock 2003; Ludwig and Asseng 2006; Anwar et al. 2007) reducing the time for the capture and the use of light and water (Anwar et al. 2007)[5]. Studies have shown that for every degree Celsius above wheat's optimal growing range (15–20^{o}C), on average there is a 2.8 day decrease in the grain-filling period and a 1.5 mg decrease in kernel weight (Streck 2005). As such, a shorter growing period may reduce yields if appropriate changes to management are not adopted, such as early planting for spring–summer crops and the use of slower-maturing winter cereal cultivars (Tubiello et al. 2000). Increased temperatures are also likely to affect the phenological development of cotton, with hastened development potentially leading to decreases in boll fruit retention (Richardson et al. 2002).

Some crops are subject to direct heat stress or deterioration during heat waves. The grain protein composition of crops such as wheat deteriorates after several days above 35^{o}C (Pittock 2003). This presents a risk to winter crops as their grain-filling occurs late in the season when temperatures are increasing. However, up to certain temperature increases (4 ^{o}C mean warming) there may be little change in heat shock for grain (Pittock 2003) due to faster phenological development and earlier

[5] Phenological development refers to the relation of developmental stages of plants to seasonal changes.

planting schedules. For cotton, higher temperatures could increase the risk of heat stress/shock resulting in lower boll set and lint yield (Liu et al. 2006b; Singh et al. 2007).

Vernalisation, a process (required by some crops, for example, some wheat varieties) in which exposure to low temperatures induces seed germination or flowering, could also be negatively impacted. Increased temperatures will lead to a reduction in the number of cold days available for this process.

On the positive side, increased temperatures could result in a reduction in frost risk, reducing frost damage. It may allow earlier flowering in some dryland winter cropping sites (van Ittersum et al. 2003; Howden et al. 2004) and enable the use of earlier-flowering wheat cultivars (Howden and Crimp 2005) to avoid late season high temperatures. Higher temperatures could have a positive effect on cotton yields because of fewer cold shock days than currently occur on average.

Impacts of increased temperatures on grain yield strongly depended on location (Ludwig and Asseng 2006) and simulated temperature effects on grain yield have been found to be different in varying soil types and locations (van Ittersum et al. 2003; Ludwig and Asseng 2006). Therefore the impacts of climate change will also vary significantly depending on the dominating soil type in the particular system

2.2.3 Impacts of altered rainfall regimes

Due to the predicted increase in rainfall variability, crops and pastures will be faced with stresses from both higher and lower levels of rainfall compared to current levels.

Heavy rainfall events can lead to flood damage, waterlogging, anoxic (lacking oxygen) soils and disruption to planting and harvesting. Too much water blocks the entry of oxygen into soil (Buchanan et al. 2000). When oxygen becomes scarce around roots in a waterlogged environment, roots and microorganisms lose 85–95 per cent of their capacity to produce energy and they cease to grow (Atwell et al. 1999). Also, toxic microelements appear in oxygen-limited soil environments due to carbohydrates being broken down via a fermentative pathway (Atwell et al. 1999). These environments may also result in toxic metal ions (e.g. aluminium ions) which are normally bound in the soil substrata being made available to plants to uptake.

In contrast, insufficient rainfall could lead to:

- low soil moisture status
- failure of seeds to germinate or of seedlings to establish
- small pinched grains at the time of harvest resulting in reduced yields.

Tissue death results if the relative water content of a given organ drops below a critical value, which varies among plant species (Buchanan et al. 2000). Crop plants generally fail to survive reductions in relative water content to values below 30 per cent of normal (Atwell et al. 1999). The processes of plant cell growth, which are dependent on water content, and later phases of leaf expansion are particularly sensitive to water stress (Atwell et al. 1999). Because plants dissipate heat mainly through transpiration, this process is inhibited when there is a water deficit and thus heat stress can ensue (Buchanan et al. 2000).

In addition, the timing of rainfall is important. Rain falling on ripe wheat crops may induce pre-harvest germination for grain while still in the ear, rendering the grain unsuitable for commercial processing (Atwell et al. 1999). Similarly, insufficient water at flowering time can lead to infertility, even if the crop's water supply may be adequate at other times (Passioura 2006).

Depending on other factors such as temperature increase and carbon dioxide concentration, changing rainfall can have a positive or negative effect. For example, Ludwig and Asseng (2006) used computer models to examine the effect that increased temperature (+2, 4 and 6°C), elevated carbon dioxide concentration (525 and 700ppm) and five different rainfall scenarios (historic rainfall, -15, -30, -60 and +10 per cent) had on wheat yield and grain protein in the wheatbelt of south-west Australia. The results of the modelling indicated that higher carbon dioxide concentration increased yield, especially at drier sites; whilst higher temperatures had a positive effect in the cooler and wetter part of the region. The authors found that elevated carbon dioxide concentrations decreased grain protein concentration and lower rainfall increased protein levels at all sites (Ludwig and Asseng 2006).

2.2.4 Combined impacts

The impact of specific climate change drivers on plants is dependent on changes in other climate change drivers. For example, plant responses to increased atmospheric carbon dioxide concentrations are dependent on other variables such as temperature, rainfall, soil moisture and soil nutrient availability (Howden et al. 2004; Tubiello et al. 2007). No individual change is likely to compensate for the impacts of any negative environmental stress(es) due to other variables. For example, it is likely that the beneficial effects of higher temperatures are only relevant for scenarios where rainfall increases (Howden and Crimp 2005).

Ultimately there will be variable direct impacts on plants and, consequently, variable production results (quantity, quality and spatial distribution) due to the complex interactions between climate change drivers and also with other factors, such as the responses of insects, pathogens, weeds and other pests to climate change.

2.3 Impacts of climate change on insect pests, pathogens and weeds

The distribution, abundance and management of insects, pathogens, weeds and other pests will be affected by climate change [6]. For example, the likelihood that pests, particularly those of tropical or semi-tropical origin, will spread southward in Australia, or become established after an incursion, increases with climate warming (Pittock 2003).

It is important to consider the impact of climate change on pest biology and ecology because of the indirect impacts on crops and pastures (Pittock 2003). The impacts of insect pests, pathogens and weeds are influenced by changes to both the host and the pest, and their interactions with each other, as well as the environment. A change to any of these factors will affect the incidence and severity of a pest.

The greatest impact of elevated carbon dioxide on insects and pathogens is related to the altered condition of the plant host in this environment and not to any direct impact on these organisms (Chakraborty et al. 2002; Ziska and Runion 2006). For example, crops growing in a marginal climate and experiencing an environmental stress could be exposed to new or increased levels of insect and disease outbreaks (Coakley et al. 1999). Similarly, a plant host stressed by the environment could have an altered physiology and chemical composition, which may render it more susceptible to pests or diseases (BRS Workshop 2007) due to altered concentrations of defensive compounds (Ziska and Runion 2006). The amount of crop or pasture plant tissue available as host or food for a pest may also increase (Chakraborty et al. 2002).

Efficacy of current control measures could be altered—for example increased canopy density may protect pests from chemical sprays because the sprays penetrate the crop or pasture less.

Host-pathogen relationships may also change if the host crop or pasture species are being grown in land areas altered by climate change. However, if the population size of biological control agents (e.g. beneficial predatory insects) also increases under climate change conditions, the negative impacts may not be as significant.

Australia's biosecurity risks may also be altered because of new and emerging risks. Biotechnology has the ability to counteract and contribute to plant adaptation or resistance to these impacts.

---

[6] A pathogen is an organism or agent which causes disease (Alberts 2002).

Due to the complexity of interactions between pests, hosts and the environment, as well as a lack of empirical data, impacts of climate change are extremely difficult to predict (Tubiello et al. 2007). Despite this, there is considerable literature examining the potential impacts of climate change on insects, pathogens and weeds. The following section summarises some of these predictions.

2.3.1 Impact of climate change on insects

A changing climate will directly and indirectly affect the distribution and infestation of insects (Patterson et al. 1999). For example:

- Increased temperatures may affect insect life cycles, such as changing the rate of insect development from egg through to adult because of the importance of temperature in these processes (Fuhrer 2003; Ziska and Runion 2006). Climate and weather affect lifespan duration, fecundity, fitness, dormancy, dispersal, re-establishment, mortality and genetic adaptations of insects and insect populations (Drake 1994; Patterson et al. 1999; Ziska and Runion 2006). Although there is much uncertainty, it is generally expected that with climate warming in mid- to high-latitude regions, insect pests will become more abundant (Fuhrer 2003). Although shifts in climate are likely to affect the geographical range of insects, expansions may be limited by the ability of the host plant to be cultivated under such changed conditions (Fuhrer 2003).
- Increased pest fecundity and population size due to increased temperatures could result in accelerated evolution to overcome host plant resistance (Chakraborty and Datta 2003) and faster development of resistance to current control measures.
- Winter survival of insects could be increased if temperatures increase in temperate zones (Coakley et al. 1999; Fuhrer 2003). This creates an opportunity for insects to become more prolific or lengthen the time over which they may be able to feed on crops.
- Generation time may be reduced enabling more rapid population increase to occur and poleward migration may be accelerated during the crop season (Patterson et al. 1999).
- Decreased nitrogen and increased carbohydrate concentrations in plants have been found to be correlated with increased insect herbivory (Fuhrer 2003) because leaves are more digestible, resulting in faster development and potentially heavier insects.

Other factors contributing to insect distributions under climate change include competition with existing species, the ability to adapt to new conditions and the presence of natural enemies in the area (Patterson et al. 1999).

2.3.2 Impact of climate change on pathogens and the diseases they cause

Temperature, rainfall, humidity, radiation and dew all contribute to the occurrence of plant pathogens (Patterson et al. 1999). The speed with which a pathogen migrates to follow host plants will depend on a number of factors including its mechanisms of dispersal and its ability to survive on sources other than its primary host (Chakraborty et al. 2002). As dispersal of some pathogens is controlled by rain and winds (Pittock 2003), changes to these factors could also affect the spread of pathogens. In addition:

- Elevated atmospheric carbon dioxide and the subsequent climate changes could alter stages and rates of development of the pathogen (Coakley et al. 1999). For example, plant pathogens with a short generation time, high reproductive rate and effective dispersal are likely to respond rapidly to climate change. An increased number of generations in microclimates in dense canopies may lead to the development and proliferation of well-adapted and potentially more destructive sub-populations (Chakraborty et al. 2002). Durability of resistance may be threatened if the number of infection cycles within a growing season increases and this leads to rapid evolution of aggressive pathogen races (Coakley et al. 1999).

- If a viral pathogen currently has only a limited number of vectors (agents which transfer pathogens) and/or limited population(s) of a vector, increased survival of pathogen reservoirs could increase the survival rate of a pathogen and hence the economic losses caused by pathogen infection (Coakley et al. 1999).
- Wetter summers may enable fungal pathogens to bridge cropping seasons in some areas (BRS Workshop 2007).
- A potential increase in canopy size, density and humidity is likely to promote foliar diseases like rusts, powdery mildews, leaf spots and blights (Coakley et al. 1999; Ziska and Runion 2006).
- Dry and hot summers could generally reduce infestations of most fungal diseases because plant resistance is increased (Patterson et al. 1999; Fuhrer 2003).
- Disease development is generally favoured by warm, moist conditions. An increase in rainfall is likely to increase the spread of pathogens because rain and water splash spread spores, and wet surfaces are often needed for germination (Ziska and Runion 2006).
- It may become more difficult to predict disease outbreaks in periods of rapidly changing climate and unstable weather (Patterson et al. 1999).
- Some currently pathogen-resistant cultivars may be adversely affected under elevated carbon dioxide concentrations although this would depend on the resistance mechanism (Chakraborty et al. 2002).
- Enhanced plant growth due to carbon dioxide fertilisation depends on the effect of the disease and the nature of host resistance (Chakraborty et al. 2002).
- Changes in temperature and precipitation may affect the longevity of fungicide residues on crop foliage (Coakley et al. 1999).

It is evident impacts will vary greatly and there are limitations to the ability to predict specific impacts because there is currently no certainty about exact climate changes at specific locations (Chakraborty et al. 2002). As mentioned previously, more research is needed because most experiments consider only single factors, which provide useful information but have a limited ability to predict consequences for agro-ecosystems (Ziska and Runion 2006).

2.3.3 Impact of climate change on weeds

The impact of climate change on weeds will depend on a large number of variables, including the competing species, temperature, precipitation and other environmental factors (Patterson et al. 1999). For example:

- As with crop species, weeds are likely to benefit from elevated carbon dioxide concentrations due to improved water-use efficiency (see page 7) (Patterson et al. 1999; Ziska and Runion 2006).
- Reproduction is often increased in response to elevated concentrations of carbon dioxide (Ziska and Runion 2006).
- Temperature and moisture availability affect both the uptake and metabolism of herbicides by crops and target weeds. Reduction in transpiration and changes in leaf anatomy and leaf surface characteristics, caused by elevated carbon dioxide concentrations or other climatic factors, could also affect plant uptake of herbicides thus reducing their ability to control weeds (Patterson et al. 1999).
- Higher temperatures could lead to the expansion of some weeds into higher latitudes or higher altitudes (Ziska and Runion 2006).

- A greater increase in night-time temperature relative to day-time temperature could decrease seed production in crops relative to weed species and thus affect crop/weed competition (Ziska and Runion 2006).
- Increases in carbon dioxide concentrations have the potential to enhance C_3 weed growth relative to C_4 weed growth at a given location. However, predicted climate change temperature increases are likely to be more important in affecting relative plant growth of C_3 and C_4 plants, potentially favouring C_4 weeds (Dukes and Mooney 1999), such as Parramatta grass (*Sporobolus indicus*). This could see C_4 weeds spread further south and pose new or increased weed threats in some crops.
- Limited data examining the interaction between C_4 weeds and C_3 crops indicate that the crop-to-weed biomass ratio increases with elevated carbon dioxide concentrations, which is consistent with known biochemical responses (Ziska and Runion 2006). However, making generalisations about C_3:C_4 biomass ratios in elevated carbon dioxide concentration environments is difficult because the ratios will depend on the particular species involved and on the specific environment (Dukes and Mooney 1999).
- At higher atmospheric carbon dioxide concentrations there may be increased competition between trees and grasses in semi-arid rangeland areas (Howden et al. 2004).

Currently there is little information on the relative competitiveness of crops and weeds as a function of elevated carbon dioxide concentration and almost no data examining how crop-weed interaction is altered by increases in carbon dioxide concentration as other climatic variables vary (Ziska and Runion 2006).

2.4 Impacts on crop and pasture systems

In addition to direct impacts on plants and pests, climate change has the potential indirectly to alter crop and pasture systems. Impacts could include storm and wind damage (for example, flattened crops); greater soil erosion and soil drying from increased wind speed; increased humidity due to increased density and height of plants (Ziska and Runion 2006); and waterlogging and hail damage.

2.4.1 Evaporation

Higher temperatures are likely to increase evaporation, particularly when there is also a decrease in rainfall (CSIRO 2001). Modelling of increases in potential evaporation and altered rainfall patterns has shown an overall pattern of decreased moisture balance (Howden et al. 2004). Insufficient rainfall and low soil moisture status could result in lower and more variable pasture production (Howden et al. 2004).

Modelling of temperature increases has demonstrated an increase in soil evaporation (van Ittersum et al. 2003). Evaporation is not influenced by temperature alone (Ohmura and Wild 2002) but is primarily dependent, for a given rainfall, on solar irradiance, vapour pressure deficit and wind speed. In addition, as mentioned above, precipitation must be a fundamental consideration when assessing soil moisture. In a scenario of increased evapotranspiration (loss of water from both soil and from vegetation), the water requirements of plants will increase and, where coupled with predicted reductions in rainfall, this will further reduce soil moisture and increase the severity of dry conditions.

2.4.2 Altered rainfall patterns

The impact of changing rainfall patterns on crop and pasture systems will vary depending on the climatic region. Higher rainfall in semi-arid areas is likely to increase yield but less rain would further limit production (Ludwig and Asseng 2006). Increased rainfall in high rainfall areas could reduce crop growth due to increased soil waterlogging and nutrient leaching (Ludwig and Asseng

2006). Modelling of reductions in precipitation have predicted reduction in wheat yields in the Mediterranean environment of Western Australia (van Ittersum et al. 2003).

Altered rainfall patterns could lead to flood damage and a disruption to harvesting for winter dryland crops and cotton. It could also result in greater inter-annual variability in pasture production (Howden et al. 2004) and increased demand for irrigation water for the cotton industry.

For many cool-temperate systems, climate change conditions may bring new opportunities provided rainfall did not decline substantially. For warm-temperate and tropical regions, the impacts may be significant and negative, with increasing water stress (Bindi and Howden 2004).

There are likely to be north-south differences in the response of pasture production to climate change, as well as differences between the more arid rangelands and those regions with moderate rainfall (Howden et al. 2004).

2.4.3 Temperature

Warmer temperatures are likely to lengthen the growing season of cotton (Richardson et al. 2002) as well as summer pastures, particularly those dominated by C_4 species (Howden et al. 2004). This could lead to higher yields and increased pasture growth.

An increase in plant biomass, slower decomposition of litter, and higher winter temperature could increase pathogen survival on overwintering crop residues and increase the amount of initial inoculum available to infect subsequent crops (Coakley et al. 1999).

Modelling has predicted that deep drainage of wheat crops will be slightly higher under elevated carbon dioxide concentrations, but when higher temperatures were modelled in conjunction with higher carbon dioxide concentrations, this was reversed. Deep drainage was greatly reduced in low precipitation scenarios (van Ittersum et al. 2003).

2.4.4 Other system-based impacts

There will also be variable impacts on the degree and extent of dryland salinity (van Ittersum et al. 2003) and wind and water erosion is likely to increase (Pittock 2003), with biodiversity management and conservation likely to become a higher priority.

Finally, the impact of the complex climate change interactions on demand, supply and price of agricultural products around the world is not yet fully understood, particularly because farmers and markets will react in a variety of ways to climate change and information about it. Hence, the market and trade impacts will be even more difficult to predict than the impacts on the crops and pastures themselves.

Chapter 3 – Dealing with the predicted climate change impacts

3.1 High level strategies and initiatives

In response to projected changes in climate, Australian governments have endorsed the National Agriculture and Climate Change Action Plan 2006–2009 (NACCAP). The NACCAP provides a policy framework that promotes adaptation to climate change as well as a practical approach to mitigation (Natural Resource Management Ministerial Council 2006). It has a strong focus on building knowledge through research and development to provide innovative solutions, tools and frameworks that will enable farm businesses to deal with the challenges arising from climate change.

The Action Plan identifies four key areas to manage the multiple risks to agriculture in an environment of climate change:

- adaptation strategies to build resilience into agricultural systems;
- mitigation strategies to reduce greenhouse gas emissions;
- research and development to enhance the agricultural sector's capacity to respond to climate change; and
- awareness and communication to inform decision-making by primary producers and rural communities.

In March 2007, the NACCAP *Taking the Next Steps* workshop was held in Canberra. The workshop generated a broad ranging discussion on the key issues for the agricultural sector in relation to climate change. Industry, research organisations and government participants were able to share ideas on how to work collectively in implementing NACCAP. A number of recommendations were generated from the workshop including a need for further research and development into biotechnologies to achieve productivity, biodiversity and abatement benefits under changing climatic conditions. More information on NACCAP is available from: http://www.daff.gov.au/climatechange.

In April 2007, the Council of Australian Governments (COAG) endorsed the National Climate Change Adaptation Framework. The Framework outlines the future agenda of collaboration between governments to address key issues on climate change impacts. It includes possible actions to assist the most vulnerable sectors (such as agriculture) and regions to adapt to the impacts of climate change.

Also announced was the establishment of a new $43.6 million National Research Flagship on Climate Change Adaptation to be run by CSIRO. The National Research Flagship will have the initial research themes of: Pathways to Adaptation; Sustainable Cities and Coasts; Managing Species and Ecosystems; and Adaptive Primary Industries, Enterprises and Communities. This final theme aims to provide practical strategies and develop new management techniques or technologies for agriculture to adapt to climate change at the enterprise and industry levels, supporting transformative change and using participatory engagement to improve handling of uncertainty in management and governance systems.

In December 2007, COAG established the Working Group on Climate Change and Water, tasking it to provide COAG with proposals on long-term adaptation to climate change, including accelerating implementation of actions under the agreed National Adaptation Framework across all jurisdictions.

Also in 2007, the Australian Government announced the $130 million Australia's Farming Future initiative, a coordinated set of programs to help farmers adapt to climate change and to prepare for a carbon pollution reduction scheme. This initiative will focus on potential solutions, including enhancing carbon sequestration on agricultural land, which will play a role in a comprehensive response to the challenges of climate change.

3.2 Biotechnology: one piece of the jigsaw in the climate change puzzle

In looking for solutions to the challenges presented by climate change, farmers will need access to a variety of tools and options. Biotechnology is one tool that is likely to play an important role in helping agricultural industries adapt to climate change as well as mitigate greenhouse gas emissions.

Biotechnology in its broadest definition is the use of living things to perform a function for humans. Although biotechnology can refer to basic breeding techniques, the scope of this study was restricted to modern biotechnology, which includes:

- genomics and other technologies to study groups or systems of biological molecules;
- enhanced genetic mapping techniques such as molecular markers;
- genetic modifications; and
- DNA and immuno-diagnostic techniques for detecting and controlling plant diseases.

Genomics is the discipline that defines and characterises the complete genetic makeup of an organism. It includes studies of the physical structure of the genome (the sequence and organisation of the genes in an organism) and the products of genes and their interactions. The development of genomics, in conjunction with other related ‘omics’ (such as ‘transcriptomics’, the study of the messenger ribonucleic acids (mRNAs) written from genes and ‘proteomics’, the study of expressed proteins), has increased the speed at which basic plant science can be applied to produce improved crop varieties.

Molecular markers are short sections of DNA already present in a species that have a known location on a chromosome and may be associated with a particular gene or trait. Marker-assisted selection uses these markers to identify and track the inheritance of desired traits in breeding programs. This technology provides traditional plant breeders with greater accuracy and speed in screening large populations for desired traits and greater control over the genes retained during plant breeding. By using markers, plant breeders can also combine greater numbers of desirable traits in a single breeding cycle, without the need for screening thousands of plants for physical and chemical characteristics under particular environmental conditions. For example it could be possible to track and transfer genes associated with stabilised yields under dry conditions, without having to expose successive generations of plants to drought, so that the breeding process can continue even through wetter seasons (Edmeades et al. 2004).

Genetic modification is another modern biotechnology tool available to plant breeders. It allows the development of new plant varieties through the direct incorporation, deletion or modification of specific genes (including those from other species). The resulting plants are known as ‘genetically modified’ (GM) or ‘genetically engineered’ organisms. Genetic modification can allow the transfer of genes between unrelated species, increasing the size of the gene pool available for desirable traits and so providing breeders with increased genetic diversity for developing crop varieties.

In addition to providing tools for breeding, modern biotechnology has the potential to play an important role in plant disease diagnosis. Early and accurate diagnosis of disease is a crucial component of any crop management system. Plant diseases can be managed more effectively if control measures are introduced at an early stage of disease development. Reliance on symptoms is not always adequate in this regard as by the time symptoms appear the disease may be well underway. Laboratory-based techniques such as Enzyme-Linked Immunosorbent Assay (ELISA) and Polymerase Chain Reaction (PCR) are already utilised in plant biosecurity, with the potential for future developments to lead to hand-held devices for in-field diagnosis.

Despite the advantages and opportunities modern biotechnology can provide in both plant breeding and disease diagnostics, it is important that it is not viewed as a ‘silver bullet’ solution to the problems climate change is likely to present to Australian agriculture. Rather, it is simply one tool to be utilised in conjunction with a number of strategies in adapting to and mitigating climate change.

3.3 Adaptation to climate change – options and approaches

The options for adaptation to climate change by Australian agriculture can be grouped into three main categories:

- current land use pattern is retained and new crop varieties or improved farm management practices to adapt to changing climate conditions are developed
- the land use itself is changed in response to the changing climate
- new products are developed or new demands for products are created as part of mitigating climate change, such as the demand for biofuels.

Modern biotechnology has a role to play in the first and third of these response categories.

In developing new crop varieties for Australian agriculture under climate change, most people primarily think about breeding crops to be ‘drought-tolerant’. However, the range of traits that could be beneficial for crops and pastures in a changed climate is much broader than only of traits relevant to improving plant performance in dry conditions. This reflects the complexity of climate change impacts on cropping and pasture systems which, as noted above, are far more extensive and complex than simply reductions in rainfall. In addition to decreased water availability, potential yields can be limited by weeds, pest and disease, poor nutrition, frost (if plants are sown earlier to take advantage of altered rainfall patterns), heat and even waterlogging (e.g. from increased storm events). New crop varieties or improved farm management practices that help deal with any of these limitations will help to improve the yield in changed abiotic and biotic stress conditions (European Plant Science Organization (EPSO) 2005). Modern biotechnology has an important role in developing adapted crop varieties that will help to improve yield under these stresses or with the adoption of beneficial farm management practices. Biotechnology may also help in plant biosecurity and disease diagnostics.

Biotechnology may also help farmers adapt to climate change through the development of crops and pastures which offer alternative land use options. Plants used for biofuels or bioenergy, as well as plants engineered to produce novel pharmaceutical and industrial products, may provide important alternative sources of income for farmers.

Part 2 discusses these adaptation opportunities in further detail.

3.4 Mitigating greenhouse gas emissions – options and approaches

The Australian Greenhouse Office (AGO) (2007) reported that the agricultural sector is estimated to have generated 16.8 per cent of Australia’s net greenhouse gas emissions in 2005. However, this figure excludes greenhouse gas emissions generated through energy use, transport and land use change, which could be partially attributed to the agricultural sector. Agriculture is the dominant national source of the greenhouse gases methane (58.9 per cent of net national emissions) and nitrous oxide (84.2 per cent). Sources include enteric fermentation (methane which is produced by micro-organisms in place in the digestive systems of ruminant animals such as cattle and sheep), agricultural soils (nitrous oxide from nitrogen fertiliser applications), savanna burning and manure management. The largest agricultural source of greenhouse gas emissions is enteric fermentation, which represented 67 per cent of the sector’s greenhouse gas emissions in 2005 (equivalent to 87.9 Mt of carbon dioxide equivalent) (AGO 2007).

Biotechnology offers several approaches which can contribute to greenhouse gas mitigation. The digestibility of pasture for livestock could be improved to reduce methane emissions from enteric fermentation. Methane from enteric fermentation could also be reduced by targeting or modifying bacteria in the rumen which are responsible for methane production. Nitrous oxide emissions can be reduced by improving the efficiency of nitrogen use by crops, as well as improving animal feed efficiency. The development of crops that require fewer inputs and hence reduced fuel use, can lead to reductions in on-farm carbon dioxide emissions. The development of biofuels to replace fossil fuels may also lead to net reductions in greenhouse gas emissions.

In addition to reducing current sources of greenhouse gas emissions, applications of biotechnology could help mitigate climate change through increasing the capacity of farming systems to sequester carbon from the atmosphere and act as a carbon sink, for instance by modifying plants roots to increase carbon input into soil.

Part 3 discusses these mitigation opportunities in further detail.

Part 2 – Can biotechnology help? – Adaptation

Chapter 4 – Adapting crops and pastures to climatic stressors

A range of traits are being developed in crop and pasture species to help farmers adapt to the impacts of climate change. Traits which improve water-use efficiency, improve the ability of plants to take up water, or improve waterlogging tolerance will be important to adjusting to changes in rainfall patterns. Traits for heat tolerance and reduced reliance on vernalisation are desirable for adapting to increases in temperatures. Frost tolerance is also important as it will allow winter crops to be sown earlier and thus avoid high temperatures or drought late in the season. Decreases in protein and nitrogen content in grains and leaves due to elevated carbon dioxide concentrations can be addressed through improving the nitrogen-use efficiency of crops and pastures. Modern biotechnology has a role to play in the development of varieties with these traits. Examples of research into developing molecular markers and genetically modified varieties for such traits are outlined in this chapter.

4.1 Water-limited stress and 'drought tolerance'

Drought can have different meanings for different people, with the diversity of meanings typically due to the different time scales of interest. For farmers and agronomists, drought commonly means that the water supply substantially limits the yield of a crop over a season (Passioura 2007a). Drought tolerance has been used to describe a range of plant responses, from the ability of a plant merely to survive severe water deficits to the ability of crops growing in the field to maintain yields despite limited water availability.

Coping with water-limited stress is a complex whole-of-plant response and is controlled by many genes. As a consequence, there is unlikely to be a single 'drought-tolerant' gene that will lead to improved crop performance during drought, although some genes may be more important than others. Many of the current drought-tolerant plant patents focus on plant survival under drought conditions and not necessarily on the more agronomically important traits of maintaining or increasing yield (Passioura 2006). Traits that are likely to be useful in a farming context are those that may help in enabling crops and pastures to capture more of a limited water supply and to use that water more efficiently for generating yield. Not all traits for improved yields under water-limited environments are likely to be applicable universally and some traits that are important in one region may be detrimental in another. This is because there are different types of water-limited environments so traits that may be important when a crop is growing almost exclusively on water stored in the soil are likely to be different from traits that are important for the same crop that is solely reliant on in-season rainfall for growth (Richards 2004).

When considering traits for water-limited environments, consideration must also be given to the fact that farmers in low-rainfall regions get almost all of their income in moderate and good rainfall seasons and little or none during severe droughts. So instead of developing crop traits to help tolerate severe drought, research efforts should predominantly focus on maximising crop yields in moderate to good, albeit usually water-limited, seasons (BRS Workshop 2007; Passioura 2007b).

Some traits under investigation to improve water-use efficiency and/or access to water include:

- *Long coleoptiles*—one option for improving access to water is deep sowing. This can enable seedlings to access water deeper in the soil profile as well as avoid high soil surface temperatures which inhibit germination (Reynolds et al. 2000). However if semi-dwarf crop varieties are used, deep sowing can lead to the seed being covered in too much soil and the coleoptile may not reach the surface. Long coleoptiles for semi-dwarf varieties may therefore be advantageous in water-limited environments (Passioura 2007a; Rebetzke et al. 2007).

- *Root architecture*—differences in the size, structure and function of root systems impact on the ability of plants to extract water from soils. In water-limited environments, the usefulness of particular root traits in improving yield is largely determined by the pattern of water stress the crops and pastures experience. For example, winter crops grown in environments which are reliant on stored soil moisture, such as the north-eastern wheat belt, are best served with root systems that reduce water use early in the season and have increased access to water from deeper soil. This helps to maintain water access during grain filling late in the season when water is often limited. Compact, uniform root systems with greater root length and density at depth have been suggested as desirable in such climates. In Mediterranean climates where winter crops rely on in-season rainfall, large, shallow root-systems with increased potential for water extraction from the top soil layers during the vegetative growth phase are important (Manschadi et al. 2006). To date, limited knowledge of root system growth and functioning and the lack of simple root screening methods, has meant root-related drought adaptive characteristics have been neglected in breeding programs (Manschadi et al. 2006; Passioura 2006).
- *Early vigour*—crops that develop leaf area quickly early in the season (often referred to as early vigour) have been found to have advantages in accessing water and reducing water loss. Early vigour can shade the soil surface, reducing soil evaporation and retaining more moisture in the soil for the crop. Greater leaf area early in the season can also helps crops suppress and shade-out weeds, which would otherwise compete for available soil moisture. Preliminary research with wheat varieties has found greater early vigour is also associated with increased root growth. As discussed above, larger root systems can intercept water and nutrients that would otherwise be leached beyond the roots. This trait would be most useful in cropping areas that are reliant on in-season rainfall, but less so for crops grown on stored soil moisture. This is because the increased biomass production early in the season may result in more rapid depletion of soil moisture and may lead to earlier onset of terminal drought for crops reliant on stored soil moisture (Reynolds et al. 2000; Botwright et al. 2002).
- *Increasing stem-stored carbohydrates*—grain growth and development in crops is reliant on carbohydrates produced by photosynthesis, which are either produced post-anthesis (after anthers of a flower have released their pollen) and translocated directly to the grains or are remobilised from stores in the stem. The remobilisation of stem-stored carbohydrates is important for grain-filling if photosynthesis (and hence carbohydrate production) is inhibited late in the season due to water-limited stress. Increasingly, the capacity for and remobilisation of stem-stored carbohydrates is an important objective in improving yields affected by late-season drought. Options for achieving this could include long and thick stem internodes, with extra storage tissue (Reynolds et al. 2000; Ehdaie et al. 2006).
- *Stay-green*—as the name suggests, stay-green genotypes maintain green leaf area under post-anthesis drought. Stay-green genotypes possess higher leaf chlorophyll content at all stages of development and more photosynthetically active leaves. In sorghum, higher yields and improved transpiration efficiency under water-limited conditions have been reported in stay-green compared with conventional genotypes (Borrel et al. 2000; Reynolds et al. 2000). However, the stay-green trait may be detrimental in some water-limited conditions if the trait is associated with a lack of ability to remobilise stem-stored carbohydrates (Blum 1998).
- *Leaf morphology*—changes to leaf posture (leaf angle), rolling, waxiness, pubescence (hairiness), thickness and number of stomata (pores in leaves through which gas exchange occurs) have all been linked to improving plant production under drought. The traits aim to decrease radiation load to the leaf surface and/or lower evapotranspiration rates, reducing water loss from the plant. Some of these traits (such as posture, waxiness, thickness) can also reduce the risk of photo-inhibition (Reynolds et al. 2000), a reduction in a plant's

capacity for photosynthesis caused by exposure to strong light (Adir et al. 2003). Changes to leaf morphology, however, may be associated with reduced radiation-use efficiency, which would reduce yield in conditions favourable to crop growth (Reynolds et al. 2000).

- *Low carbon isotope discrimination*—in nature, there are several different types (isotopes) of carbon. The most common form of carbon is ^{12}C, which accounts for 98.9 per cent of the carbon in the atmosphere. ^{13}C accounts for almost all of the rest and is actively discriminated against by plants during photosynthesis because of its slightly heavier atomic weight. Researchers have found that C_3 plants with low carbon isotope discrimination (that is, those that have a low discrimination against ^{13}C) have increased transpiration efficiency. This equates to increased photosynthesis per unit of transpiration and has been used to develop crops with improved water-use efficiency (Richards 2004; Passioura 2006).
- *Improved rubisco*—one of the key enzymes in photosynthesis is rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase). It catalyses the first major step of carbon fixation, a process by which atmospheric carbon dioxide is made available to organisms in the form of energy-rich molecules such as sucrose. Rubisco activity is often rate-limiting for photosynthesis, so increasing its efficiency will lead to increased photosynthesis efficiency. This in turn could lead to improved water-use efficiency (Morell et al. 1992).
- *Improved disease and weed management*—this is discussed further in Chapter 5.

A number of these traits are currently the focus of research in Australia.

CSIRO is conducting research into understanding the genetic control of early vigour. Genes that increase the size of the embryo, reduce leaf thickness and promote earlier tillering have all been linked to early vigour. Researchers are currently identifying chromosomal regions containing these genes for the development of molecular markers[7].

CSIRO have also identified a number of genes in wheat which play a role in controlling stem-stored carbohydrates (Xue et al. 2007). Some of these genes are now the subject of further research, with the aim being to perform genetic manipulation or assist conventional breeding for the improvement of grain yield under water-limited environments.

Molecular markers for stay-green traits are being researched and developed for use in Australian grain sorghum breeding programs. Under post-anthesis drought, stay-green genotypes have higher grain yield than aging genotypes due to increased green leaf area at maturity, leaf nitrogen status and transpiration efficiency. Also, the stay-green trait is not a constraint on yields when water is not limiting (Borrel et al. 2000).

The Australian Centre for Plant Functional Genomics (ACPFG) has identified genes involved in improving yields under drought conditions, such as root architecture and leaf morphology. These genes can be incorporated into cereal breeding lines either through transgenic technologies or by using conventional breeding techniques and molecular markers[8].

Australian research is also being conducted on improving photosynthesis efficiency through modifying rubisco (Morell et al. 1992; Andrews and Whitney 2003).

A number of GM crops with improved water-use efficiency are being trialled in Australia. The Gene Technology Regulator has approved proof-of-concept field trials for drought tolerant GM wheat (DIR071/2006), GM wheat and barely with enhanced tolerance to abiotic stresses (DIR077/2007) and GM cotton (DIR064/2006) and sugarcane (DIR070/2006) with improved water-use efficiency (OGTR 2006a; c; 2007; 2008a).

---

[7] http://www.csiro.au/files/files/p2ki.pdf accessed 15 October 2008

[8] http://www.acpfg.com.au/files/latest_media/f556.pdf accessed 15 October 2008

Although genetic modification has an important role to play in developing new crop varieties with improved water-use efficiency, new varieties developed using only conventional breeding techniques will continue to be the approach for breeding many, if not most, new varieties. For example, CSIRO has developed two conventionally bred wheat varieties, Drysdale and Rees, which have low carbon isotope discrimination. Both varieties have increased water-limited yields in dry years compared to those of widely sown cultivars. Importantly, the yields from the two varieties in wet years are also competitive (Richards 2004; Passioura 2006). These successful new crop varieties emphasise that while genetically modified crops will be important to assist in adapting to climate change, they should not be promoted to the detriment of traditional breeding practices. Rather a combined breeding effort making use of all the tools and techniques available needs to be adopted.

4.2 Heat stress

Heat stress is defined as the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development. It is a complex function of heat intensity (temperature in degrees), duration (seasonal compared to daily temperature extremes) and rate of increase in temperature (Wahid et al. 2007). As with water-limited stress, different plant tissues and plants at various growth stages will be affected in different ways by heat stress. Accordingly, there are a number of different strategies plants use to minimise the effects of elevated temperature on normal growth and metabolism. This is further complicated because plants rarely face heat stress in isolation from other environmental stressors such as lack of water. Many of the traits identified for improving yield under water-limited stress, have also been linked to heat tolerance, including early vigour, stay-green, leaf morphology and photosynthetic rate (Reynolds et al. 2001).

Other physiological traits are also associated with heat tolerance. One of the major roles of transpiration is leaf-cooling. Leaf and spike (flowering axis) temperatures in wheat can be lower than ambient air temperature, with the degree of cooling reflecting the rate of evapotranspiration on the surface of the plant canopy (Ayeneh et al. 2002). This trait is referred to as canopy temperature depression (CTD) and has been shown to be positively correlated with yield in both warm and temperate environments. Preliminary data suggests that the trait is heritable (Reynolds et al. 2001). As CTD is a complex, multi-genic trait, it is unlikely that transgenic technologies could be easily used to introduce the responsible genetic elements into breeding lines; however, molecular markers could be developed for this trait.

Another trait associated with heat-tolerant varieties is plant membrane thermostability. Plant lipid membranes[9] receive the most physiological injury from heat, with disruption and damage to membranes altering their permeability and resulting in the loss of solutes from cells. Cellular membrane thermostability can be determined by measuring the amount of solute leakage (Reynolds et al. 2001; Rahman et al. 2004). Since membrane thermostability is in part heritable and shows high genetic correlation with yield, there is potential for plant breeding to be applied in this area (Reynolds et al. 2001).

At the molecular level, a central role in the heat stress response is played by heat shock proteins (HSPs) under the control of heat stress transcription factors. HSPs were first identified as proteins that are strongly induced by heat stress. Subsequently they have been shown to also be essential for normal growth and metabolism, hence it has been difficult to unravel the precise role they play in response to heat stress (Kotak et al. 2007). Such genetic complexity has limited the effectiveness of attempts to increase tolerance to heat stress by over-expressing single HSP genes.

[9] The membranes surrounding cells within plant cell walls, surrounding cell organelles, and present in other parts of plant cells.

Other molecular components linked to the heat stress response in plants that are currently being researched include:

- calcium (Ca^{2+}) dependent signalling (Liu et al. 2005)
- phytohormones such as abscisic acid, salicylic acid and ethylene (Larkindale and Huang 2004; Larkindale et al. 2005; Liu et al. 2006a)
- components that increase the production of antioxidants to ameliorate oxidative stress (for example, the production of the antioxidant glycinebetaine in tobacco has been shown to protect the plant's photosynthetic machinery from heat stress induced oxidative damage (Yang et al. 2007)).

4.3 Frost tolerance

Rather than trying to adapt plants to survive high temperatures and dry conditions which are often experienced late in the growing season for winter crops, another option is to make the flowering window earlier in the season. This option would require the development of plants adapted to cope with lower temperatures and frosts. Scientists from Victorian Department of Primary Industries discovered a gene from Antarctic hairgrass (*Deschampsia antarctica*) which has the ability to inhibit ice crystal growth as a mechanism for freezing tolerance. The findings have major implications for improving frost tolerance in crop and pasture species, with the ice re-crystallisation inhibition proteins (IRIPs) being tested in transgenic systems including *Arabidopsis* and wheat (John and Spangenberg 2005). This research is now being undertaken within the ACPFG, with the aim for field trials of GM frost-tolerant crops in 2010 (ACPFG 2006).

4.4 Waterlogging

As mentioned above, research efforts should perhaps be focused on improving yields in good rainfall seasons. One problem farmers often face in good rainfall years, however, is waterlogging. The potential for transient waterlogging may increase under climate change with the predicted increase in heavier precipitation events. Traits that would allow crops to cope with waterlogging would therefore be important.

Waterlogging reduces oxygen levels in the soil, leading to a build up of toxic chemicals and altered nutrient levels around roots. This causes damage and death to the plant roots, which in turn impacts on production. In Western Australia, waterlogging typically results in wheat crop losses between 10–50 per cent and wheat yield losses across Australia in the order of A$300 million. Australian cotton is also affected by waterlogging and it can be quite severe if rainfall occurs during and after irrigation. On average, one bale of cotton per hectare (approximately 11 per cent of cotton yield) is lost due to waterlogging. In severe cases, yield losses can reach 40 per cent. Canola and barley crops also experience significant yield losses to waterlogging (Dennis et al. 2000).

Research is being conducted into improving crop response to waterlogging. CSIRO has developed GM cotton lines that contain a genes derived from cotton and *Arabidopsis* that are expected to enhance tolerance to waterlogging. The cotton lines will contain one or more of three introduced genes that include *Pdc2* and *Ahb1* from *Arabidopsis* that encode the enzyme pyruvate decarboxylase and the plant haemoglobin 1 protein respectively. The third gene to be introduced is the *Adh* gene from cotton that encodes the alcohol dehydrogenase enzyme. Field trials of these cotton lines with expected enhanced tolerance to waterlogging stress have been approved by the Gene Technology Regulator (DIR067/2006; DIR083/2008) (OGTR 2006b; 2008d). Work is also being conducted to try to identify molecular markers for waterlogging tolerance for wheat breeding programs (Cakir et al. 2005).

4.5 Alterations to plant environment cues

The timing of flowering in agricultural crops is very important to achieving high yields. For example, in dryland winter-cropping the timing of flowering needs to be early enough to avoid the worst of the heat and large evaporative demands of late spring and late enough to avoid frost damage during flowering (Richards 1991; Passioura 2007a). The timing of flowering is a response to both the plant's development stage and to external environmental conditions. Many plants that flower in spring, including winter wheats, must experience an extended period of cold to promote or accelerate flowering. This is known as vernalisation. Time of flowering can also be influenced by length of day or photoperiod. A long-day plant requires short nights to induce flowering, while short-day plants require longer periods of darkness in order to flower. Conventional selective breeding has produced crop varieties with flowering times to suit different agricultural regions. For example, spring wheats, which are grown in warm areas, do not require vernalisation to trigger flowering.

In the well-developed agricultural regions of Australia, the timing of flowering is well controlled and has been suggested to be as appropriate as possible, given that the optimal time is necessarily an average over successive growing seasons (Passioura 2007a). However, climate change is likely to both disrupt average rainfall and temperatures as well as increase their variability. In some areas that have traditionally grown crops sensitive to vernalisation, winter temperatures may increase, eliminating the cold period needed to trigger flowering. This would require farmers to shift to varieties with decreased sensitivity to vernalisation. Changes in the desired time of flowering or in the latitudinal area in which the crops are grown due to climate change may also require varieties with different photoperiod sensitivities.

Scientists from CSIRO have identified a major gene in both cereal and *Brassica* crops that is responsible for determining the timing of flowering. The *flc* gene is the master flowering gene that operates in plants such as canola and mustard, while in cereals such as wheat, barley and rice, the *wap1* gene serves the same purpose. It is hoped that these genes could be used in breeding programs to predict vernalisation and flowering time[10]. Controlling the activity of the genes directly may also provide more control over the flowering of crops. Manipulation of the major flowering gene could also prevent flowering in pasture grasses so they remain in a vegetative state to provide reliable feed for livestock[11]. These developments, in addition to conventional selective breeding programs, will assist in providing farmers with crop varieties suited to flower under a different climate.

4.6 Reduced protein and nitrogen content in grains and leaves.

Enhancing the nitrogen assimilation of crops and pastures, for example by increasing nitrogen-use efficiency, may help in preventing reductions in grain or pasture nutrition as a result of elevated carbon dioxide concentrations. Also, increased nitrogen-use efficiency will help combat nutrient deficiencies that may arise from increased weed competition.

Research in Australia and overseas is investigating improving nitrogen-use efficiency in a variety of plants using GM techniques. Detail of this research is outlined in Section 8.2.

4.7 Traits enabling C_4 plants to acclimatise to carbon dioxide enriched environments.

As mentioned above, plants can be classified by their means of fixing carbon, with the two main types being C_3 or C_4 plants. C_4 plants, which include corn (maize) and sorghum, perform very efficiently under conditions of high temperatures and bright sunlight when compared to C_3 plants.

---

[10] http://www.csiro.au/files/files/p2fv.pdf accessed 15 October 2008

[11] Ibid.

However, increases in C_4 plant yields under elevated carbon dioxide concentrations have been reported to be less than in C_3 plants due to the differences in carbon fixation. Increased atmospheric carbon dioxide concentrations may make competing with C_3 weeds more difficult for C_4 crops (Parry 1990; Li et al. 2007). Therefore, traits that improve the performance of C_4 plants under elevated carbon dioxide levels may be important in Australia's future climate. It has also been speculated that increases in temperature will lead to C_4 weeds extending their geographic range and, if they become more prevalent, weed competition in C_3 crop systems may intensify (Dukes and Mooney 1999).

Researchers are investigating the acclimation of C_4 plants to carbon dioxide enriched environments (Driscoll et al. 2006; Prins et al. in prep.). These studies may lead to a greater understanding of how to breed C_4 plants with improved performance under these conditions.

4.8 Perennial pastures and crops

Perennial plants may have increased potential for both pastures and cropping under climate change. Perennial pastures can provide benefits through increasing the sustainability of cropping rotations through their role in increasing out-of-season water use, reducing leakage to the water table and providing groundcover over summer months to reduce erosion (Ellis et al. 2006). Other benefits of growing perennial pastures include:

- out-of-season green feed
- increased carrying capacity due to improved seasonal distribution of feed and pasture use
- reduced wool faults and maintenance of wool fibre diameter and staple strength
- reduced fodder conservation (cutting hay; selling surplus hay)
- the opportunity to defer grazing on annual pasture paddocks after the break of the season (Moore et al. 2006).

Research is also underway to develop perennial versions of some crops that are traditionally grown as annuals. A feasibility study has recently been conducted for growing perennial wheat in Australia (Wade et al. 2007). A number of potential benefits were identified in growing perennial wheat rather than annual wheat. Because perennial wheat is deep-rooted, it could lead to reduced soil waterlogging and decreased groundwater recharge and dryland salinity. Perennial wheat could also provide benefits similar to conservation tillage practices, such as improved soil health and structure, while the perennial cover during summer would reduce soil erosion. Compared to annual wheat, perennial wheat is expected to have reduced fuel costs and improved nutrient-use efficiency, which would improve its economic attractiveness compared to annual wheat. Finally, in mixed cropping-livestock systems, perennial wheat might provide higher quality stubble for grazing livestock during summer and autumn, and increase flexibility between grazing and grain enterprises (Bell et al. 2006). These benefits would be important in adapting to many of the changes in climate predicted for 2030 and beyond.

There are still, however, many constraints that need to be overcome before perennial wheat could be adopted in Australia. Constraints include lower grain yields and inferior grain qualities. Perennial wheat may provide a 'green bridge' over summer for foliar fungal diseases such as stem, leaf and stripe rusts. There is therefore a need for improved pest and disease management (Bell et al. 2006; Wade et al. 2007). Biotechnology could play a role in developing perennial wheat varieties, particularly to improve pest and disease management.

Chapter 5 – Insect pests, diseases and weeds – control and diagnosis

With the potential for increased pressure from insect pests, pathogens and weeds under climate change, improved crop resistance to these biotic stresses is important. GM crops have already been proven to provide farmers with improved tools for insect pest and weed management. GM crops with disease resistance are also being developed. This chapter details these achievements and likely future developments of these crops (outlining the most attainable goals for GM crops in the immediate future). It also outlines biotechnology techniques and applications that are used in diagnostic tests and surveillance for biosecurity purposes.

5.1 Control of insect pests

GM insect-resistant (IR) crops have proven to be very effective in controlling many of the world's main crop pests. GM IR crops have been widely adopted, particularly in cotton and corn (maize) with 20 million hectares grown worldwide in 2006. In addition, 22 million hectares of GM crops with combined insect resistance and herbicide tolerance traits were grown (James 2008). In Australia, GM IR cotton accounts for around 90 per cent of cotton production(Holtzapffel et al. 2008).

Nearly all of the commercially released GM IR crops have been modified with *cry* genes from the soil bacterium *Bacillus thuringiensis* (*Bt*). *Cry* genes encode a variety of insecticidal crystal proteins that are toxic specifically to various agriculturally important insect and other invertebrate pests. *Bt* strains have been discovered that produce cry proteins that are toxic to lepidopterans (butterflies and moths), coleopterans (beetles), dipterans (flies and mosquitos), lice, mites and nematodes. These proteins are non-toxic to mammals and other non-target organisms (Ranjekar et al. 2003; Federici 2005).

The first *Bt* cotton crop grown in Australia was Ingard® cotton. Commercialised in 1996, Ingard® cotton contained a single *cry* gene which encoded for a protein toxic to *Helicoverpa* caterpillar pests. In 2003, Bollgard II® cotton was commercialised, replacing Ingard® varieties by 2004–05. Bollgard II® expresses two different *cry* genes for increased efficacy and decreased risk of insect resistance developing to the insecticidal proteins.

In addition to the *cry* genes, a number of other insecticidal proteins expressed during the vegetative growth phase of *B. thrungiensis* have also been indentified. These vegetative insecticidal proteins (vip) have a different mode of toxicity to cry proteins. Syngenta Seed Inc. has trialled two cotton lines (Cot102 and Cot202) in Australia that have been modified with a *vip* gene. The gene encodes a protein that is highly toxic to numerous economically important lepidopteran pests of cotton (DIR 034/2003) (OGTR 2003a).

GM IR cotton crops could facilitate adaptation to climate change by enabling cotton growing areas to be established in more northerly regions where rainfall is predicted to increase. Until now, some of the northern areas such as north Queensland, the Northern Territory and north Western Australia could not be farmed economically partly due to the prevalence of insect pests. The Gene Technology Regulator has granted licences (DIR 066/2006, and DIR 062/2006) for the commercial release of GM IR and/or herbicide-tolerant varieties north of latitude 22° South (OGTR 2006d). However, before a release takes place in northern Australia, agronomic, plant breeding and seed production trials of GM cotton suitable for cultivation in that area need to be undertaken, in addition to consideration of industry, infrastructure and community issues (Holtzapffel et al. 2008).

Other strategies for engineering pest resistance in plants include the expression of toxins produced by foreign plants (such as proteinase inhibitors, lectins, amylase inhibitors), animals (insect chitinases) and other bacteria, as well as investigating insecticidal viruses. The development of plants expressing vip proteins and other insecticidal toxins is important in providing growers with additional tools for pest management and ensuring the risk of target insect pests developing resistance to current control methods is minimised (Ranjekar et al. 2003; Federici 2005). This could be particularly important if changes in pest populations and distributions occur as expected under climate change and lead to increased pest severity.

An important consideration when developing GM IR crops for a changing climate is whether or not their pest control efficacy is affected by environmental conditions. Australian field trials of the Cot102 line (containing the *vip3A* gene) in 2003 found a decline in efficacy late in the season that may allow some larval survival. This could lead to selection of insects with resistance to the insecticidal protein. The loss of efficacy coincided with rainy, cloudy weather that led to reductions in temperatures and solar radiation. This suggests that temperature, irradiance or waterlogging may influence the efficacy of Cot102. The efficacy of Cot202 (also containing the *vip3A* gene) was not affected, possibly due its higher initial expression levels of the toxin (at least two-fold greater than the Cot102 line).

Reduced efficacy of the insecticidal protein that could be attributed to linked to cool weather, lower soil temperatures and/or extended wet weather was also noted in controlled experiments and bioassays with Ingard® cotton. Whilst Ingard® cotton is no longer grown commercially, such results indicate the importance of considering future weather conditions when developing IR crops (Llewellyn et al. 2007).

5.2 Control of diseases

There are many examples of Australian biotechnology research into disease-resistant crop plants, including both the development of GM disease-resistant crops and identifying molecular markers for disease resistance for use in conventional breeding programs. Examples of recent Australian research include:

- proof-of-concept field trials of GM funga- resistant cotton, which has inhibitory activity against *Fusarium* wilt, black root rot and *Verticillium* wilt (DIR 063/2005) (OGTR 2007)
- field trials of GM white clover resistant to the Alfalfa Mosaic Virus (DIR 047/2003 (OGTR 2003b)
- identification of molecular markers in wheat for resistance to the Barley Yellow Dwarf Virus [12]
- identification of molecular markers in wheat for resistance to the *Ug99* strain of the wheat fungus black stem rust[13]
- markers for flax and wheat resistance to stem, leaf and stripe rust[14]. Recent advances in the flax rust system are now being applied to important cereal rust diseases such as wheat stem rust
- high-throughput screening of wheat varieties for resistance to the *Fusarium* fungus and potential identification of molecular markers[15]
- identification of molecular markers for resistance to cereal cyst nematodes in wheat (Passioura 2006)
- proof-of-concept field trials of GM disease-resistant banana. Up to 16 lines contain a gene which encodes a protein that is expected to confer disease resistance by preventing cells from undergoing programmed cell death in response to infection by certain pathogenic microorganisms (DIR079/2007) (OGTR 2008b).

---

[12] http://www.csiro.au/files/files/p2jg.pdf accessed 15 October 2008

[13] http://www.csiro.au/files/files/pm2o.pdf accessed 15 October 2008

[14] http://www.csiro.au/files/files/pbb8.pdf accessed 15 October 2008; http://www.csiro.au/files/files/pju1.pdf accessed 15 October 2008

[15] http://www.csiro.au/files/files/pb2k.pdf accessed 15 October 2008

A number of GM disease-resistant crops have been approved for commercial production overseas (although not all are currently commercially grown). These include:

- potato varieties resistant to potato virus Y or potato leafroll virus in the United States and Canada[16]
- papaya, resistant to ringspot virus in the United States[17]
- squash resistant to cucumber mosaic virus, zucchini yellow mosaic virus and watermelon mosaic virus in the United States[18]
- plum trees resistant to plum pox virus in the United States[19].

In addition to assisting farmers to manage changes to the incidence and occurrence of diseases, biotechnology tools for disease control are also important in improving the water economy of crops. Disease resistance can improve the ability of crops to use available water by retaining photosynthetic area in the presence of foliar disease or by maintaining a healthy root system which is able to access more available water in the presence of root diseases (Passioura et al. 2007). Passioura (2006) identifies cereal cyst nematode resistance as the most important marker identified to date in wheat breeding programs for improving the water productivity of the crop.

5.3 Control of weeds

The development of herbicide-tolerant (HT) crops has been an important tool for farmers in managing weeds. HT plants are able to survive treatment by specific herbicides, providing more options for weed control. The potential benefits of HT crops include (Gene Technology Task Force 2002):

- effective control of difficult weeds
- reduced risk of damage to crops if herbicide is applied at the wrong dose
- reductions in tillage required for weed removal, which reduces damage to soil
- improved rotational options through a reduction in residual herbicides.

HT crops can help in the adoption of farm management practices such as no-till farming and dry sowing, which can have beneficial yield impacts in water-limited environments (see Chapter 6). Improved weed control with HT crops also reduces competition between crops and weeds for water and nutrients.

In Australia, both conventionally bred and GM HT crops are grown commercially. Two conventionally bred HT canola varieties are grown; one is tolerant to imidazolinone herbicides and the other to triazine herbicides. Two conventionally bred wheat varieties tolerant to imidazolinone are also available. The only GM HT crops currently approved to be grown commercially in Australia are cotton and canola. For cotton, Roundup Ready® and Roundup Ready Flex® cotton (both tolerant to glyphosate) and Liberty Link® cotton (tolerant to glufosinate ammonium) are grown in Australia. Two varieties of GM herbicide-tolerant canola have also been approved for commercial release in Australia. Roundup Ready® canola tolerates applications of glyphosate and Invigor® hybrid canola tolerates glufosinate ammonium. State moratoria in South Australia, Tasmania and Western Australia currently prevent the growing of either GM canola variety in these states. New South Wales and Victoria approved GM canola to be grown in these states in

---

[16] http://www.agbios.com/dbase.php?action=ShowProd&data=RBMT15-101%2C+SEMT15-02%2C+SEMT15-15 accessed 15 October 2008

[17] http://www.agbios.com/dbase.php?action=ShowProd&data=55-1%2F63-1 accessed 15 October 2008

[18] http://www.agbios.com/dbase.php?action=ShowProd&data=CZW-3 accessed 15 October 2008

[19] http://www.agbios.com/dbase.php?action=ShowProd&data=C5 accessed 15 October 2008

2008, so that Roundup Ready® canola is being grown commercially in Australia for the first time (Gene Technology Task Force 2002; Holtzapffel et al. 2008; in prep.).

Overseas, almost 72 million hectares of GM HT crops are grown, which accounts for 63 per cent of all GM crops grown worldwide. As mentioned in Section 5.1, an additional 22 million hectares of GM crops with combined HT and IR traits are grown. The main GM HT crops grown commercially are soybean, corn (maize), canola, cotton and to a lesser extent, lucerne (James 2008).

5.4 Biosecurity, diagnostics and surveillance

Biotechnology techniques and applications are used in many diagnostic tests and surveillance for biosecurity purposes. These tools could become increasingly important with the need to detect and identify new and emerging pathogens that may have a stronger ability to establish and spread, or to become more abundant under changed climatic conditions.

Currently, taxonomic identification of pests is often carried out through visual means, perhaps using light, scanning or transmission electron microscopes, and perhaps involving sterile culture techniques and the inoculation of another plant with the infected tissue. The reliability and accuracy of these methods depend largely on the professional skills of the person conducting the diagnosis (McCartney et al. 2003).

Enzyme-Linked Immunosorbent Assay (ELISA) is a protein-based technique that is often used to detect pathogens in plants and works by detecting specific proteins of the target pathogen. It is widely used as a first line diagnostics test in the surveillance of plant (and animal) pathogens in Australia and commercial ELISA kits are available for many viruses, bacteria and fungi (Schaad and Frederick 2002).

Polymerase Chain Reaction (PCR) is a DNA-based technique that amplifies a particular, targeted segment of DNA so it is abundant enough to be detected in subsequent analyses. As such, PCR is often used when there is a need to detect the targeted pathogens present in low concentrations and offers a high level of sensitivity (Boonham et al. 2007). It has been used to detect the fungi and fungal spores of Eucalyptus rust (caused by *Puccina psidii*— a serious biosecurity threat for the Australian forestry industry) and has the potential to be used as a diagnostic tool to identify other pathogens such as viruses and bacteria.

Immunofluorescence techniques use fluorescent-labelled antibodies that react with antigens and allow for direct visualisation of cells with a fluorescence microscope (Schaad and Frederick 2002). It is used extensively for plant biosecurity purposes and pathogens are detected through a tissue section cut from the fruit, leaves or stems.

Novel sequencing technologies which determine DNA genetic codes, such as a sequencing technique on fibre-optic slides (Margulies et al. 2005), may become more significant under potential climate change impacts because they provide the ability to identify new and unknown pathogens.

Globally, there is extensive research into the development of diagnostic technologies for the agricultural sector (Tothill 2001). The aim is to develop hand-held devices that can be used for in-field diagnosis by incorporating different technologies into these instruments. The technologies include biosensors, which could detect protein, DNA or a whole live microorganism; and microarrays, which identify unknown samples by simultaneously testing for many pathogens. As biosensors can be used in field for quick diagnosis they have, for example, the advantage of being able to detect fungal spores in asymptomatic plants, avoiding the need to use more traditional techniques (outlined above) which take longer and cost more. Microarrays have already been used successfully to identify plant pathogens (Koch et al. 2005).

Chapter 6 – Biotechnology and farm management practices

In addition to plant improvement and crop development responses to climate change, improved and altered farm management practices are also important. Farm management changes often have shorter development and implementation time-frames than breeding new crop varieties and can allow quicker response to climate variability. A number of farming practices including conservation tillage and dry sowing have been identified as improving the resilience of Australian cropping and pastoral lands to the predicted impacts of climate change. Biotechnology has and will have an important role in helping farmers adopt these practices through making a wider and improved range of crop varieties suited to these practices available to farmers.

6.1 Conservation tillage

Conservation tillage has been one farming technique that has helped improve the sustainability of certain production systems, particularly in semi-arid rain-fed regions (Lyon et al. 2004). Conservation tillage is variously defined and encompasses no-till and reduced tillage practices that restrict the amount of tillage, with crops sown through the stubble residue of previous crops into undisturbed soil. The benefits of such practices compared to conventional tillage include reduced soil loss from wind or water erosion; increased water infiltration; increased soil water storage efficiency; and increased soil organic matter (Doyle 1983; Papendick and Parr 1997; Lyon et al. 2004)—all of which will help farmers to adapt to predicted climate change. There are, however, potential issues associated with no-till and reduced tillage practices, particularly with regard to weed control. One of the purposes of tillage is to remove weeds. In no-till and reduced tillage farming systems, herbicides become the main form of weed control. Some challenges that have emerged from the use of herbicides include the development of herbicide-resistant weeds and difficulties in controlling perennials (Fawcett and Towery 2002). Concerns with weed control as well as the cost of herbicides have been identified in several surveys of farmers as the main reason for not adopting conservation tillage (Fawcett and Towery 2002; D'Emden and Llewellyn 2004; Lyon et al. 2004). The adoption of a variety of HT crops has helped alleviate some of these concerns, by providing farmers with additional weed control options. HT crops allow a particular herbicide to be applied after the emergence of the crop, which reduces the need for pre-emergent herbicide applications. The use of HT crops can provide cheaper and easier weed control and their introduction has led to increased adoption of conservation tillage farming practices in Australia and overseas (Fawcett and Towery 2002; Ammann 2005).

6.2 Dry sowing

Dry sowing is the practice whereby seeds are planted into dry soil (in late-summer or early-autumn in temperate areas) to await the autumn rains. Once germinated by rain, farmers can remove weed seedlings from a HT crop by spraying the appropriate herbicide so that the crop seedlings are free to use water and nutrients without competition from weeds.

It is important for farmers to have the option of dry sowing because for many winter crops, there is a strong relationship between the time of sowing and yield. Canola yields are estimated to decrease by as much as 5 per cent per week of delayed sowing (Norton 2003). With conventional non-HT crops, weed control measures are usually implemented after the opening rains. This typically involves the use of pre-sowing ‘knock-down’ herbicide (such as glyphosate), which is applied once weeds have germinated and emerged. This delays sowing when opening rains are late.

Biotechnology can help farmers to practice dry sowing. HT crops (both GM and non-GM) allow the option of dry sowing because broad ‘knock-down’ weed control can be undertaken after the crop has germinated by applying the relevant herbicide over the top of the crop. Using HT crops in this way can enable an early start to the growing season, adding at least one week to the growing season window (Norton 2003). This can be very significant in terms of yield especially when growing seasons are cut short in changing climates because the end of season becomes hot and dry.

6.3 Other management practices

There are a number of other areas where biotechnology and GM crops are relevant to altered farm management practices. The introduction of HT and IR crops has provided farmers with increased flexibility in the management of pests and weeds. For example, GM IR cotton has led to a 75 per cent reduction in the number of applications of insecticide used on the crop in Australia (Doyle et al. 2005). Also, the conditions-of-use requirements for GM crops have led to improved record keeping and more data collection. Stewardship protocols and integrated pest or weed management strategies have been implemented concurrently with GM crops because of the need to maintain the efficacy of the technology (BRS Workshop 2007). These practices help improve the flexibility and/or the resilience of farming systems to stresses and will thus be important in helping adapt to climate change.

Rotation or sequence cropping and the use of break crops are other practices that have been shown to improve soil fertility, reduce pest and disease build ups and help control weeds (Angus et al. 2001). Despite the agronomic value of break crops, the decreasing price currently received for many break crops in Australia means that it is often no longer economically viable to grow them (Mewett et al. 2007). GM crops that produce industrial and pharmaceutical products could be used as new, higher value rotation crops and provide farmers with a viable alternative. New crops and pastures developed through biotechnology are discussed further in Chapter 7.

Biotechnology could also have a role in improving diagnostic systems for monitoring environmental conditions or plant responses.

Chapter 7 – New or alternative crops and pastures

The impacts of climate change could encourage or force farmers to consider growing new or alternative crops or changing land use patterns. For example, canola-quality Indian mustard (*Brassica juncea*) could replace canola in low rainfall regions, or traditional pasture lands may instead be used for broad-acre cropping with lower irrigation requirements. In addition to assisting farmers to adapt to climate change, alternative crops for biofuels may also contribute to greenhouse gas mitigation—this aspect of biofuels is discussed in Part 3 of this report.

The development of biofuels as a viable alternative to fossil fuels could be important in providing farmers with alternative land use options, as could the modification of crops and pastures to produce industrial and pharmaceutical products (BRS Workshop 2007). These new plants could provide Australian agriculture with the opportunity to diversify from traditional food and feed markets into new markets that may offer higher profit margins. They may also provide a greater return from break crops used in rotational cropping systems. This potential for increased flexibility and profitability could be important in improving the overall resilience of farming in Australia to stresses caused by climate change.

It should be noted that most of the pharmaceutical and industrial crops identified are unlikely to be any better adapted to the predicted impacts of climate change than regular food crops. Rather, their importance for farmers lies in their potential to increase the profitability of farms during good years or providing greater return for any yields achieved during bad years.

7.1 Biofuels

The term biofuels refers to fuels obtained from biomass. Biomass includes any organic material of plant or animal origin, derived from agricultural and forestry production and resulting by-products, and from the renewable portion of industrial and urban wastes (OECD 2007). Aside from reducing fuel use through changing farm management practices, biotechnology also provides the opportunity for reducing transportation fossil fuel use through the production of biofuels.

Much of the current focus on biofuels is on the development and use of ethanol and biodiesel for transport purposes[20]. Ethanol is derived from agricultural feedstocks, such as grain, molasses and starch products, and is used as an extender for petrol. Biodiesel is made from feedstocks such as soybean, canola and palm oil, and vegetable or animal fats (tallow). Biodiesel is used on its own or as an extender in a blend with automotive diesel (Quirke et al. 2008).

Biofuels are a form of biotechnology in the traditional sense of living things being used to create a product. There are many examples of first generation biofuels—that is, processes and feedstocks currently used to produce biofuels— however a detailed discussion of this aspect is beyond the scope of this report.

With regard to providing alternative land use options for farmers trying to adapt to climate change, current biofuel feedstocks and processes may have limited impact because current technologies are largely reliant on traditional agricultural food and feed crops for biofuel feedstocks, including sugarcane, corn (maize) and grains for ethanol and oilseed rape (canola), soybeans and oil palm for biodiesel. As such, farmers growing these crops for biofuels may be no better adapted for climate change than farmers growing the same crops for food use. The possible exceptions to this are biofuels made from genetically-modified high-sugar sugarcane and from the wastes from the processing of food and fibre crops, which would allow value to be obtained from more of the crop. In Australia, 'C molasses' (a waste product from the processing of sugarcane) and waste starch

[20] In terms of energy content, a litre of fuel ethanol contains about two-thirds the energy of a litre of petrol and biodiesel typically contains 88 to 98 per cent of the energy of conventional diesel fuel.

from flour processing are the main feedstocks of ethanol production (Love and Cuevas-Cubria 2007).

There are also a number of concerns about the viability of using current biofuel technologies. These include:

- the cost of production, with biofuels costing more to produce than petroleum fuels and the biofuels industry being largely a creation of government subsidies and support policies (Biofuels Taskforce 2005; Hill et al. 2006)
- growing awareness and scepticism about the effectiveness of biofuels to provide greenhouse gas benefits and about their overall environmental impact
- the direct competition between biofuels and using crops for food and feed, which has the potential to drive up food prices and affect food security.

Although current biofuel feedstocks and processes may not provide opportunities for adaptation to climate change, future biofuel technologies hold much greater promise. Second generation biofuels are biofuels developed using new production methods and feedstocks, for example the conversion of plant lingo-cellulose into a range of fuels.

Ligno-cellulosic biofuels technologies allow the break-down of complex structural plant compounds, such as lignin and cellulose, into simpler carbohydrates and sugars for ethanol production. This technology, which is still some years away from being commercially viable, can theoretically be adapted to utilise almost any plant-based material, including non-food crops, such as grasses, fast-growing trees and crop residues, as a feedstock.

Future biofuel feedstock crops could be grown in more marginal areas than traditional crops and some, such as tree crops, could be grown in conjunction with traditional agricultural crops. This would mean that farmers would have alternative crops to grow in areas becoming increasingly marginal due to climate change. By growing them in marginal areas they do not directly compete with food crops for arable land, and they do not raise the prices of commodities used for food and feed. However, these feedstocks do have the potential to compete indirectly with food and feed through competition for water and labour resources.

Modern biotechnology is likely to have a very important role to play in improving the viability of biofuels and thus providing more realistic options for farmers to adapt to climate change with alternative crops. Biotechnology techniques could be utilised to improve feedstocks by developing crops with:

- higher carbon to nitrogen ratios
- higher biomass, sugar or oil yields
- altered or reduced lignin content for better processing characteristics
- genetically engineered enzymes to aid processing
- greater energy capture
- greater adaptability to marginal conditions (The Royal Society 2008).

Processing techniques can also be improved by using biotechnology tools to develop micro-organisms and enzymes with:

- greater tolerance of alcohol
- the ability to process diverse feedstocks and a range of sugars
- greater tolerance of heat
- the ability to break down lignin efficiently (The Royal Society 2008).

In Australia, GM sugarcane is being developed for more efficient production of ethanol from leaf material without compromising the plant's commercial sugar products located in the cane. The modification includes the insertion of cellulases, enzymes which operate after harvest to convert cellulose in leaf material into fermentable sugars in a highly efficient manner (Farmacule 2006). Cellulases are a very significant component of the cost of production of ligno-cellulosic ethanol from sugarcane. By producing them within the plant, it is hoped the process will become more economical.

CSIRO's Energy Transformed Flagship has a significant focus on Australian second generation biofuels research. A major work area aims to increase the efficiency and improve ligno-cellulose production steps through discovery of novel enzymes and through engineering of existing enzymes (Warden and Haritos 2008).

Overseas, biotechnology is being used to explore and improve both the feedstock and the processing technique for the production of biofuels. Significant efforts are underway to discover or engineer novel enzymes that provide easier and more effective options for the bioethanol industry (Eijsink et al. 2008) and plant-cell-wall-degrading enzymes that are expressed in the plant have the potential to make improvements in ligno-cellulosic biorefineries in the short- to mid-term (Taylor et al. 2008).

GM corn (maize) lines are also being developed which modify biomass properties using two strategies:

- modifying the characteristics and properties of starch or ligno-cellulose for easier conversion to the desired products
- introducing biomass conversion enzymes into plants to aid the conversion process more efficiently (Torney et al. 2007).

Despite this basic research being carried out using corn (maize) as a model organism, it is likely that once the mechanisms are properly understood, they could be applied to other crops.

7.2 Plant molecular farming

Plant molecular farming is the cultivation of GM plants as 'biofactories' to produce novel pharmaceutical and industrial products. In the context of helping farmers to adapt to climate change, plant molecular farming has the potential to offer two opportunities for Australian agriculture:

- the ability to diversify from traditional food and feed markets into new markets that may have higher profit margins (for example the production of alternative sugars in sugarcane)
- the development of new industries, based on new crop plants (for example the production of industrial proteins such as bioplastics).

Due to factors of scale, more opportunities for Australian broadacre agriculture are likely to exist in GM plants with industrial applications (which are typically low- to mid-value, high volume products) rather than pharmaceutical applications (which are often high-value, low volume products) (Mewett et al. 2007).

7.3 Multi-purpose crops

In addition to producing plants that can make novel products and biofuels, research is also being conducted into genetically modifying plants to produce multiple products. This is achieved through partitioning different parts of the plant for different applications. This could help farmers adapt to climate change by increasing the value obtainable from cropping a given land area. An example of such a multi-purpose crop is the potential for producing both sugar and bioplastics from the same sugarcane plant. If the polyhydroxyalkanoates (PHAs) are expressed only in the leaves, this allows sugar to continue to be extracted from the stem by conventional means (Mewett et al. 2007).

Similarly, Farmacule BioIndustries' modifications to sugarcane to produce more cost-effective biofuels do not compromise the commercial sugar products. This means both the sugar and the sugarcane waste can be sources of income (Farmacule 2006). Metabolix is focusing on developing switchgrass (*Panicum virgatum*) that can produce high levels of PHAs, with residue biomass used for biofuel production (Metabolix 2005).

Developing multi-purpose crops allows production of multiple products using a similar level of input as would be required for a crop used for only a single product. In this way, value is added to existing cropping operations and has the potential to increase farmer profits in good seasons. Importantly, it also provides alternative crops for farmers to choose from when adapting to climate change.

Part 3 – Can biotechnology help? – Mitigation

Chapter 8 – Reducing emissions

8.1 Methane reduction

Enteric fermentation is the dominant source of methane from agriculture. One approach to reducing methane emissions from enteric fermentation is to improve the digestibility of pastures. As the digestibility of pastures increases, the intake by ruminants increases per day, as does the daily production of methane. However the products (milk, meat) from ruminants on high digestibility pastures can be generated in less time and therefore with less methane (in total) compared to the same animal products generated on low digestibility pastures. Provided certain stocking practices are implemented, such as reducing the pasture area grazed, high digestibility pastures may help in reducing total methane emissions (Hegarty 2001).

Biotechnology can provide options for increasing the digestibility of pastures. Research is being conducted by the Molecular Plant Breeding Cooperative Research Centre (MPBCRC) into altering the lignin composition and content of perennial ryegrass. Lignin, the part of the plant cell wall responsible for strength and rigidity, increases in pasture grasses as they mature and reduces digestibility. The genes controlling the key enzymes for lignin production in perennial ryegrass have been isolated and plants have been produced that have their genes for lignin production 'turned down' (Glover et al. 2005; MPBCRC undated). Proof-of-concept field trials for perennial ryegrass (*Lolium perenne*) and tall fescue (*Lolium arundinaceum*) that have been genetically modified for altered lignin content for improved digestibility have been approved by the Gene Technology Regulator (DIR82/2007) (OGTR 2008c).

Methane emissions from enteric fermentation can also be reduced through targeting the rumen bacteria that produce methane, known as methanogens. Several different types of compounds have been found to be toxic to methanogens, including a range of fatty acids. Other compounds, such as malate, deprive methanogens of hydrogen, which reduces methane production. In extensively managed herds and flocks of forage-fed ruminants, regular feeding or treatment of animals with such compounds to reduce methane emissions is impractical, especially if the water supply is not reticulated (Hegarty 2001). One potential option is to modify pasture plants that express these compounds. Scientists are already modifying fatty acid compositions in forage plants as well as designing GM pastures that express antibodies against methanogens (BRS Workshop 2007).

Although not directly related to plant biotechnology, there have also been efforts to engineer microbes present in ruminant's stomachs. Research has previously been conducted into genetically modifying gut microbes to reduce methane production (McSweeney et al. 1994). There is also current research into adapting kangaroo rumen bacteria (which do not produce methane) to cattle[21].

8.2 Nitrous oxide reduction

Many agricultural crops are very inefficient at using nitrogen, with between 20–80 per cent of nitrogen applied to soils escaping without being used by the plant for growth or production (Peoples et al. 2004). Some of this applied nitrogen escapes into the atmosphere as nitrous oxide. Improving the efficiency of nitrogen use by crop plants leads to reductions in nitrogenous fertiliser use, reducing nitrous oxide emissions and providing economic savings (BRS Workshop 2007).

Research into improving the nitrogen-use efficiency (NUE) of crops and pastures through genetic modification is being conducted in Australia and internationally. Overseas, field trials have already been conducted with canola with increased NUE achieved through the over-expression of a

---

[21] http://www.mla.com.au/NR/rdonlyres/525628F4-B106-4845-974A-ABB313FBCA38/0/Thekangarooquestion.pdf

naturally occurring enzyme, alanine aminotransferase. If successful, it is hoped that this technique can be applied to other crop plants (Good et al. 2007; Manning et al. 2007). Research into improving the NUE of grains is also being conducted at the Australian Centre for Plant Functional Genomics (ACPFG), in collaboration with Pioneer Hi-Bred in the United States. Using a variety of biotechnology techniques, the ACPFG is currently focusing on increasing the NUE of corn (maize) (Garnett 2006) by increasing the efficiency of mechanisms that plants use to accumulate and utilise nitrogen.

Another agricultural source of nitrous oxide emissions is from animal excretions. The simplest way to reduce animal waste is to improve feed efficiency. This can be achieved with changes in the amino acid profile of feed grain (such as increasing the levels of lysine and methionine) which allows essential amino acid requirements to be met with lower-protein diets. This is particularly important for pigs and poultry. Lower-protein diets reduce excess levels of non-essential amino acids and hence reduces nitrogen excretion (Toride 2002; Etherton 2003). Monsanto has received regulatory approval for a high-lysine GM corn (maize) variety in the United States (US FDA 2005; USDA/APHIS 2006). The corn (maize) line LY038 contains the *cordapA* gene from *Orynebacterium glutamicum* (a bacterium), which results in the accumulation of lysine in the corn (maize) grain. The high-value animal feed has also been approved for human consumption by Food Standards Australia New Zealand (FSANZ 2007), though no application has been lodged to grow the variety in Australia.

8.3 Fossil fuel use reduction

Reducing on-farm fuel use can also help in mitigating climate change through reducing carbon dioxide emissions. Biotechnology has already proven to be successful in indirectly helping to reduce fossil fuel use. As mentioned previously, GM IR crops require significantly fewer insecticide applications than conventional varieties which leads to a reduction in the fuel use associated with applications. The adoption of HT crops and the subsequent increased adoption of reduced tillage practices have also reduced on-farm fuel use. Reduced tillage requires less fuel and provides positive benefits in greenhouse gas mitigation. Brookes and Barfoot (2006; 2008) calculated the carbon dioxide savings in 2006 from reduced fuel use due to the worldwide adoption of GM herbicide-tolerant and insect-resistant crops to be 1215 million kg of carbon dioxide. This equated to removing approximately 540 000 cars from the road each year.

As mentioned previously, aside from reducing fuel use through changing farm management practices, biotechnology also provides the opportunity for reducing transportation fossil fuel use through the production of biofuels. At a basic level, biofuels can be considered carbon neutral, because the carbon they emit to the atmosphere when burned is offset by the carbon that plants absorb from the atmosphere while growing. Such an assessment, however, fails to include energy and emissions involved in the growing of the biofuel crops (including inputs such as fertilisers, pesticides, labour, machinery, irrigation, electricity), the transportation of the feedstock, the construction and running of the processing plant, treatment of any wastes and distribution of the resultant fuel to consumers. The size of greenhouse gas reductions through replacing fossil fuels with biofuels is very much dependent on the feedstock crop, the practices involved in growing the crop and the processing technologies used (O'Connell et al. 2007; The Royal Society 2008).

Given these sensitivities, it is not surprising that whole lifecycle assessments of greenhouse gas emissions from biofuels differ widely in the literature. Hill et al. (2006) calculated reductions in greenhouse gas emissions of 12 per cent for ethanol from corn (maize) and 41 per cent for biodiesel from soybeans, relative to the fossil fuels they replace. The Royal Society (2008) reported that biofuels from cereals, straw, sugarbeet and oilseed rape reduced greenhouse gas emissions by 10-80 per cent (average 50 per cent). Zah et al. (2007) investigated 26 different biofuels and found that 21 of the biofuels reduced greenhouse gas emissions by more than 30 per cent relative to petrol.

In contrast, findings by Crutzen (2008) have indicated that the nitrous oxide emissions from fertiliser applications in biofuel production are 3–5 times larger than assumed in current life-cycle analyses. When these increases in nitrous oxide emissions are considered, the global warming potential of two of the three common biofuels assessed were found to exceed that of fossil fuels. Biodiesel from rapeseed had a relative warming of 1.0–1.7 compared to diesel while the relative warming of ethanol from corn (maize) compared to petrol was 0.9–1.5. Only ethanol from sugarcane was found to have a lower relative warming potential, ranging from 0.5–0.9 compared to petrol (Crutzen et al. 2008).

Another important consideration in assessing the benefits of biofuels in mitigating greenhouse gas emissions is the land use of the cropping area prior to cultivation. The clearing of rainforests and the draining and burning of peatlands in order to establish biofuel crops such as palm oil and sugarcane will result in increases in emissions. Drainage of south-east Asian peatlands could lead to carbon dioxide emissions of up to 100 tonnes per hectare per year; double or triple this if the peatland is then burnt (The Royal Society 2008). Leaving land forested sequesters two to nine times as much carbon over a 30-year period than would be saved by using biofuels (Kleiner 2008). So while sugarcane and palm oil are efficient ways to produce biofuels, they are only beneficial in greenhouse gas terms if they are established on fallow land or agricultural land already being utilised (Kleiner 2008; Scharlemann and Laurance 2008).

Future feedstocks and processes are likely to lead to greater savings in greenhouse emissions, especially if feedstocks with low nitrogen and input requirements were used. Ligno-cellulosic ethanol is likely to show at least a two-fold increase in the average mitigation potential when compared with biofuels derived from food crops (The Royal Society 2008). In addition, improvements in the nitrogen-use efficiency of crops through biotechnology will also help to improve the potential of biofuels to mitigate of greenhouse gas.

8.4 Reducing other inputs

In addition to reducing on-farm fuel costs, reducing the amount of fertiliser, herbicide and insecticide use can also reduce carbon dioxide emissions further up the production line. This includes reducing the energy required for their manufacture, which is particularly significant for nitrogenous fertilisers (BRS Workshop 2007), as well as fossil fuel use in transporting the products.

Chapter 9 – Carbon sinks

9.1 Sequestration

Greenhouse gases can be reduced by increasing the sequestration (storage) of carbon in sinks such as the oceans, soils and biomass. Sequestering carbon by increasing the amount of organic matter in soil could reduce levels of greenhouse gases in the atmosphere while also improving the soil's contribution to agriculture productivity, creating a 'win–win' situation (Walcott 2008).

Two important factors need to be considered when trying to increase the amount of carbon sequestered from the atmosphere by cropping and pastures systems. The first is to maximise the amount of carbon that can be delivered to the soil, which can be achieved through increasing net primary production (NPP). Once the carbon is deposited in soil, the other factor is to maximise its residence time in the soil. Reducing rates of organic matter decomposition can help in increasing soil carbon residence time (U.S. Department of Energy 1999). It should be noted that the amount of carbon that can be sequestered is also strongly influenced by the soil type and climate.

Plant biotechnology provides a number of potential opportunities for increasing agricultural carbon sequestration. Increased NPP and carbon inputs into the soil can be achieved through:

- increased photosynthetic efficiency
- manipulating the partitioning of photosynthates to plant roots
- improved pest and disease resistance
- improved water-use and nutrient-use efficiency.

Strategies for reducing the rate of organic matter decomposition in soils through biotechnology include:

- manipulating the content of lignin and other polymers in plants
- producing plants with deeper roots
- improved water-use efficiency of plants
- promoting conservation tillage practices.

As mentioned in Section 4.1, the main focus of increasing photosynthetic efficiency in crop plants is through modifying the enzyme rubisco. Improving the efficiency of rubisco could lead to faster plant growth and increased sequestration of carbon dioxide from the air, provided it was coupled with increased 'sink' activity (Metting et al. 2001). Researchers in Australia have been involved in a worldwide consortium working on marine arctic algae, which have been found to have a superior form of rubisco that leads to greater photosynthesis efficiency. The ultimate goal is to transfer the responsible genes into crop plants (Andrews and Whitney 2003). Scientists overseas have found that C_3 plants growing in hot arid conditions have evolved forms of rubisco with improved efficiency which may be good candidates for introduction into crop plants (Galmes et al. 2005). Research has also been conducted into inserting randomly mutated genes encoding rubisco into *Escherichia coli* and screening for the most efficient resulting rubisco enzyme. The most efficient rubisco genes could be candidates for introduction into crop plants (Parikh et al. 2006).

Greater NPP can also be achieved through reducing impediments to optimal plant growth, such as water stress, pests and diseases. As previously discussed, biotechnology research is being conducted into improving water-use and nitrogen-use efficiency as well as further developing herbicide-tolerant, insect- and disease-resistant plant varieties. Improving plant water-use efficiency can also help reduce decomposition rates. Increased water-use efficiency should reduce 'excessive' water use and produce drier soils, which in turn will reduce microbial activity (U.S. Department of Energy 1999).

Manipulating the lignin content of plants is another potential strategy for increasing soil carbon. Lignin is a carbon compound that does not decompose easily and is more persistent in soils than cellulose and other non-aromatic compounds (Metting et al. 2001). As identified previously, research is already being conducted into reducing the lignin content of plants and particularly pasture grasses. Knowledge of the synthetic pathways for lignin production gained from such research could be used to increase lignin composition. However, any increase in lignin content would need to ensure that crop yield or pasture digestibility is not affected. This could potentially be achieved by increasing lignin production only in the roots or stems.

Other modifications to plant roots can also help in both increasing carbon input into the soil as well as slowing its degradation. Increasing the partitioning of photosynthates (the products of photosynthesis) to roots or increasing the growth of below-ground components would help in delivering greater amounts of carbon to the soil (Metting et al. 2001). The rates of organic decomposition decrease as depth increases, due to lower temperatures and reduced aeration. Deeper roots would therefore be desirable in slowing decomposition rates, as carbon can be deposited at depths where its residence time is increased (U.S. Department of Energy 1999). As with changing lignin composition, any manipulation of plant roots for increased carbon sequestration would have to ensure yield was not detrimentally impacted.

In addition to breeding plants to sequester more carbon, biotechnology has a role in assisting in the adoption of farming practices such as no-till that can increase soil carbon. Tilling soils after harvesting breaks up soil aggregates, exposing organic matter to rapid oxidation by microorganisms (provided soil moisture and oxygen are adequate). This results in a quick loss of carbon from the soil and the release of carbon dioxide into the atmosphere. No-till or reduced tilling practices can slow the rate of decomposition and lead to an accumulation of carbon in the soil (Crovetto 2000; Dalal and Chan 2001).

The extent of carbon sequestration under no-till farming differs based on climate and soils. It has been suggested that the level of carbon sequestration through no-till practices may be limited in parts of Australia and will be much less than levels reported in the Northern Hemisphere. This is related to both Australia’s dry and hot climate, and the naturally low levels of organic carbon in Australian soils (Wang et al. 2004; Grace 2007; Umbers 2007). However, even small increases in the amount of carbon sequestered would have environmental benefits.

Part 4 – Opportunities and Conclusion

Chapter 10 – Opportunities

In Parts 2 and 3 of this report, a number of traits are described that may either directly or indirectly (through encouraging the adoption of beneficial farm management practices) help farmers adapt to the impacts of climate change and mitigate agricultural greenhouse gas emissions. Some of these traits are more attainable in the short to medium term than others.

For biotechnology to help agriculture overcome the detrimental effects of climate change, it has been suggested that there are three key criteria which need to be addressed: technical feasibility; financial viability; and community acceptability (BRS Workshop 2007). While it is beyond the scope of this report to present an analysis of financial viability and community acceptability, a brief discussion highlighting key considerations in these and other areas is provided below.

10.1 Technical feasibility

The extent to which genetic modification can help develop particular traits typically depends on the genetic complexity of the trait and the current access to genetic diversity within that crop species. The more genetic diversity there is available, the easier it is for plant breeders to find variants that are better able to cope with new abiotic or biotic stressors. However, domesticated crops often have a long history of selection for uniformity of agronomic traits to make harvesting easier and therefore have limited diversity.

GM crops with insect resistance, herbicide tolerance, high-lysine content and, to a lesser extent, disease resistance have already proven to be technically possible. These are traits which are controlled by manipulating or inserting a single gene. As a general rule, the more complex the trait, the more genes are required to control that trait and hence the longer it would take to develop using GM techniques. Most complex phenological traits such as water-use efficiency and heat tolerance have multi-genic inheritance patterns and, therefore, plants modified for these traits have not progressed far down the product development pipeline. However, there are examples where manipulation of single genes can affect complex traits, such as salinity tolerance, nitrogen-use efficiency, aluminium tolerance and cold tolerance (BRS Workshop 2007). Progress with complex traits is also being made by combining or 'stacking' genes in multi-gene cassettes.

10.2 Financial viability

When developing crop and pasture plant traits in laboratories, yield, productivity or profit of the resulting crop need to be maintained or increased; otherwise farmers would be unlikely to adopt the variety produced. For example, in developing crops for water-limited environments, many patents claiming to have developed drought-tolerant varieties have focused on improving plant desiccation tolerance (Passioura 2006). This may result in the improved survival of the plant under water stress without actually having any impact on improving yields in water-limited environments.

Another important consideration in developing stress-tolerant plant varieties is the performance in optimal conditions. As mentioned previously, most farmers make the majority of their profit in good years and try to minimise losses in bad years. Varieties with traits that result in marginally improved yields in bad years, but have a detrimental impact on yield in good years, are unlikely to be adopted.

In considering crop variety traits for reducing greenhouse gas emissions, it is unlikely they will be adopted if the traits have a negative impact on yield. The only exception to this may be under a carbon trading scheme, in which there are financial incentives for farmers for reducing greenhouse gas emissions or increasing carbon sequestration.

10.3 Community acceptance

For GM crops, many of the decisions that impact on their adoption are made based on references to community acceptance to the GM crops or foods, but these decisions are often based on perceptions of attitudes rather than a solid understanding of what the public really think or how they behave in the market place. Understanding consumer attitudes, or more importantly consumer behaviours, will be necessary for the commercial viability of GM crops in the product development pipeline.

A survey of community attitudes towards biotechnology in Australia conducted for Biotechnology Australia was released in June 2007. One part of this survey looked at the perceived value of the objectives of different GM crop traits. Traits that aimed to make plants drought resistant were perceived to be most valuable, with 69 per cent of respondents rating this objective as very valuable. This was followed by making food healthier (58 per cent very valuable) and making plants pest resistant (52 per cent very valuable). The group discussions that were conducted as part of the study found there was widespread agreement that any solutions to environmental problems that biotechnology can provide are worthwhile. Many of these objectives were characterised as human-made solutions to human-made problems. In addition, drought resistance, pest resistance and frost resistance were all seen as minimising the risk of adverse events, with farmers and consumers the likely beneficiaries. However, traits to make plants herbicide-tolerant were not rated as valuable by the respondents, with only 29 per cent rating this objective as very valuable and as not at all valuable by 17 per cent of participants (Eureka Strategic Research 2007).

These findings suggest that any GM crops that combat climate change or provide additional environmental benefits are likely to find greater acceptance in the community.

10.4 Other considerations

Although many of the traits described in this report are being studied individually, there is a need for them to be considered as a package. The impacts from climate change on agricultural production will not occur in isolation. Crops and pastures will experience a number of stresses throughout a growing cycle, with some stresses compounding the impacts of others. For example, in a single season a crop may be exposed to frosts and cold shock early in the season, then endure the combined impacts of drought and heat stress late in the season. A pest or disease incursion during the season will compound impacts. This reinforces the need to develop crop plants with multiple adaptive traits that can produce high yields under a wide range of conditions (Iba 2002). Doing this would require increased understanding of the basic science of the plant and its interactions with the environment. Those organisations that assemble large integrated multidisciplinary teams to tackle the issue of water-use efficiency and other abiotic stresses are likely to be the ones to make the most progress towards agriculturally relevant traits.

There is also a need to maintain strong background knowledge of biological and agricultural systems to which biotechnological tools can be applied. For example, research needs to be well funded so that applications of biotechnology are integrated into the best available varieties and farming systems which are appropriate for Australian environments. Communication and integration between disciplines needs to be strong so practical tools to address climate change are developed sooner. Farmers and agronomists need to be able to communicate priorities to plant physiologists, crop breeders, biochemists and molecular biologists, and the feasibility of targets has to be assessed and communicated back along the chain.

10.5 Attainable options and approaches

The more attainable goals for plant breeders to develop varieties better adapted to changed climates are the simpler traits where there are single gene solutions. Based on the criteria of technical feasibility, financial viability and community acceptance, insect-resistant crop varieties could be viewed as meeting all three criteria. This is evident with GM insect-resistant cotton varieties, which have already been successfully developed and commercially grown in Australia. From a technical and financial viability viewpoint, herbicide-tolerant varieties can also be seen as an important development, with GM herbicide-tolerant cotton and canola both grown commercially. However, there is still uncertainty in the community of the value of such a trait. This may be overcome if the benefits of herbicide tolerance continue to be promoted, not just in terms of weed control, but also the indirect benefits of decreased competition for water and allowing the adoption of farming practices such as no-till which provide reductions in carbon dioxide emissions and improve water retention. For future developments, crops with stacked traits of insect resistance and herbicide tolerance are increasingly being developed and commercialised. Disease resistance is also viewed as a very realistic goal for biotechnology, in particular for those crops for which there is a thorough understanding of the cellular basis of resistance (BRS Workshop 2007). GM plants resistant to fungal pathogens are a possibility over the next ten years. As well as reducing yield losses due to fungal pathogens for the crop in question, such crops would also give farmers more flexibility in their choice of crops (for example, by being able to sow wheat after wheat instead of having to use break crops to reduce disease levels in wheat).

It has been argued that in the short term, conventional breeding techniques, with the aid of molecular marker technologies, are more likely than genetic modification to result in significant yield improvement under water-limited stress due to the complex nature of polygenic traits (Tardieu 2005). This is likely to be the case for most complex phenological traits. GM crops with traits such as water-use efficiency, nitrogen-use efficiency, frost resistance, waterlogging tolerance and control of the timing of flowering are all likely to be further from realisation than GM crop and pasture species with herbicide tolerance and pest and disease resistance. However, these traits are all viewed as attainable within the next decade (BRS Workshop 2007). Proof-of-concept field trials are being conducted in Australia with crops genetically modified for water-use efficiency, nitrogen-use efficiency and waterlogging tolerance. As mentioned in Chapter 4, several examples of single genes controlling complex traits have been discovered and such discoveries could speed up the time to commercialisation for these traits.

Attainable options in terms of developing crops through biotechnology that produce industrial and pharmaceutical products are limited in the short-term. Most of the advances with plant-made pharmaceuticals, plastics and research/analytical products have been with laboratory-scale and glasshouse-scale operations. These are not suitable to broadacre farming and thus will not provide new cropping options for farmers. Much of the research into broadacre crops that produce industrial and pharmaceutical products is in the early stages of development, and commercialisation in Australia is therefore unlikely to be attainable in the next decade. Similarly, this report has described a large number of limitations associated with current biofuel technologies which limit the opportunities biofuels could provide to farmers, both in terms of climate change adaptation and mitigation. Only with the development of future technologies such as lingo-cellulosic ethanol as well as crop development, are biofuels likely to play a significant role in both Australia's future transport and agricultural industries.

Of the traits described in this report which assist in reducing greenhouse gases generated by agriculture, herbicide-tolerant and insect-resistant crops (which can lead to practices that reduce carbon emissions) are the most attainable biotechnology goals in the immediate future. The other main trait that has already proven to be technically feasible and financially viable is GM high-lysine corn (maize)—significant for reducing nitrous oxide emissions in animal excretions—which has been approved for commercial cultivation in the United States. In addition to GM crops with improved nitrogen-use and water-use efficiency, GM pastures with altered lignin content have been approved for proof-of-concept field trials in Australia and are likely to be attainable in the next decade. The complex nature of traits such as improved photosynthetic efficiency means that commercially available crops with these traits are further from realisation.

Chapter 11 – Conclusion

Australia is very likely to experience increasing climate change over the next 30 to 50 years. The scale of that change and the way it will be manifested in different regions is less certain. The Australian cropping and pastoral sectors will be particularly vulnerable to climate change which could see increases in atmospheric carbon dioxide, temperature and uncertain rainfall patterns. Climate change impacts will be complex and will vary greatly across different cropping and pasture regions. Impacts could include heat stress, drought, waterlogging and changes in the distribution and severity of insect pests, pathogens and weeds. There is potential for some impacts to be positive, such as increased water-use efficiency of plants as a result of higher atmospheric carbon dioxide. However, it is not certain if this positive effect will be offset by the effects of increased temperature and changes in water availability.

Farming systems will need to be resilient, flexible and able to respond to changing environmental conditions. Adaptation of crops and pastures involving a variety of traits will be required. Biotechnology, more specifically the use of genetic modifications and molecular markers, will play an important role in helping speed up plant breeding programs to deliver these new traits and varieties sooner. Some traits, such as water-use efficiency and heat tolerance, may directly address climatic stressors. Other traits such as herbicide tolerance may provide both direct (improved weed control) and indirect assistance (adoption of farm management practices which reduce water loss, such as conservation tillage) in adapting to climate change.

The adoption of GM insect-resistant cotton has already proven to be very effective in controlling crop pests and technology such as this may become increasingly important when addressing altered pest distributions. Insect-resistant cotton could also enable production areas to be extended to more northerly regions where rainfall is predicted to increase and where farming has previously been uneconomical partly due to prevalence of insect pests. Australian and international research into disease resistance, also an important trait for crop adaptation, is significantly underpinned by modern biotechnology techniques. Biotechnology may also provide farmers with alternative land use options, such as the use of plants for biofuel, industrial or pharma crops, which could help in improving the resilience and flexibility of farming systems.

This study has also described how biotechnology can help mitigate greenhouse gas emissions from agriculture. The agricultural sector accounts for 16–18 per cent of Australia’s net greenhouse gas emissions and as a net emitter, agriculture needs to take steps to reduce emissions and/or increase carbon storage, which is particularly challenging for intensive cropping. New varieties developed through genetic modification and molecular markers may help in reducing methane and nitrous oxide emissions—such as Australian research to improve the nitrogen-use efficiency of cereals, and reducing methane emissions from cattle by modifying pasture plants to improve digestibility of the feed. Biotechnology can also indirectly contribute to greenhouse gas mitigation by facilitating the adoption of farm management practices which reduce carbon dioxide emissions and increase carbon sequestration activities. Notably, GM insect-resistant crops require significantly fewer insecticide applications than conventional varieties, which leads to a reduction of fuel use associated with applications.

In order to realise the potential of biotechnology to help Australian agriculture adapt to and mitigate climate change, a collaborative approach between farmers and scientists from various disciplines is needed. This will ensure suitable traits and farm management practices are developed and adopted. All of the traits described in this report are already being researched and developed in Australia and/or overseas, but some traits will be easily achievable and more desirable than others. Factors contributing to the success of traits include technical feasibility, financial viability and community acceptance. It is important that the opportunities for crop and pasture development which are most achievable and desirable are identified and communicated. It is also important to identify those traits and commodities which are most needed and/or would have the most impact for mitigating climate change.

Applications of enabling technologies such as biotechnology for the agriculture sector need to be further encouraged and adequately funded. Prioritisation of biotechnology applications relevant to climate change scoped in this study, based on a comparative analysis of their relative benefits and impacts in various agriculture sectors (crops, pastures, horticulture and forestry), would help identify priority applications for research and development.

Acknowledgements

This study was financially supported by the Australian Government Department of Agriculture, Fisheries and Forestry, Agricultural Productivity Division using funds provided by the National Biotechnology Strategy.

The authors wish to acknowledge all the BRS Workshop 2007 attendees who contributed to this report. They were very generous with their time and provided valuable input to this report. Thanks must go to: Sam Nelson and Jim Walcott, BRS, who assisted in the planning of this project as well as providing input on the climate change aspects; Rob Smart, BRS, for providing the maps; and Alice McRorie and Cristal Jones, Australian National University, for providing the background research for the biofuels and biosecurity sections of the report.

Thanks also to the reviewers of this report who provided extensive and valuable feedback.

Glossary

Abiotic stress	Stress caused to living organisms resulting from environmental factors such as drought, temperature extremes and soil conditions (eg: salinity).
Annuals	A plant that completes its life cycle within one year or season.
Anthropogenic	Originating from the activity of humans.
Biennial	A plant that takes two years or seasons to complete its life cycle.
Biomass	Total amount of biological material. Often used in reference to the plant material that can be used as a source of energy.
Biotechnology	A broad term to describe the process of using living things to make products or perform tasks for people.
Biotic stress	Stress caused to living organisms resulting from attack by other living organisms such as insect pests, viruses, bacteria and fungi.
C_3 photosynthesis	The most common type of photosynthesis. It is more efficient than C_4 photosynthesis under cool and moist conditions and average light levels.
C_4 photosynthesis	A type of photosynthesis found, for example, in many tropical grasses in which photosynthesis occurs faster and more efficiently under high temperature and light, and conserves more water in comparison to the more typical C_3 photosynthesis.
Carbon fixation	The part of the photosynthetic process in green plants in which carbon atoms from atmospheric carbon dioxide are converted into organic compounds (i.e. sugars). Is catalysed by rubisco.
Cellulase	Enzymes that operate after harvest to catalyse the breakdown of cellulose in leaf material into fermentable sugars.
Chromosome	A structure in plant and animal cells composed of a very long DNA molecule and associated proteins that carry part or all of the hereditary information of an organism.
DNA	Deoxyribonucleic acid (DNA) serves as the store of hereditary information within a cell for most known organisms and is the carrier of this information from generation to generation.
Dormancy	The resting or inactive phase of plants or seeds.
Functional genomics	The analysis of genetic information and its biological function. It focuses on understanding the function of genes and other parts of the genome.
Gene	The region of DNA that controls a wide range of hereditary characteristics such as physical, biochemical and physiological traits, and also developmental processes.

Gene silencing (RNA interference)	Selective degradation of RNA that is intended to remove foreign RNAs, such as those of viruses. It is exploited in a technique used to silence the expression of selective genes.
Genomics	The discipline that aims to define and characterise the complete genetic makeup of an organism.
Heat tolerance genes	Genes that are expressed in increased amounts in response to an elevated temperature, usually to help the cell survive the stress.
High throughput assays	Used to describe methods by which a researcher can conduct a large number of chemical or biological tests in a short period of time.
Hybridisation	Interbreeding of species, races, varieties and so on; a process of forming a hybrid by cross-pollination of two genetically unlike individuals.
Marker-assisted breeding	See molecular markers.
Metabolomics	The large-scale study of the full complement of 'secondary metabolites', which are molecules that have roles associated with the environment, for example for defence or as attractants.
Molecular Markers	Short fragments of DNA already present in a species that can be used by breeders to quickly and accurately identify and track the inheritance of a desired trait in a breeding programme.
Multi-gene cassette	The presence of more than one transgene in a cloning vector.
Mutagenesis	The production of mutations.
Mutation	Heritable change in the nucleotide sequence of a chromosome.
Nitrogen-use efficiency	The amount of nitrogen that is utilised by the plant compared to the volume applied as part of a nitrogenous fertiliser.
Perennials	Plants with a lifespan that spans at least two years or seasons, as distinct from annuals and biennials.
Phenological development	The relation of developmental stages of plants to seasonal changes.
Phenology	The study of the relationship between climate and the timing of periodic natural phenomena such as flowering.
Phenomics	The study of the physical characteristics of an organism.
Photoperiod	The length of daylight or period of daily illumination provided for growth.
Photoreceptor	A cell or molecule that is sensitive to light.
Photosynthesis	The process by which green plants, algae and some bacteria use the energy of sunlight to drive the synthesis of organic molecules, such as sugar, from carbon dioxide and water.

Phytochromes	The primary photoreceptors involved in sensing photoperiod and light quality.
Polygenic trait	Trait that is controlled by more than one gene.
Promoter	The region of DNA to which RNA polymerase binds to begin transcription. This region of DNA helps to determine where and when each gene is expressed within an organism.
Proteomics	The study of expressed proteins.
RNA	Ribonucleic acid (RNA) is a single stranded molecule used in the process of building proteins from the instructions contained in DNA. Also, some viruses use RNA instead of DNA as their genetic material.
Rubisco	Ribulose-1,5-biphosphate carboxylase oxygenase (rubisco) is thought to be the most abundant single protein on earth and is required for carbon dioxide assimilation by all plants.
Sleeper weeds	Naturalised (exotic) plant species that are currently limited in their distribution (making eradication feasible) but which have potential to become significant weeds.
Transcriptomics	The study of gene transcripts, that is, all the messenger RNAs produced from genes.
Transgene	A gene from one genome that has been incorporated into the genome of another organism.
Vernalisation	The process by which exposure to low temperatures induces seed germination or flowering.
Vigour	For a plant to have active vegetative growth.
Water-use efficiency	The amount of biomass produced per unit of water consumed.

Appendix

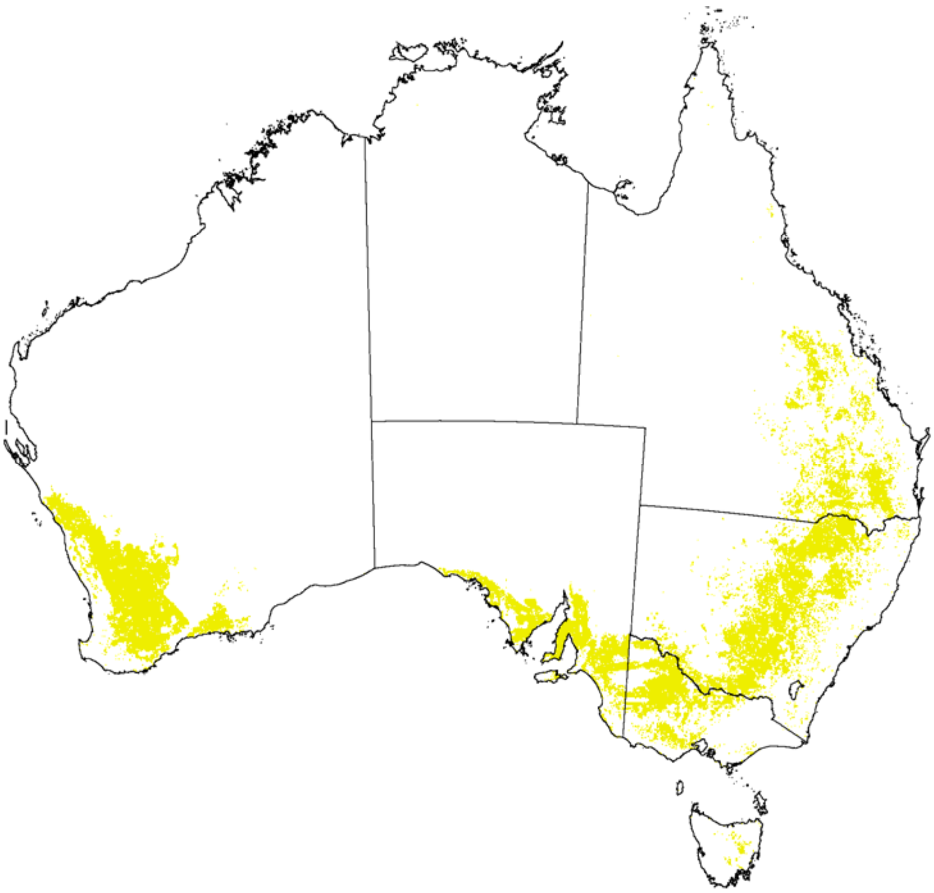

Figure 1: Australian winter dryland cropping sector

Source: 2000/01 Land use of Australia Version 3, Bureau of Rural Sciences, 2006.

Winter and summer dryland cereals (excluding rice).

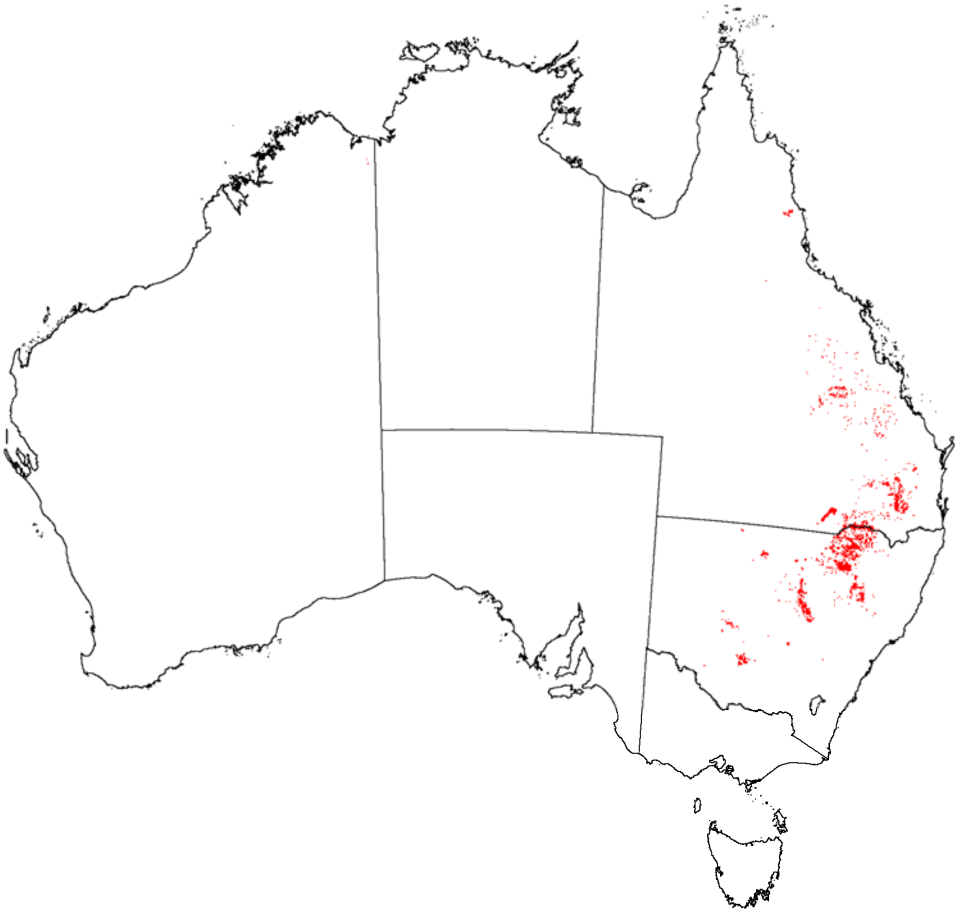

Figure 2: Australian cotton growing sector

Source: 2000/01 Land use of Australia Version 3, Bureau of Rural Sciences, 2006.

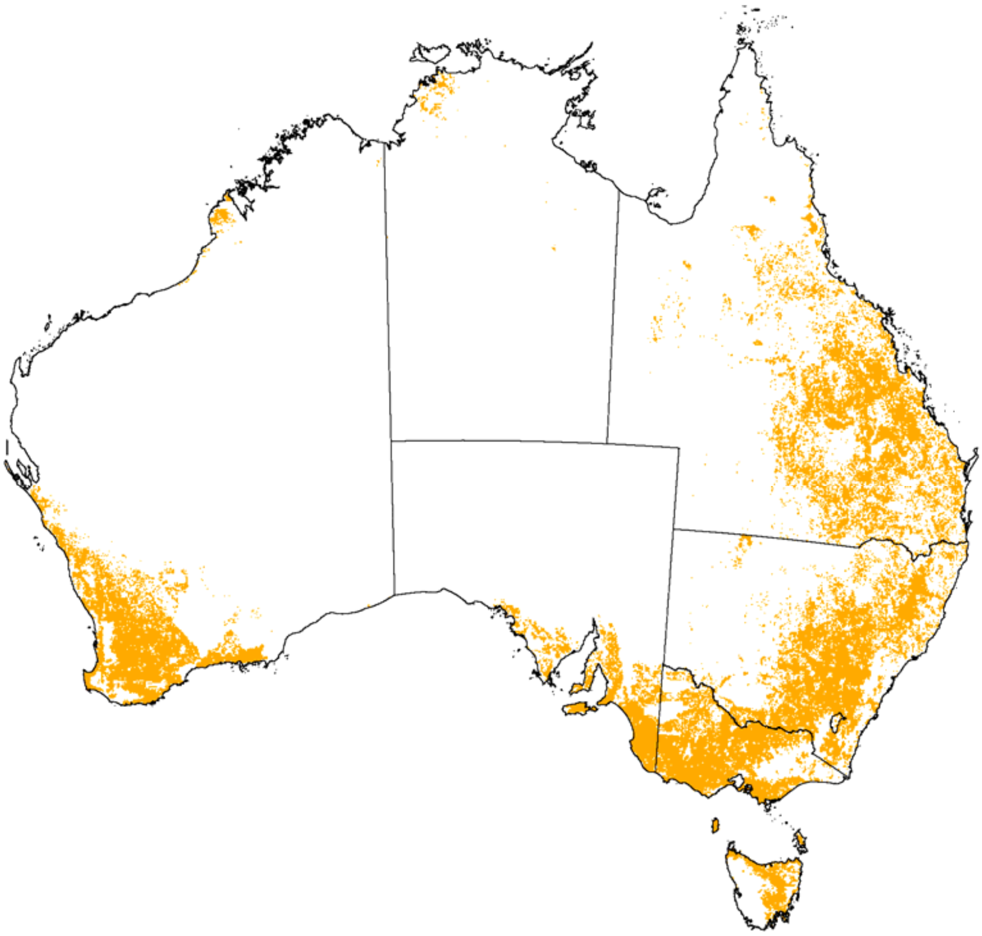

Figure 3: Sown pastures in Australia

Source: 2000/01 Land use of Australia Version 3, Bureau of Rural Sciences, 2006.

References

ABARE 2007, *Australian Crop Report, September 2007 no.143*, ABARE, Canberra, Australia.

ABARE and MAF 2006, *Agricultural Economies of Australia and New Zealand: Past, Present, Future*, Canberra, Australia.

ABS 2007, *Water Use on Australian Farms 2005-06 Preliminary*, Australian Bureau of Statistics, Canberra.

ACPFG 2006, *Australian Centre for Plant Functional Genomics 2006 Annual Report*, ACPFG, Adelaide.

Adir N, Zer H, Shocat S and Ohad I 2003, 'Photoinhibition - a historical perspective', *Photosynthesis Research*, 76: 343-370.

AGO 2007, *Australia's National Greenhouse Accounts: National Inventory Report 2005 - Volume 1*, Australian Greenhouse Office, Canberra.

Ammann K 2005, 'Effects of biotechnology on biodiversity: herbicide-tolerant and insect-resistant GM crops', *Trends in Biotechnology*, 23: 388-394.

Amthor J S 2001, 'Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration', *Field Crops Research*, 73: 1-34.

Andrews T J and Whitney S M 2003, 'Manipulating ribulose bisphosphate carboxylase/oxygenase in the chloroplasts of higher plants', *Archives of Biochemistry and Biophysics*, 414: 159-169.

Angus J F, Kirkegaard J A and Peoples M B 2001, 'Rotation, Sequence and Phase: Research on Crop and Pasture Systems', *Science and Technology: Delivering Results for Agriculture? - Proceedings of the 10th Australian Agronomy Conference*, Australian Society of Agronomy, Hobart, Tasmania.

Anwar M R, O'Leary G, McNeil D, Hossain H and Nelson R 2007, 'Climate change impact on rainfed wheat in south-eastern Australia', *Field Crops Research*

`Ground-breaking Stuff'- Proceedings of the 13th Australian Society of Agronomy Conference, 10-14 September 2006, Perth, Western Australia, 104: 139-147.

Atwell B J, Kriedemann P E and Turnbull C G N 1999, *Plants in Action - Adaptation in Nature, Performance in Cultivation*, The Australian Society of Plant Physiologists South Yarra, Victoria.

Ayeneh A, van Ginkel M, Reynolds M P and Ammar K 2002, 'Comparison of leaf, spike, penducle and canopy temperature depression in wheat under heat stress', *Field Crops Research*, 79: 173-184.

Bell L W, Wade L J and Ewing M A 2006, 'Perennial wheat: a paradox with possibility', *Ground-breaking Stuff, Proceedings of the 13th Australian Agronomy Conference* The Australian Society of Agronomy, Perth.

Bindi M and Howden M 2004, 'Challenges and opportunities for cropping systems in a changing climate', *New directions for a diverse planet. Proceedings of the 4th International Crop Science Congress*, Australia.

Biofuels Taskforce 2005, *Report of the Biofuels Taskforce to the Prime Minister*, Australian Government Biofuels Taskforce, Canberra.

Blum A 1998, 'Improving wheat grain filling under stress by stem reserve mobilisation', *Euphytica*, 100: 77-83.

Boonham N, Tomlinson J and Mumford R 2007, 'Microarrays for rapid identification of plant viruses', *Annual Review of Phytopathology*, 45: 307-328.

Borrel A K, Tao Y Z and McIntyre C L 2000, *Physiological Basis, QTL, and MAS of the Stay-Green Drought Resistance Trait in Grain Sorghum*, in J-M Ribaut and D Poland, *Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-Limited Environments*, A Strategic Planning Workshop held at CIMMYT, El Batan, Mexico, 21-25 June 1999. CIMMYT, Mexico.

Botwright T L, Condon A G, Rebetzke G J and Richards R A 2002, 'Field evaluation of early vigour for genetic improvement of grain yield in wheat', *Australian Journal of Agricultural Research*, 53: 1137-1145.

Brookes G and Barfoot P 2006, 'Global impact of biotech crops: Socio-economic and environmental effects in the first ten years of commercial use.', *AgBioForum*, 9: 139-151.

Brookes G and Barfoot P 2008, *GM crops: global socio-economic and environmental impacts 1996-2006*, PG Economics Ltd, Dorchester, UK.

BRS 2007, *Australian Agriculture, Fisheries and Forestry At A Glance*, Australian Government Bureau of Rural Sciences, Canberra, Australia.

Buchanan B B, Gruissem W and Jones R L 2000, *Biochemistry and Molecular Biology of Plants*, American Society of Plant Physiologists, Rockville, Maryland.

Cakir M, Appels R, Waters I, Verbyla A, Drake-Brockman F, Carter M and Setter T 2005, 'Mapping QTLs for waterlogging tolerance in wheat', *Plant & Animal Genomes XIII Conference*, January 15-19, San Diego, CA.

Chakraborty S and Datta S 2003, 'How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate?', *New Phytologist*, 159: 733-742.

Chakraborty S, Murray G and White N 2002, *Impact of Climate Change on Important Plant Diseases in Australia*, Rural Industries Research and Development Corporation, Canberrra, Australia.

Coakley S M, Scherm H and Chakraborty S 1999, 'Climate change and plant disease Management', *Annual Review of Phytopathology*, 37.

Cotton Australia 2006, *Growing Cycle*, http://www.cottonaustralia.com.au/factSheets/resources/growing%20cycle.pdf, accessed 17 August 2007.

Crovetto C 2000, 'No Till, the Stubble and the Soil Nutrition', *Manitoba-North Dakota Zero Tillage Farmers Association 22nd Annual Workshop*, http://www.mandakzerotill.org/books/proceedings/Proceedings%202000/Carlos%20Crovetto.htm, accessed 18 January 2008.

Crutzen P J, Mosier A R, Smith K A and Winiwarter W 2008, 'N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels', *Atmospheric Chemistry and Physics*, 8: 389-395.

CSIRO 2001, *Climate Change Projections for Australia*, CSIRO Atmospheric Research, Aspendale.

CSIRO and BOM 2007, *Climate Change in Australia. Technical Report.*, CSIRO, Canberra, Australia.

D'Emden F H and Llewellyn R S 2004, 'No-till adoption and cropping issues for Australian grain growers', *New directions for a diverse planet - Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004*, Crop Science, Brisbane, Australia.

Dalal R C and Chan K Y 2001, 'Soil organic matter in rainfed cropping systems of the Australian cereal belt', *Australian Journal of Soil Research*, 39: 435-464.

Dennis E S, Dolferus R, Ellis M, Rahman M, Wu Y, Hoeren F U, Grover A, Ismond K P, Good A G and Peacock W J 2000, 'Molecular strategies for improving waterlogging tolerance in plants', *Journal of Experimental Botany*, 51: 89-97.

Doyle A P 1983, 'Stubble Retention', *Proceedings Riverina Outlook Conference*, Wagga Wagga, NSW.

Doyle B, Reeve I and Coleman M 2005, *The Cotton Consultants Australia 2005 Bollgard Comparison Report: A survey of cotton growers' and consultants' experience with Bollgard in the 2004-05 season*, University of New England Institute of Rural Futures, Armidale, Australia.

Drake V A 1994, 'The influence of weather and climate on agriculturally important insects: an Australian perspective', *Australian Journal of Agricultural Research*, 45: 487-509.

Driscoll S P, Prins A, Olmos E, Kunert K J and Foyer C H 2006, 'Specification of adaxial and abaxial stomata, epidermal structure and photosynthesis to CO2 enrichment in maize leaves', *Journal of Experimental Botany*, 57: 381-390.

Dukes J S and Mooney H A 1999, 'Does global change increase the success of biological invaders?', *Trends in Ecology & Evolution*, 14: 135-139.

Edmeades G O, McMaster G S, White J W and Campos H 2004, 'Genomics and the physiologist: bridging the gap between genes and crop response', *Field Crops Research*, 90: 5-18.

Ehdaie B, Alloush G A, Madore M A and Waines J G 2006, 'Genotypic variation for stem reserves and mobilization in wheat I. Postanthesis changes in internode dry matter (vol 46, pg 736, 1998)', *Crop Science*, 46: 1420-1420.

Eijsink V G H, Vaaje-Kolstad G, Vårum K M and Horn S J 2008, 'Towards new enzymes for biofuels: lessons from chitinase research', *Trends in Biotechnology*, 26: 228-235.

Ellis S L, Ryan M, Angus J F and Pratley J E 2006, 'Wheat yields after perennial pastures under drought conditions', *'Ground-breaking stuff' - Proceedings of the 13th Agronomy Conference 10-14 September 2006*, N C Turner, T Acuna and R C Johnson, The Australian Society of Agronomy, Perth, WA.

Etherton T 2003, 'Improving animal agriculture through biotechnology', *Economic Perspectives Agricultural Biotechnology*, 8: 26-28.

Eureka Strategic Research 2007, *Community Attitudes to Biotechnology - Report on Food and Agriculture Applications*, prepared for Biotechnology Australia, Canberra, ACT.

European Plant Science Organization (EPSO) 2005, 'European plant science: a field of opportunities', *Journal of Experimental Botany*, 56: 1699-1709.

Farmacule 2006, *Genetic technology to produce cheaper ethanol from sugarcane*, Farmacule Bioindustries Pty Ltd, http://farmacule.com/news/news7/, accessed 18 September 2007.

Fawcett R and Towery D 2002, *Conservation tillage and plant biotechnology: How new technologies can improve the environment by reducing the need to plow*, Conservation Technology Information Center, West Lafayette.

Federici B A 2005, 'Insecticidal bacteria: An overwhelming success for invertebrate pathology', *Journal of Invertebrate Pathology*, 89: 30-38.

FSANZ 2007, *First Review Report Application A549 Food Derived from High Lysine Corn LY038*, http://www.foodstandards.gov.au/_srcfiles/FRR_A549.pdf, accessed 18 January 2008.

Fuhrer J 2003, 'Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change', *Agriculture, Ecosystems & Environment*, 97: 1-20.

Galmes J, Flexas J, Keys A J, Cifre J, Mitchell R A C, Madgwick P J, Haslam R P, Medrano H and Parry M A J 2005, 'Rubisco specificity factor tends to be larger in plant species from drier habitats and in species with persistent leaves', *Plant Cell and Environment,* 28: 571-579.

Garnett T 2006, 'The ACPFG turns to dwarves to improve nitrogen use', *ACPFG Vector*, Issue 3: 10.

Gene Technology Task Force 2002, *Agricultural Biotechnology: Herbicide Tolerant Crops in Australia*, Bureau of Rural Sciences, Canberra.

Glover J, Mewett O, Tifan M, Cunningham D, Ritman K and Morrice B 2005, *What's in the Pipeline? Genetically modified crops under development in Australia*, Australian Government Bureau of Rural Sciences, Canberra.

Good A G, Johnson S J, De Pauw M, Carroll R T, Savidov N, Vidmar J, Lu Z, Taylor G and Stroeher V 2007, 'Engineering nitrogen use efficiency with alanine aminotransferase', *Canadian Journal of Botany*, 85: 252-262.

Grace P 2007, 'Carbon farming - facts and fiction', *Can Australian soils sustain our agricultural systems? Proceedings of the Healthy Soils Symposium.*, Healthy Soils for Sustainable Farms, Sunshine Coast, Australia.

Hegarty R 2001, *Greenhouse Gas Emissions From The Australian Livestock Sector - What Do We Know, What Can We Do?*, Australian Greenhouse Office, Canberra, Australia.

Hill J, Nelson E, Tilman D, Polasky S and Tiffany D 2006, 'Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels', *Proceedings of the National Academy of Sciences of the United States of America*, 103: 11206-11210.

Holtzapffel R, Mewett O, Wesley V and Hattersley P 2008, *Genetically modified crops: tools for insect pest and weed control*, Australian Government Bureau of Rural Sciences, Canberra.

Holtzapffel R, Mewett O, Wesley V and Hattersley P in prep., *Genetically modified crops: tools for insect pest and weed control*, Australian Government Bureau of Rural Sciences, Canberra.

Howden S M and Crimp S 2005, 'Assessing dangerous climate change impacts on Australia's wheat industry', *MODSIM 2005 Internatonal Congress on Modelling and Simulation*, A Zerger and R M Argent.

Howden S M, Harle K J, Dunlop M and Hunt L 2004, *The Potential Impact of Climate Change on Wool Growing in 2029*, CSIRO Sustainable Ecosystems, Canberra.

Howden S M, Reyenga P J, Meinke H and McKeon G M 1999, *Integrated Global Change Impact Assessment on Australian Terrestial Ecosystems Overview*, CSIRO Wildlife and Ecology, Canberra.

Hunsaker D J, Hendrey G R, Kimball B A, Lewin K F, Mauney J R and Nagy J 1994, 'Cotton evapotranspiration under field conditions with CO2 enrichment and variable soil moisture regimes', *Agricultural and Forest Meteorology*, 70: 247-258.

Iba K 2002, 'Acclimative Response to Temperature Stress in Higher Plants: Approaches of Gene Engineering for Temperature Tolerance', *Annual Review of Plant Biology*, 53: 225-245.

IPCC 2007, *Summary for Policymakers*, in S D Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambidge, U.K. New York, USA.

James C 2008, *Global Status of Commercialized Biotech/GM Crops: 2007*, ISAAA Brief No. 37, International Service for the Acquisition of Agri-biotech Applications (ISAAA), Ithaca, NY.

John U P and Spangenberg G C 2005, 'Xenogenomics: genomic bioprospecting in indigenous and exotic plants through EST discovery, cDNA microarray-based expression profiling and functional genomics', *Comparative and Functional Genomics*, 6: 230-235.

Kimball B A, Morris C F, Pinter P J J, Wall G W, Hunsaker D J, Adamsen F J, La Morte R L, Leavitt S W, Thompson T L, Matthias A D and Brooks T J 2001, 'Elevated CO2, drought and soil nitrogen effects on wheat grain quality', *New Phytologist*, 150: 295-303.

Kleiner K 2008, 'The backlash against biofuels', *Nature Reports Climate Change*, 2.

Koch C A, Li P C H and Utkhede R S 2005, 'Evaluation of thin films of agarose on glass for hybridization of DNA to identify plant pathogens with microarray technology', *Analytical Biochemistry*, 342: 93-102.

Kotak S, Larkindale J, Lee U, von Koskull-Doring P, Vierling E and Scharf K D 2007, 'Complexity of the heat stress response in plants', *Current Opinion in Plant Biology*, 10: 310-316.

Larkindale J, Hall J D, Knight M R and Vierling E 2005, 'Heat stress phenotypes of arabidopsis mutants implicate multiple signaling pathways in the acquisition of thermotolerance', *Plant Physiology*, 138: 882-897.

Larkindale J and Huang B 2004, 'Thermotolerance and antioxidant systems in Agrostis stolonifera: Involvement of salicylic acid, abscisic acid, calcium, hydrogen peroxide, and ethylene', *Journal of Plant Physiology*, 161: 405-413.

Lesslie R, Hill M, Woldendorp G, Dawson S and Smith J 2006, *Towards Sustainability for Australia's Rangelands - Analysing the options*, Australian Government Bureau of Rural Sciences, Canberra.

Li P, Bohnert H J and Grene R 2007, 'All about FACE - plants in a high-[CO2] world', *Trends in Plant Science*, 12: 87-89.

Liu H T, Liu Y Y, Pan Q H, Yang H R, Zhan J C and Huang W D 2006a, 'Novel interrelationship between salicylic acid, abscisic acid, and PIP2-specific phospholipase C in heat acclimation-induced thermotolerance in pea leaves', *Journal of Experimental Botany*, 57: 3337-3347.

Liu H T, Sun D Y and Zhou R G 2005, 'Ca2+ and AtCaM3 are involved in the expression of heat shock protein gene in Arabidopsis', *Plant Cell and Environment*, 28: 1276-1284.

Liu Z, Yuan Y L, Liu S Q, Yu X N and Rao L Q 2006b, 'Screening for high-tempeature tolerant cotton cultivars by testing in vitro pollen germination, pollen tube growth and boll retention', *Journal of Integrative Plant Biology*, 48: 706-714.

Llewellyn D J, Mares C L and Fitt G P 2007, 'Field performance and seasonal changes in the efficacy against *Helicoverpa armigera* (Hübner) of transgenic cotton expressing the insecticidal protein vip3A', *Agricultural and Forest Entomology*, 9: 93-101.

Love G and Cuevas-Cubria C 2007, 'Outlooks for Biofuels in Australia: The Challenges Ahead', *Australian Commodities*, 14: 212-220.

Ludwig F and Asseng S 2006, 'Climate change impacts on wheat production in a Mediterranean environment in Western Australia', *Agricultural Systems*, 90: 159-179.

Lyon D, Bruce S, Vyn T and Peterson G 2004, 'Achievements and Future Challenges in Conservation Tillage', *New directions for a diverse planet - Proceedings of the 4th International Crop Science Congress, 26 Sep – 1 Oct 2004*, Crop Science, Brisbane, Australia.

Manning C, Theodoris G, Fazio G, Gallawa P, Ndukaku O, Palamo A, van Boxtel J, Lu Z and Kridl J 2007, 'Nitrogen Use Efficiency in Transgenic Canola', *Plant Biology and Botany 2007 Joint Congress*, Chicago, Illinois.

Manschadi A M, Christopher J, deVoil P and Hammer G L 2006, 'The role of root architectural traits in adaptation of wheat to water-limited environments', *Functional Plant Biology*, 33: 823-837.

Margulies M, Egholm M, Altman W E, Attiya S, Bader J S, Bemben L A, Berka J, Braverman M S, Chen Y J, Chen Z T, Dewell S B, Du L, Fierro J M, Gomes X V, Godwin B C, He W, Helgesen S, Ho C H, Irzyk G P, Jando S C, Alenquer M L I, Jarvie T P, Jirage K B, Kim J B, Knight J R, Lanza J R, Leamon J H, Lefkowitz S M, Lei M, Li J, Lohman K L, Lu H, Makhijani V B, McDade K E, McKenna M P, Myers E W, Nickerson E, Nobile J R, Plant R, Puc B P, Ronan M T, Roth G T, Sarkis G J, Simons J F, Simpson J W, Srinivasan M, Tartaro K R, Tomasz A, Vogt K A, Volkmer G A, Wang S H, Wang Y, Weiner M P, Yu P G, Begley R F and Rothberg J M 2005, 'Genome sequencing in microfabricated high-density picolitre reactors', *Nature*, 437: 376-380.

McCartney H A, Foster S J, Fraaije B A and Ward E 2003, 'Molecular diagnostics for fungal plant pathogens', *Pest Management Science*, 59: 129-142.

McSweeney C, Mackie R and White B 1994, 'Transport and intracellular metabolism of major feed compounds by ruminal bacteria: the potential for metabolic manipulation', *Australian Journal of Agricultural Research*, 45: 731-756.

Meehl G A, Stocker T F, Collins W D, Friedlingstein P, Gaye A T, Gregory J M, Kitoh A, Knutti R, Murphy J M, Noda A, Raper S C B, Watterson I G, Weaver A J and Zhao Z-C 2007, *Global Climate Projections.*, S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller, Cambridge University Press, Cambridge.

Metabolix 2005, *Biotechnology Foundation: Biotech to Bioplastics*, Metabolix, http://www.metabolix.com/biotechnology%20foundation/structurespace.html, accessed 20 February 2008.

Metting F B, Smith J L, Amthor J S and Izaurralde R C 2001, 'Science needs and new technology for increasing soil carbon sequestration', *Climatic Change*, 51: 11-34.

Mewett O, Johnson H and Holtzapffel R 2007, *Plant molecular farming in Australia and overseas*, Australian Government Bureau of Rural Sciences, Canberra.

Moore G, Sanford P and Wiley T 2006, *Bulletin 4690 Perennial pastures for WA*, Department of Agriculture and Food, WA, Perth, WA.

Morell M K, Paul K, Kane H J and Andrews T J 1992, 'Rubisco: Maladapted or Misunderstood', *Australian Journal of Botany*, 40: 431-441.

MPBCRC undated, *Pasture Research Fact Sheet*, Molecular Plant Breeding CRC, http://www.molecularplantbreeding.com/pdfs/MPB_FactSheet-Pastures.pdf, accessed 11 January 2008.

Natural Resource Management Ministerial Council 2006, *National Agriculture and Climate Change Action Plan 2006-2009*, Australian Government Department of Agriculture, Fisheries and Forestry, Canberra.

Norton R 2003, *Conservation farming systems and canola*, The University of Melbourne, Melbourne, Victoria.

O'Connell D, Batten D, O'Connor M, May B, Raison J, Keating B, Beer T, Braid A, Haritos V, Begley C, Poole M, Poulton P, Graham S, Dunlop M, Grant T, Campbell P and Lamb D 2007, *Biofuels in Australia - issues and prospects*, Rural Industries Research and Development Corporation (RIRDC), Canberra.

OECD 2007, *Biofuels for Transport: Policies and Possibilities*, Organisation for Economic Co-operation and Development, http://www.oecd.org/dataoecd/18/8/39718027.pdf, accessed 26 February 2008.

OGTR 2003a, *DIR 034/2003: The Evaluation of Transgenic Cotton Plants Expressing the VIP Gene*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir034.htm, accessed 4 June 2008.

OGTR 2003b, *DIR 047/2003: Field Evaluation of Genetically Modified White Clover Resistant to Infection by Alfalfa Mosaic Virus*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir047.htm, accessed 4 June 2008.

OGTR 2006a, *DIR 064/2006: Limited and controlled release of water-efficient GM cotton*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir064.htm, accessed 4 June 2008.

OGTR 2006b, *DIR 067/2006: Limited and Controlled release of GM waterlogging tolerant cotton*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir067.htm, accessed 18 September 2007.

OGTR 2006c, *DIR 070/2006: Limited and Controlled release of GM sugarcane*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir070.htm, accessed 4 June 2008.

OGTR 2006d, *Risk Assessment and Risk Management Plan for DIR 066/2006. Commercial release of GM herbicide tolerant and/or insect resistant cotton lines north of latitude 22°South*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/dir066-3/$FILE/dir066rarmp2.pdf, accessed 17 October 2008.

OGTR 2007, *DIR 071/2006: Limited and Controlled release of GM drought tolerant wheat*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/ir/dir071.htm, accessed 17 September 2007.

OGTR 2008a, *DIR 077/2007: Limited and controlled release of wheat and barley genetically modified for enhanced tolerance to abiotic stresses or increased beta glucan*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/dir077-2007, accessed 16 October 2008.

OGTR 2008b, *DIR 079/2007: Limited and controlled release of banana genetically modified for disease resistance*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/dir079-2007, accessed 16 October 2008.

OGTR 2008c, *DIR 082/2007: Limited and controlled release of perennial ryegrass and tall fescue genetically modified for improved forage qualities*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/dir080-2007, accessed 15 September 2008.

OGTR 2008d, *DIR 083/2007: Limited and controlled release of cotton genetically modified for enhanced waterlogging tolerance*, Office of the Gene Technology Regulator, http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/dir083-2007, accessed 16 October 2008.

Ohmura A and Wild M 2002, 'Is the hydrological cycle accelerating', *Science*, 298: 1345-1346.

Papendick R I and Parr J F 1997, 'No-till farming: The way of the future for a sustainable dryland agriculture', *Annals of Arid Zone*, 36: 193-208.

Parikh M R, Greene D N, Woods K K and Matsumura I 2006, 'Directed evolution of RuBisCO hypermorphs through genetic selection in engineered E.coli', *Protein Engineering Design & Selection*, 19: 113-119.

Parry M L 1990, *Climate change and world agriculture*, Earthscan Publications, London.

Passioura J 2006, 'Increasing crop productivity when water is scarce - from breeding to field management', *Agricultural Water Management*, 80: 176-196.

Passioura J 2007a, 'The drought environment: physical, biological and agricultural perspectives', *Journal of Experimental Botany*, 58: 113-117.

Passioura J 2007b, *Workshop on Pre-Breeding Alliance for Better Performance Under Drought, 5-6 September*, Australian Winter Cereals Pre-Breeding Alliance, Canberra.

Passioura J, Spielmeyer W and Bonnett D G 2007, *Requirements for success in marker-assisted breeding for drought-prone environments*, in M A Jenks, P M Hasegawa and S Mohan Jain, *Advances in Molecular Breeding towards Drought and Salt Tolerant Crops*, Springer, Dordrecht, The Netherlands.

Patterson D T, Westbrook J K, Joyce R J V, Lingren P D and Rogasik J 1999, 'Weeds, insects and diseases', *Climate Change*, 43.

Peoples M B, Boyer E W, Goulding K W T, Heffer P, Ochwoh P, Vanlauwe B, Wood S, Yagi K and van Cleemput O 2004, *Pathways of Nitrogen Loss and Their Impacts on Human Health and the Environment*, in A R Mosier, J K Syers and J R Freney, *Agriculture and the Nitrogen Cycle*, Island Press.

Pittock B 2003, *Climate Change: An Australian Guide to the Science and Potential Impacts*, Australian Greenhouse Office, Canberra.

Prins A, Mukubi J M, Till K. Pellny, Verrier P, Beyene G, Kunert K J and Foyer C H *in prep.*, 'Acclimation of maize source leaves to CO2 enrichment involves regulation of serine protease inhibitors by redox and hexose-signalling'.

Quirke D, Steenblik R and Warner B 2008, *Biofuels at what cost – Government support for ethanol and biodiesel in Australia*, International Institute for Sustainable Development, Geneva.

Rahman H, Malik S A and Saleem M 2004, 'Heat tolerance of upland cotton during the fruiting stage evaluated using cellular membrane thermostability', *Field Crops Research*, 85: 149-158.

Ranjekar P K, Patankar A, Gupta V, Bhatnagar R, Bentur J and Kumar A P 2003, 'Genetic engineering of crop plants for insect resistance', *Current Science*, 84: 321-329.

Rebetzke G J, Richards R A, Fettell N A, Long M, Condon A G, Forrester R I and Botwright T L 2007, 'Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat', *Field Crops Research*, 100: 10-23.

Reddy K R, Hodges H F and Kimball B A 2000, *Crop ecosystem responses to global climatic change: Cotton*, in K R Reddy and H F Hodges, *Climatic Change and Global Crop Productivity*, CAB International,, Wallingford, 162-187.

Reddy V R, Reddy K R and Acock B 1995, 'Carbon-dioxide and temperature interactions on stem extension, node initiation, and fruiting in cotton', *Agriculture, Ecosystems & Environment*, 55: 17-28.

Reynolds M P, Nagarajan S, Razzaque M A and Ageeb O A A 2001, *Heat Tolerance*, in M P Reynolds, J I Ortiz-Monasterio and A McNab, *Application of Physiology in Wheat Breeding*, CIMMYT, Mexico, 124-135.

Reynolds M P, Skovmand B, Trethowan R and Pfieffer W 2000, *Evaluating a conceptual model for drought tolerance*, in J-M Ribaut and D Poland, *Molecular approaches for the genetic improvement of cereals for stable production in water-limited environments: a strategic planning workshop held at CIMMYT, El Batan, Mexico, 21-25 June 1999*, CIMMYT, Mexico, 49-53.

Richards R A 1991, 'Crop improvement for temperate Australia: Future opportunities', *Field Crops Research*, 26: 141-169.

Richards R A 2004, 'Physiological traits used in the breeding of new cultivars for water-scarce environments', *New directions for a diverse planet: Proceedings of the 4th International Crop Science Congress*, T Fischer, Brisbane, Australia.

Richardson A G, Reddy K R and Boone M L 2002, 'Sensitivity analysis of climate change impacts on cotton production using the GOSSYM crop model', *International Journal of Biotronics*, 31: 25-49.

Schaad N W and Frederick R D 2002, 'Real-time PCR and its application for rapid plant disease diagnostics', *Canadian Journal of Plant Pathology-Revue Canadienne De Phytopathologie*, 24: 250-258.

Scharlemann J P W and Laurance W F 2008, 'Environmental science - How green are biofuels?', *Science*, 319: 43-44.

Singh R P, Prasad P, Sunita K, Giri S and Reddy K R 2007, 'Influence of high temperature and breeding for heat tolerance in cotton: A review', *Advances in Agronomy*, 93.

Stafford N 2007, 'Future crops; The other greenhouse effect', *Nature*, 448: 526-528.

Steffen W and Canadell P 2005, *Carbon Dioxide Fertilisation and Climate Change Policy*, Australian Greenhouse Office, Canberra.

Steffen W, Sims J and Walcott J 2006, *Farming profitably in a Changing Climate, a risk management approach*, Bureau of Rural Sciences, Canberra.

Streck N A 2005, 'Climate change and agroecosystems: the effect of elevated atmospheric CO2 and temperature on crop growth, development and yield', *Ciencia Rural*, 35: 730-740.

Tardieu F 2005, 'Plant tolerance to water deficit: physical limits and possibilities for progress', *Comptes Rendus Geoscience*, 337: 57-67.

Taylor L E, Dai Z, Decker S R, Brunecky R, Adney W S, Ding S-Y and Himmel M E 2008, 'Heterologous expression of glycosyl hydrolases in planta: a new departure for biofuels', *Trends in Biotechnology*, 26: 413-424.

The Royal Society 2008, *Sustainable biofuels: prospects and challenges*, The Royal Society, London, UK.

Toride Y 2002, 'Lysine and other amino acids for feed: production and contribution to protein utilization in animal feeding', *Protein sources for the animal feed industry.*, Bangkok, Thailand, 161-165.

Torney F, Moeller L, Scarpa A and Wang K 2007, 'Genetic engineering approaches to improve bioethanol production from maize', *Current Opinion in Biotechnology*, 18: 193-199.

Tothill I E 2001, 'Biosensors developments and potential applications in the agricultural diagnosis sector', *Computers and Electronics in Agriculture*, 30: 205-218.

Tubiello F N, Donatelli M, Rosenzweig C and Stockle C O 2000, 'Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations', *European Journal of Agronomy*, 13: 179-189.

Tubiello F N, Soussana J F and Howden S M 2007, 'Crop and pasture response to climate change', *Proceedings of the National Academy of Sciences of the United States of America*, Easterling W, 19686-19690.

U.S. Department of Energy 1999, *Carbon Sequestration: State of the Science - A working paper for roadmapping future carbon sequestration R&D*, Office of Fossil Energy, United States.

Umbers A 2007, *Carbon in Australian Cropping Soils, A background paper for the Grains Council of Australia*, http://www.grainscouncil.com/Policy/Carbon/07_July_Soil_carbon_background.pdf, accessed 11 January 2008.

US FDA 2005, *Biotechnology Consultation Agency Response Letter BNF No. 000087*, http://www.cfsan.fda.gov/~rdb/bnfl087.html, accessed 18 September 2007.

USDA/APHIS 2006, *USDA/APHIS Environment Assessment and Finding of No Significant Impact - Monsanto Company and Renessen LLC Petition 04-229-01p for Determination of Nonregulated Status for Lysine Corn Line LY038*, US Department of Agriculture/Animal and Plant Health Inspection Service.

van Ittersum M K, Howden S M and Asseng S 2003, 'Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO_2, temperature and precipitation', *Agriculture, Ecosystems & Environment*, 97: 255-273.

Wade L J, Bell L W, Ewing M A and Byrne F n F 2007, *Prospects for Perennial Wheat: Pre-Feasibility Study - A Case for Further Research*, CRC for Plant-based Management of Dryland Salinity M081, University of Western Australia, Crawley.

Wahid A, Gelani S, Ashraf M and Foolad M R 2007, 'Heat tolerance in plants: An overview', *Environmental and Experimental Botany*, 61: 199-223.

Walcott J 2008, *Soil carbon for carbon trading: a review of issues for agriculture and forestry*, Australian Government Bureau of Rural Sciences, Canberra.

Wang W J, Dalal R C and Moody P W 2004, 'Soil carbon sequestration and density distribution in a Vertosol under different farming practices', *Australian Journal of Soil Research*, 42: 875-882.

Warden A and Haritos V 2008, *Future Biofuels for Australia. Issues and opportunities for conversion of second generation lignocellulosics*, Rural Industries Research and Development Corporation, Canberra.

Xue G P, McIntyre C L, Jenkins C L D, Glassop D, van Herwaarden A F and Shorter R 2007, 'Molecular Dissection of Variation in Carbohydrate Metabolism Related to Water-Soluble Carbohydrate

Accumulation in Stems of Wheat', *Plant Physiology*, 146: 1-14.

Yang X H, Wen X G, Gong H M, Lu Q T, Yang Z P, Tang Y L, Liang Z and Lu C M 2007, 'Genetic engineering of the biosynthesis of glycinebetaine enhances thermotolerance of photosystem II in tobacco plants', *Planta*, 225: 719-733.

Zah R, Böni H, Gauch M, Hischier R, Lehmann M and Wäger P 2007, *Ökobilanz von Energieprodukten: Ökologische Bewertung von Biotreibstoffern*, Empa, Bern, Switzerland.

Zhao D L, Reddy K R, Kakani V G, Mohammed A R, Read J J and Gao W 2004, 'Leaf and canopy photosynthetic characteristics of cotton (*Gossypium hirsutum*) under elevated CO_2 concentration and UV-B radiation', *Journal of Plant Physiology*, 161: 581-590.

Ziska L H and Runion G B 2006, *Future Weed, Pest, and Disease Problems for Plants*, in P C D Newton, Carran, R.A., Edwards, G.R., Niklaus, P.A, *Agroecosystems in a changing climate*, CRC Press, Boca Raton, 261-287.