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# Using enabling technologies to meet demands for food security and sustainability

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# Summary

While Australia has a high level of food security, global food security will continue to be an issue as long as people are chronically undernourished or experiencing famine.

For developing countries, solutions to food security will be found in liberalisation of international trade in agricultural commodities, economic development and greater agricultural productivity through research and development. In some cases, regional and country-specific challenges, such as land tenure reform and political stability, will need to be achieved for food security to become a reality.

While Australia can do many things to improve global food security, increasing the amount of food it produces and increasing the sustainability of its production systems is a logical part of the nation's response to global food security now and into the future. Australia produces more food than its population consumes and exports of food constitute a considerable share of total export earnings. Increasing median wealth in Asia suggests demand for our agricultural products will remain strong while our production systems remain competitive.

Australia has a modern agricultural system and its farmers are among the most efficient in the world. Even so, innovation, through research and development, will be required to increase current food production levels and improve the sustainability of production. Australia will also be required to remain competitive in international markets. Newer technologies, such as biotechnology, nanotechnology, and information and communications technology have the potential to increase food production and sustainability of food production systems.

This report focuses on the improvement of cropping output and sustainability of cropping practices using enabling technology, including biotechnology, nanotechnology and other emerging technologies.

The amount of grain produced can be increased by:

- **increasing potential yield**—on average and over regional scales, new elite crop varieties that have maximal potential yield will result in higher crop production even when conditions are suboptimal
- **closing the yield gap (increasing farmer yield)**—this will allow farmers to produce crops that approach their maximum potential. Improved crop management combined with better crop varieties can increase farmer yield by reducing the impact of pest and weed pressure and poor soil conditions.

Technologies can help in both these areas. Biotechnology is being used to increase the potential of crops under optimum conditions. Plant breeding has always strived for increased potential yield of crop species; however, the application of biotechnology will also help the continued improvement of plant performance. Modern DNA sequencing and identification methods allow DNA markers to be used in plant breeding, making the process more efficient. Genetic modification could also be applied to plant breeding to improve yield potential; for example, by modifying processes such as photosynthesis in crop plants. Plant breeding and genetic modification are the only technologies available that can maximise the yield potential of crops.

Both genetic modification and modern plant breeding techniques have the potential to increase the ability of crops to resist pests and diseases, resist competition from weeds, cope with suboptimal soil or environmental conditions and use nutrients more efficiently. Crops with these

better characteristics will require fewer external inputs, such as insecticides, herbicides and fertilisers, and this will improve the sustainability of farming systems and the environment.

Nanotechnology in the agriculture sector has potential applications in pesticide (insecticide, herbicides) delivery, fertiliser delivery and enhancing crop growth. The technology could also be used in biosensing and remediation of agricultural soils. However, most nanotechnology applications in agriculture are still in the research and development phase.

Until recently, information and communications technology has not been specifically applied to agriculture. Since the high accuracy signal of the Global Positioning System became available to the general public in 2000, the application of precision agriculture technologies has increased. Precision agriculture offers benefits particularly in the areas of more efficient fertiliser and pesticide application in cropping. It offers sustainability and financial benefits.

In addition to the benefits of new technologies, governments are often interested in the implications of new technologies for policies and programs. Australian regulatory agencies are aware of developments in biotechnology and nanotechnology and have suitably flexible systems to regulate new products and techniques when required. Precision agriculture has no obvious regulatory implications and is benefiting from recent infrastructure initiatives that give high accuracy positioning information.

Some new techniques in biotechnology may not fall under the current gene technology legislative framework and this may generate uncertainty in those developing new products using these methods. Evidence suggests the adoption of modern precision agriculture methods may be impeded by lack of timely expert extension advice for cropping. Precision agriculture is also applicable to horticulture and livestock operations. Better outcomes for all sectors may be achieved with coordinated research and development strategies. Nanotechnology holds promise for agricultural applications, but few if any products have reached commercialisation stage in Australia.

The three technologies covered in this report have potential to lift crop production in Australia and make crop farming more sustainable.

# 1 Introduction

Despite global food production being sufficient to meet demand, the number of people suffering from hunger and poverty is 870 million (FAO 2012). The world's population is predicted to reach 9.2 billion by 2050, 34 per cent higher than 2012. Providing a secure food environment for all people will be an unprecedented challenge. This report explores the potential for new and emerging technologies to help meet this challenge by increasing productivity sustainably.

## Global food security

The Food and Agriculture Organisation of the United Nations (FAO) defines food security as:

when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life.

The FAO maintains that food insecurity exists when people do not have adequate physical, social or economic access to food (FAO 2009a). The FAO highlights the importance of the twin track approach—improving both short-term access to food and food production in the medium term—in achieving long-lasting improvements in food security (FAO 2011).

Meeting the demands of a larger, more urbanised, and wealthier population will require an increase in food production of about 70 per cent (FAO 2009b) to 100 per cent (Godfray et al. 2010). The amount of global arable land has not changed appreciably in more than half a century. It is unlikely to increase dramatically because of greater urbanisation, and increasing salinisation and desertification of agricultural lands (Fedoroff et al. 2010). However, over the past 50 years, research and development has doubled global grain production when the area of land devoted to agriculture has increased by only a 9 per cent (Godfray et al. 2010).

Another challenge to food production is the predicted increase in mean global temperatures. The Intergovernmental Panel on Climate Change (IPCC 2007) estimates global crop production will be threatened by temperature increases of 1 °C, and will begin to decline significantly at increases of 3 °C and above 1980–1999 average temperatures. A recent report (PwC 2012) suggests that if the current rate of decarbonisation of the global economy were doubled, average global temperatures would still be 6 °C above 1980–1999 average temperatures by 2100.

## Sustainability

Agriculture needs to become more sustainable and reduce its negative impact on the environment. Agriculture contributes to erosion, nutrient leaching, off-site effects of some agricultural chemicals and loss of biodiversity through deforestation. Agriculture is also responsible for the emission of significant amounts of greenhouse gases.

Around 40 per cent of the world's food supply is derived from irrigated land but water is often sourced unsustainably from poorly managed aquifers. Water is also used wastefully in flood and overhead irrigation systems when more efficient delivery systems exist. (IMechE 2013) Poor management of water resources in the past has resulted in degraded waterways and a need to divert water from irrigation back to rivers to restore their health.

Approaches to agricultural production range from the subsistence farming systems of some developing countries to the highly mechanised, intensive farming systems of developed

countries including Australia. All systems should be sustainable, irrespective of their differences. Sustainable production systems (The Royal Society 2009):

- utilise crop varieties and livestock breeds with high productivity per externally derived input
- avoid the unnecessary use of external inputs
- harness agro-ecological processes such as nutrient cycling, biological nitrogen fixation, biochemical-based effects on other organisms (allelopathy), predation and parasitism
- minimise use of technologies or practices that adversely affect the environment and human health
- make productive use of human capital in the form of knowledge and capacity to adapt and innovate; and use social capital to resolve common landscape-scale problems
- quantify and minimise the effects of system management on externalities such as greenhouse gas emissions, clean water availability, carbon sequestration, conservation of biodiversity, and dispersal of pests, pathogens and weeds.

The challenge of increasing food production will be to do so in a sustainable way, with little more land available for agriculture and with changes to temperature, rainfall, storm intensity and frequency and, importantly for plants, carbon dioxide concentration. These physical changes will have biological effects such as improving the growth of some plants through higher carbon dioxide levels. However, they will also change the range, presence and intensity of pests and diseases in ways that cannot always be predicted.

The capacity of the global agricultural and food system to provide adequate supplies of food and feed will largely depend on developments in technology and innovation. The solution will also rely on a mix of domestic production, international trade, stocks and safety nets for poorer consumers, and many other measures (OECD 2010a).

## Food security in Australia

Australia has a high level of food security. Most Australians can afford to buy food and are able to access diverse, safe and plentiful amounts of nutritious food, both domestically-produced and imported (DAFF 2012).

Although Australia's food supply is secure overall, natural disasters, adverse weather conditions and other sudden and unexpected events, such as food contamination incidents, can temporarily disrupt food production and distribution. Some Australians, such as people living in remote Indigenous communities, on low incomes or with limited mobility, may face difficulties accessing and affording nutritious food (DAFF 2012).

Australia produces enough food to feed 60 million people, 40 million more than our current population. Most fresh fruit and vegetables are grown locally and Australia produces more than sufficient grains and meat to meet domestic demand (PMSIEC Expert Working Group 2010). Moir and Morris (2011) assert there is no foreseeable risk to Australia's food security because we produce twice as much food as we consume, produce almost all our fresh food, and can easily afford the food we import.

However Australian farmers need to maintain profitable and competitive farming systems and ensure their production systems are more sustainable. They need to cope with the challenges

posed by climate change and the accumulated affects of damaging practices that have degraded the natural resource base. They need to do this in the context of an increasing urban population that is encroaching on land currently used for agricultural production. Even rural farmland is facing pressures from competing land use. Competing interests lie in mining, carbon offset markets and supplying voluntary biodiversity conservation or ecosystem services markets.

Over the next 50 years, Australian farmers will have to sustainably intensify production systems to contribute to meeting the predicted increase in food demand. Linehan and colleagues (2012) forecast a positive future for Australian agriculture to 2050, especially in the areas where we have comparative advantage (such as wheat, meat and dairy). They predict a real value increase in food demand of 77 per cent, most of which will be in Asia.

The application of science and technology will help Australian agriculture increase food production and the sustainability of its farming systems. Conversely, Australian agriculture will face increased competition from countries like Brazil, China and India, which are investing relatively more in agricultural research and development than Australia and other rich economies (Pardey et al. 2012). This investment will translate into greater productivity growth in these countries and will increase their competitive advantage relative to our own.

Increasing or maintaining production while improving sustainability in Australian agriculture will require investment in scientific research to develop technologies built on existing knowledge and completely new technologies. These enabling technologies will contribute to new or more efficient practices, equipment, approaches and products that will allow Australian agriculture to remain profitable and productive.

This report will describe how new and emerging technologies might be applied to improving the total yield and sustainability of Australian cropping agriculture systems. It will also assess the policy implications of adopting new technologies, including regulatory implications and capacity requirements. While many applications could improve productivity, the report will not evaluate economic aspects or cost-effectiveness of the technologies. Australian examples are used, where possible, and relevant international research is drawn upon.

This report was funded by the Australian Government Department of Industry, Innovation, Science, Research and Tertiary Education, under the National Enabling Technologies Strategy (DIISRTE 2010). The strategy provides a framework for the responsible development in Australia of enabling technologies such as biotechnology, nanotechnology and other technologies as they emerge.

The scientific study of crop production uses the concepts of potential yield, farmer yield and yield gap to investigate yield. These concepts help explain the effects of technologies on food production and sustainability.

Potential yield (genetic yield potential) refers to the yield of a crop cultivar when grown in environments to which it is suited, with ample levels of nutrients and water, and pests and diseases effectively controlled. This value can be determined in field trials where careful crop husbandry takes place (Fischer & Edmeades 2010). Potential yield of a cultivar can vary by 10 per cent to 15 per cent over seasons and across regions.

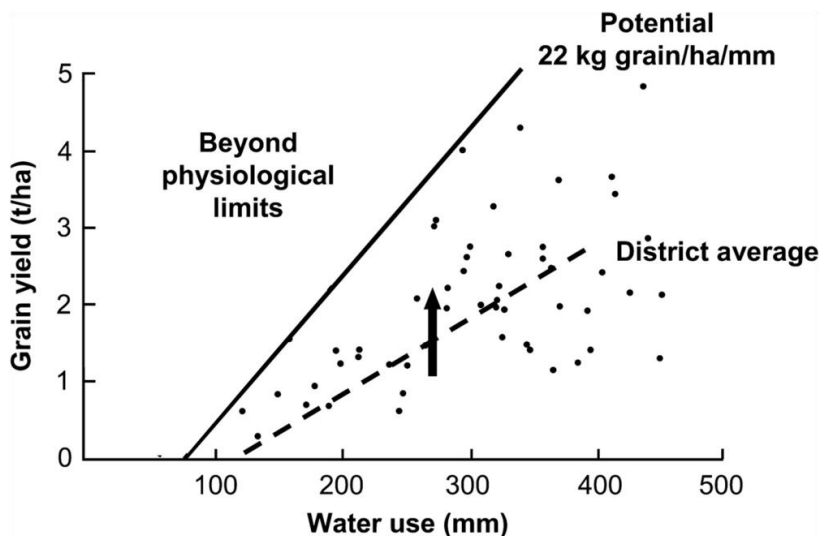
Farmer yield (actual yield) is the yield that farmers achieve with the plant cultivar in question. The difference between potential yield and farmer yield is known as the yield gap and reflects yield reductions associated with nutrient deficiencies or imbalances, poor soil quality, root and/or shoot diseases, insect pests, weed competition, waterlogging, and lodging (crop plants

falling over before harvest). Yield gap is usually expressed as a percentage of farmer yield. On average, the most productive farmers achieve a yield gap of 25 per cent. For some of these factors control options are available; however, decisions regarding their use are based on consideration of costs versus returns.

In the study of Australian cropping systems, a more relevant measure of potential yield is water-limited potential yield. This is where all crop requirements are met but water is limiting. In rainfed cropping systems, even short term, mild water stress is experienced relatively often. Before the concept of water-limited potential yield, it was common to attribute the gap between potential yield and farmer yield to water stress alone.

However, water-limited potential yield has shown that rainfed crops are constrained by factors other than water, such as nutrient deficiencies, soil toxicities or root diseases—all of which lead to suboptimal use of available water. Figure 1 shows wheat yield related to water use in terms of current water-limited potential yield, individual yield points and farmer or district average yield. Water-limited potential yield serves as a benchmark for farmers to improve the management of crops.

**Figure 1** Wheat yield related to crop water use



Note: Water limited potential yield is represented by the upper line and is currently 22 kilograms of grain per hectare per millimetre. Average farmer yield is represented by the dashed line and individual farmer yields are represented by dots.

Data source: Kirkegaard and Hunt 2010.

Food production in a given area can be increased by increasing either farmer yield or potential yield (including water-limited potential yield). Increasing potential yield can only be achieved by plant breeding. The Green Revolution achieved this by breeding shorter varieties that resisted lodging (falling over) and changed the distribution of carbohydrates from vegetative structures to the grain that increased yields. Modern plant breeding aims to boost potential yield by improving both the water use efficiency of plants and their photosynthetic efficiency. Breeding objectives may also increase potential yield; these include improved plant architecture, which influences solar interception and photosynthesis. In Australia, recent improvements in plant performance have mainly been in water-limited potential yield rather than potential yield; indicating that yield under limited water has improved more than yield when water is never limiting.

Farmer yield is largely determined by farmers' management decisions. Farmers may delay taking action to address yield constraints until losses pass a threshold and trigger action. For instance, low level pest infestation may not decrease yield to a level that justifies the cost of buying and applying a pesticide to control the pest. Estimates generally limit farmer yield to 75 per cent of potential yield.

Plant breeding can be used to increase farmer yield by introducing pest and disease resistance into crops or improving the performance of crops that are under abiotic (environmental) stress. These traits do not increase potential yield but can significantly increase farmer yield and make crop management easier. Using plant breeding could be more sustainable than relying on synthetic pesticides for pest and disease control.

Farmer yield can be increased by improving crop management. Management practices such as stubble retention, use of break crops in rotation and control of summer weeds in fallow can have positive effects on grain yield through reducing disease pressure and conserving soil moisture. Plant breeding may complement or facilitate new crop management techniques.

In terms of global food security farmer yield can be increased in many regions of developing countries. Estimates indicate that the yield gap could reach 200 per cent in African countries. In other regions, potential yield could be increased by providing varieties that are well adapted to local conditions.

Plant breeding and other technologies clearly have a role in increasing Australian and global food production by increasing potential and farmer yields.

This report evaluates three main enabling technologies—biotechnology, nanotechnology and communication and information technologies—and their applications in Australian broadacre cropping systems. Brief descriptions of each technology will be accompanied by analysis of current and potential applications and the developmental stage of these applications. The report also discusses constraints to adoption and potential policy implications for consideration by policymakers.

Table 1 outlines how use of the enabling technologies might affect potential yield, farmer yield and sustainability of food production systems.

**Table 1 Potential for enabling and other technologies to increase crop production and sustainability**

Enabling technology	Increase potential yield or water limited potential yield	Increase farmer yield	Address sustainability
Biotechnology	Plant breeding	Plant breeding for tolerance against stress, pests and diseases	Yes
Nanotechnology	No	Improved pest control, remediation	Yes
Information and communications	No	Precision agriculture and new crop management tools	Yes

Source: ABARES

## 2 Biotechnology

Biotechnology is the use of organisms to create products of use to humans. The practice is thousands of years old, beginning with the use of fermentation technologies to make beer or cheese and the selection and planting of crops. Modern biotechnology includes gene discovery, studying gene function and gene interactions, the use of genes for product development or transfer of traits to other species (genetic modification) and marker gene technology.

The Organisation for Economic Co-operation and Development (OECD 2010a) defines modern biotechnology as:

The application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services.

The OECD's lists biotechnology techniques as:

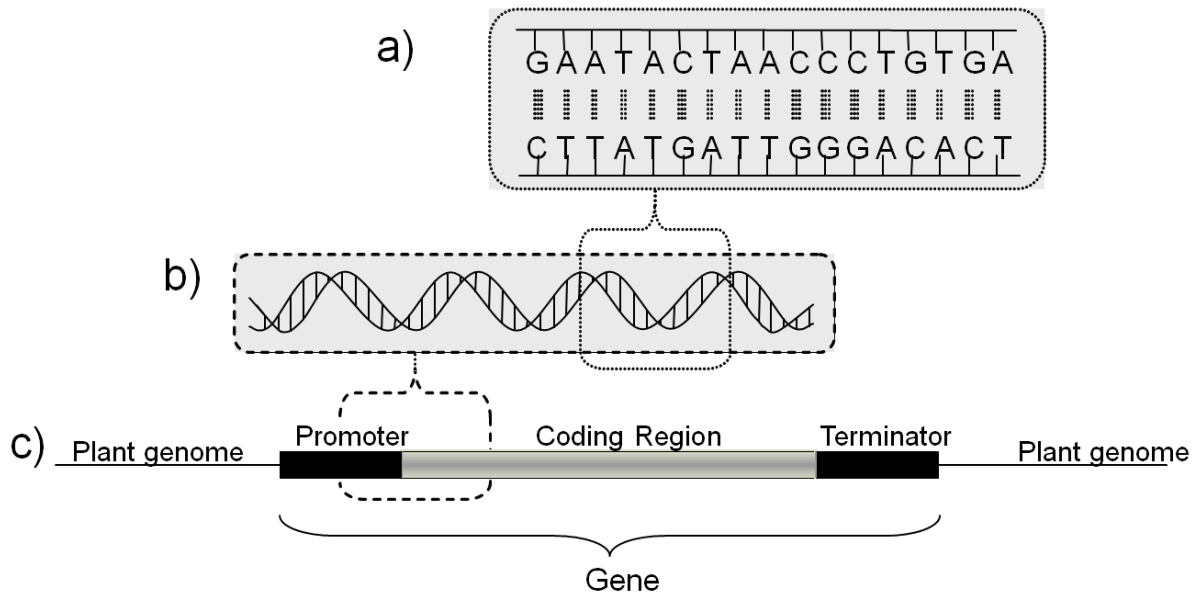
- **DNA/RNA**—genomics, pharmacogenomics, gene probes, genetic engineering, DNA/RNA sequencing/synthesis/amplification, gene expression profiling, and use of antisense technology.
- **proteins and other molecules**—sequencing/synthesis/engineering of proteins and peptides (including large molecule hormones); improved delivery methods for large molecule drugs; proteomics, protein isolation and purification, signalling, identification of cell receptors.
- **cell and tissue culture and engineering**—cell/tissue culture, tissue engineering (including tissue scaffolds and biomedical engineering), cellular fusion, vaccine/immune stimulants, embryo manipulation.
- **process biotechnology techniques**—fermentation using bioreactors, bioprocessing, bioleaching, biopulping, bioleaching, biodesulphurisation, bioremediation, biofiltration and phytoremediation.
- **gene and RNA vectors**—gene therapy, viral vectors.
- **bioinformatics**—construction of databases on genomes, protein sequences; modelling complex biological processes, including systems biology.
- **nanobiotechnology**—the tools and processes used in nano/microfabrication to build devices for studying biosystems and applications in drug delivery, diagnostics.

Not all techniques listed above are applicable to agriculture. However, an understanding of DNA and genes and how they are manipulated is important to agriculture. This chapter provides a summary of the key concepts.

### DNA holds information

The basic building blocks of all living organisms are cells, and all cells in a multicellular organism normally contain an identical full copy of the organism's DNA. This DNA is known as the organism's genome (Figure 2).

Figure 2 DNA and genes



Note: The genome, which contains the genes, is made up of DNA. Two complementary strands of nucleotide bases (a) wind around each other to form a DNA double helix (b). Regions of DNA within the genome are designated as genes (c) and are made up of a coding region bracketed by a promoter and a terminator.

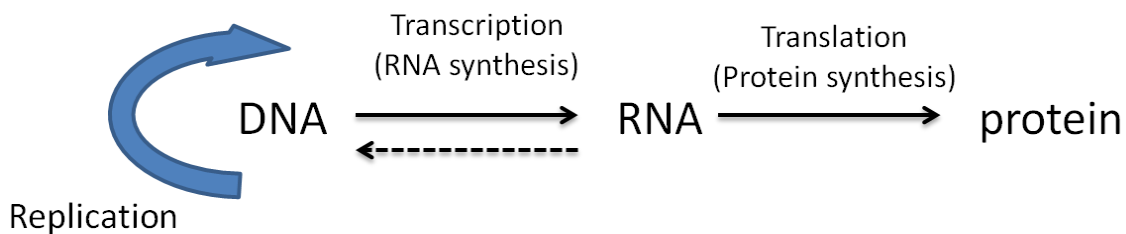
Data source: Mewett et al. 2008

**Definition of a gene**

Within the enormous expanse of a DNA molecule, particular functional regions of nucleotide sequence are defined as genes (Figure 2c). A gene is the unit that carries information for a specific trait that is passed on from one generation to the next through breeding.

Each gene is composed of a promoter, a coding region and a terminator. The promoter can be considered as the control switch, part of the cellular machinery that determines where and when or whether a gene is active or inactive. The terminator represents the endpoint of a gene or the DNA equivalent of a full stop. The sequence of DNA within the coding region, between the promoter and the terminator, is the template for the synthesis of proteins—the molecules that provide the functionality of an organism. Cells replicate DNA and use the processes of transcription and translation to transfer DNA information to cellular processes (Figure 3).

Figure 3 Information flow from DNA



Source: ABARES

## Genes in plants

*Arabidopsis thaliana*, a small plant related to cauliflower, is used by plant scientists in the same way that laboratory mice are used by animal scientists. The *Arabidopsis* genome has about 157 million base pairs and contains at least 26 000 genes. Its genome sequence was published in 2000. In 2011 the DNA sequences of 24 plant species were published, including important crops such as rice, maize, soybean, canola and potato (CoGe 2012). Availability of these genome sequences has facilitated homology-based gene research, which identifies genes of the same or similar function in other plant species.

## Techniques

### Manipulating DNA

Many operations in modern biotechnology involve manipulation and storage of DNA. Putting DNA into vectors allows DNA of interest to be easily stored, multiplied and manipulated. Vector molecules are used to transfer foreign genetic material into another cell. In this way genetic information from DNA or RNA (through complementary DNA) can be stored and further manipulated. Storage is usually achieved by creating a DNA library which is a collection of DNA fragments (in a vector). A collection of fragments representing the entire genome of an organism is called a genomic library.

Single genes can be isolated, studied and placed into another organism through genetic modification technologies or the DNA can be sequenced and used for a range of applications.

### DNA sequencing

DNA sequencing is the process by which the sequence of bases making up a DNA molecule is determined. A crop plant's complete genome sequence is important as it provides detail about its genes and the proteins it can synthesise (The Royal Society 2009). When combined with the other technologies described here, DNA sequence information can provide a powerful framework for the detailed analysis of complex biological processes.

Rapid advances in DNA sequencing technology are underpinning the development of new approaches to basic biological research and plant and animal breeding. These advances have dramatically reduced the cost of sequencing DNA and have increased accessibility and use. To illustrate the reduction in costs of sequencing; the human genome project started in 1990 with a budget of US\$3 billion and the aim to sequence approximately three billion bases. Drmanac and colleagues (2009) reported high quality sequencing of an individual human genome at US\$4400 in consumable reagents.

The increase in economic efficiency of DNA sequencing was underpinned by technological advances that significantly increased the speed of sequencing. In 1980 a machine could sequence approximately 10 000 bases per day, while the latest commercially available machines can produce sequence data at a rate of approximately 10 billion bases per day (Quail et al. 2012). It is now possible to rapidly and inexpensively sequence the genome of an individual plant, animal or microbe over a period of days.

Development of these sequencing technologies has made possible whole genome sequencing and large-scale comparative analyses at the DNA and RNA level. Genomes can be sequenced faster and cheaper than ever before. Researchers can now use direct comparative sequence analysis to reveal where changes occur in an individual's genome when compared with other individuals within a species.

## Microarray analysis/biochips

Arrays are systematically arranged samples usually prepared by robotic equipment. Microarrays consist of a grid of samples made using a serial process to ensure that each sample is placed at the correct position. The samples can be DNA, such as complementary DNA (DNA that can detect messenger RNA) or single nucleotide polymorphism arrays. The samples can also include protein and chemical compounds. A DNA microarray allows the direct and simultaneous comparison of a large number of DNA molecules to detect differences between them and a specific sample.

## Bioinformatics

Bioinformatics is the application of information technologies and sciences to the organisation, management, mining and use of life science information (Bioinformatics Industry Opportunity Taskforce report 2002). It integrates computational and mathematical methods to understand biological processes and it has been integral to the development and expansion of biotechnology.

Bioinformatics creates algorithms, computational and statistical techniques for data analyses and enables the storage and management of the large data sets acquired by these processes. It has revolutionised the ability to perform in-depth DNA sequence analyses, including comparative analyses of sequence data, a method of arranging the sequences of species or organisms to identify functional or structural similarities between the sequences.

Incorporation of mathematical and computational dimensions into the biological sciences has led to an increase in the power of analyses in comparative biology, modelling and gene and protein expression analyses. This is illustrated by developments in high throughput analyses, including complex array analyses and genomic and associated technologies such as:

- **genomics**—the study of the genome (DNA complement) of a cell, tissue or organism or the relationship between genomes
- **metabolomics**—the study of the metabolism of cells, tissues or organisms
- **phenomics**—the analysis of the phenotype of organisms; the phenotype is an organism's observable characteristics or traits and includes morphology, development, biochemical or physiological properties, and behaviour
- **proteomics**—the study of the proteins produced by cells, tissues or organisms
- **transcriptomics**—the study of the transcriptome (RNA complement) of a cell, tissue or organism.

## Molecular markers

Molecular markers are DNA sequences that have a known location on a chromosome and whose inheritance pattern can be followed. A marker closely linked (inherited together) to a trait of interest can be used to follow the inheritance of the trait without actually looking for the trait itself in whole plants. Alternatively molecular geneticists can use the marker to isolate the gene responsible for the trait.

## Gene and trait discovery

Broadly, two approaches can be taken to assigning a gene to its function—forward and reverse genetics. Forward genetics is the process of finding the genetic basis of a phenotype (trait) by experimentation.

Reverse genetics is the process of changing the function/activity of a particular gene and observing the change in the traits of the organism. DNA sequencing, and in particular the sequencing of entire genomes, has allowed the function of many genes to be determined through this approach.

Forward and reverse genetics are effective in identifying genes underlying discrete traits (traits caused by single genes). However, other traits are determined by many genes and their interaction with the environment.

### Quantitative trait loci

Often desirable traits in plants and animals vary in degree, have continuous distributions and can be attributed to polygenic effects—the product of two or more genes and their environment. These are known as quantitative or continuous traits. Quantitative trait loci are locations in the genome that contain, or are linked to, genes that underlie a quantitative trait. Quantitative traits in plants include yield, flowering time, plant architecture, temperature tolerance, water use efficiency (sometimes incorrectly called drought tolerance).

Mapping of quantitative trait loci is the process of identifying statistically significant associations of markers with a trait. Loci for particular traits can be identified by crossing two parental lines that differ significantly for the trait(s) in question and then creating a further generation. The trait of interest will be present in individuals of this generation at different levels, depending on the complement of responsible genes that it carries. Researchers can identify regions of the genome responsible for the trait by ranking the degree of the trait in individuals and relating that to an association with markers within the genome. These areas of high association are collectively known as the quantitative trait loci; many are spread across different chromosomes.

To map quantitative trait loci requires development of a genetic map for the species containing molecular/genetic markers that are distributed over the genome. Many markers can be used, including:

- restriction fragment length polymorphisms
- amplification fragment length polymorphisms
- simple sequence repeats
- random amplified polymorphic DNA
- single nucleotide polymorphisms.

The different characteristics and limitations of each marker technology are outside the scope of this report. However, many of the marker techniques in use today can be defined as biotechnology.

The process to determine quantitative trait loci where parents with different characteristics are crossed is called linkage mapping. Association mapping is a relatively new approach for quantitative trait loci analysis that has been facilitated by the arrival of rapid and relatively inexpensive DNA sequencing technology. Association mapping relies on determining many

single nucleotide polymorphisms (small changes) in DNA sequence between individuals of a species. Once this has been determined, the population of individuals can be screened for different quantitative traits. The presence of a statistical association between the favourable traits and some single nucleotide polymorphisms constitute a quantitative trait locus.

Once one or set of quantitative trait loci have been identified for a trait, the set of markers associated with it can be used to breed plants with the desired trait or guide the isolation of genes in or around the quantitative trait loci. Using the markers to breed plants with the desired traits is called marker assisted selection or marker assisted breeding and will be discussed. The functions and identities of the responsible genes need not be known for the traits to be transferred or introduced into plant varieties for farmer use. Using the markers to guide the isolation of genes in quantitative trait loci can lead to a greater understanding of the biochemical and/or physiological basis of the trait and presents the possibility of the transfer of the trait to other species through genetic modification.

### **Using markers in selection and breeding**

Marker assisted breeding and marker assisted selection rely on the use of the genetic markers, including molecular markers and phenotypic markers. Phenotypes (phenotypic markers), such as leaf shape or fruit colour have always been used in breeding. However, if molecular markers are associated with the trait then time can be saved by looking for the marker in the DNA of young plants, rather than waiting until plants mature to look for important phenotypic markers.

When trying to bring together several traits in one breeding line the advantages of marker assisted selection and breeding are even greater. In some cases the probability of bringing the traits together is quite low so plant breeders must create and screen many hundreds of progeny to ensure the desired combination is recovered. Using markers and high throughput testing platforms, the seedlings carrying the desired combinations can be identified, rather than waiting for a growing season and screening many hundreds or thousands of plants for properties such as flour characteristics or disease resistance. This is known as pyramiding, and for example, allows several disease-resistance genes to be introduced into the best cultivars to provide robust resistance that could not be achieved by incorporating single resistance genes alone.

Marker assisted recurrent selection is a marker assisted selection-based method that involves crossing individuals, selected on the basis of their molecular marker phenotype, for several generations. In principle, it allows selection of individuals with identified markers that correspond to promising traits. As such, multi-trait selection can be achieved in a single breeding line and the combining of traits can be achieved in a relatively rapid and controlled manner.

### **Advanced marker use**

Diversity arrays technology is a technique developed in Australia that facilitates whole genome profiling. It is based on microarray technology, which allows automation of both sample preparation and the screening of large numbers of samples in the space of a microscope slide. Diversity arrays technology dramatically reduces the cost of assessing markers by using the microarray platform. It enables the identification and use of reproducible molecular markers spanning a genome and increases the efficiency of plant breeding.

In order to improve plant varieties, breeders need to select and preserve multiple traits, most of which are quantitative in nature. These traits include yield, disease resistance, and ability to withstand environmental stresses. Breeders have to deal with the problem of a large number of genes, perhaps spread across the genome, that interact to influence the desired characteristics. These interactions between genes need to be established in a variety of genetic backgrounds in

order to identify marker associated traits that can then be employed in breeding programs. Comparative whole genome profiling of a breeding population using diversity arrays technology can reveal such associations, as well as identifying the contributions of single genes or quantitative trait loci without the need to perform any crosses. This reduces the amount of experimental breeding needed to generate a new cultivar.

The targeting induced local lesions in genomes method allows direct identification of mutations in a specific gene. The method combines traditional techniques for chemical mutagenesis with high-throughput screening, using molecular markers to identify the induced mutations in genes that are known only by their nucleotide sequence. It was developed in the model plant species *Arabidopsis* (Henikoff 2004; McCallum 2000).

## Genetic modification

Transgenesis is the transfer of DNA from one species to another in order to give the species new characteristics that can be transmitted to successive generations. Organisms modified by transgenesis have been with us since 1976 when genes from yeast were first transferred to bacteria. The first transgenic plants were produced in 1983. Since these early developments new techniques and methods have made transgenesis possible in most agriculturally important plants. The first commercial planting of a transgenic crop occurred in 1994 in the United States and 1996 in Australia.

To generate genetically modified organisms, a gene from one species is transferred to another species. This process is known as transformation. Several methods are available for transformation. In plants, the two main methods employed are *Agrobacterium*-mediated and biolistic transformation. *Agrobacterium tumefaciens* is a common soil bacterium that naturally causes crown gall disease in plants by inserting some of its genes into plant cells.

In the production of genetically modified plants, scientists use the native mechanisms of *Agrobacterium* to transfer desired genes into plant cells. This is usually done in tissue culture and requires that shoot or embryo formation (organogenesis) can be achieved in tissue culture. Biolistics involves coating minute gold particles, which are then shot into tissues at high speed using compressed gas. This particle bombardment has been widely used in Australia and overseas for introducing new genes into plants, particularly wheat and other monocot species that are less amenable to *Agrobacterium*-mediated transformation.

More recently chloroplast transformation has become a valuable tool for modification of plants. This is because:

- chloroplast transformation results in high levels of transgenic protein compared with modification of the nucleus.
- genetic modifications are not generally transferred in pollen
- important parts of photosynthetic enzymes are contained in the chloroplast DNA; chloroplast transformation is used if researchers want to modify Rubisco, the enzyme responsible for converting atmospheric carbon dioxide into carbohydrates.

Some distinctions are made within the field of genetic modification. Cisgenesis (intragensis) uses the same techniques for transfer of DNA as transgenesis but the source of inserted genetic components is partly or wholly from the same species or a sexually compatible species. Some commentators consider these techniques to be less risky than transgenesis because the genetic

material transferred is from sexually compatible species; meaning that transfer can be achieved by conventional breeding methods.

Gene silencing reduces or prevents the expression (knocking out the function) of a gene. The latest and most efficient technique, RNA interference, involves degrading messenger RNA molecules that are used as a template for protein synthesis. RNA interference utilises natural cellular processes involved in viral defence and gene regulation to cause degradation of specific messenger RNAs before they can be translated into proteins. In some cases it could also be considered to be cisgenic or intragenic because it uses simple rearrangement of the DNA of the targeted gene to initiate a defence response mechanism.

In recent years, plant artificial minichromosomes have been developed to overcome some of the limitations of conventional genetic modification, such as difficulties with delivery and simultaneous expression of multi-gene complexes. Minichromosomes are extremely small versions of normal chromosomes. Some can be synthesised *de novo* and *in vitro* (in the laboratory) from cloned chromosome components, while others are a truncated version of endogenous chromosomes.

### **New methods to modify the attributes of plants**

Methods for modifying organisms are being developed that do not involve the permanent introduction of DNA from other species. Rapid trait development system methodology is based on a process that occurs naturally in organisms. A synthetic molecule is made that incorporates desired DNA code changes. The synthetic molecule binds to the similar native DNA and the cell's repair mechanisms are induced to repair its DNA using the code contained in the synthetic molecule. The synthetic molecule is broken down once the code changes it contained have been incorporated into the cell's DNA.

Zinc finger nucleases are engineered enzymes (proteins) that are a fusion of two proteins: a DNA binding protein (zinc finger protein) and a DNA-cutting protein (nucleases). Zinc finger nucleases can be designed to bind to specific DNA sequences and cut DNA at a specific site in the genome to effect a desired change. This method can permanently change specific, small regions in a gene(s). Zinc finger proteins and nucleases occur naturally in plants, animals and microorganisms.

These and other new breeding technologies could appear in new plant varieties within two to three years if they are not classified as genetic modification (Lusser et al. 2011). However, if they are classified as genetic modification techniques, commercialisation will take considerably longer. A more complete description of these new technologies is given in Lusser and colleagues (2011).

## **Applications of biotechnology in plant breeding**

Biotechnology research in plants has built on longstanding research on *Arabidopsis thaliana*. This model species continues to be a major focus of plant research; its genome has been sequenced and detailed characterisation of a large number of its genes and genomic regions has been achieved. Several quantitative trait loci in *Arabidopsis* have the functional homologues (genes with the same or similar function) found in other species.

Plant breeders face several challenges to future production. Potential and farmer yields need to be increased or at least maintained when crops are more likely to be exposed to increasing abiotic and biotic stresses. Developing crops that have tolerance to these stresses is therefore of primary importance.

## Yield

The overall yield of crops can be increased by increasing the potential yield (genetic yield potential) or farmer yield.

### Increasing potential yield

Some commentators assert that the genetic advances in yield potential realised through the green revolution are unlikely to supply further increases. Zhu and colleagues (2010) claim that harvest index has been optimised through breeding; harvest index is the weight of the harvested portion of the crop as a percentage of the total weight of the crop plant. They also argue that the light interception efficiency (determined largely by crop canopy characteristics) is now optimised. While the green revolution gains have been significant, they have come with little attention to improving photosynthesis. It is argued that the increases in potential yield needed to feed the predicted world population later this century will have to come from improved photosynthesis.

Zhu and colleagues (2010) propose approaches and techniques through which improvements in crop photosynthesis could be achieved, including conventional breeding, genetic modification, computational biology and introducing novel metabolic pathways from other organisms (in whole or in part). The researchers also propose:

- increasing the rate of carbon dioxide diffusion from airspaces within the leaf to the enzyme (Rubisco) responsible for carbon dioxide fixation
- introducing Rubisco from different plant and algal species into crop plants, optimising chlorophyll content to allow efficient energy capture in photosynthesis but better light utilisation in lower leaves in the crop canopy
- reducing the energy wastage of photorespiration (Rubisco fixing <sub>oxygen</sub> rather than carbon dioxide) by introducing new metabolic pathways to certain temperate crop species
- increasing the speed at which photosynthesis can recover from photoinhibition (damage to photosynthetic systems from too much light)
- selecting for plant architecture to match the different photosynthetic capacities of leaves at different levels in the crop canopy.

All except the last proposal will require genetic modification, while breeding for plant architecture would probably involve the use of molecular markers.

Zhu and colleagues (2010) are pessimistic about future gains from the approaches that have defined the green revolution. By contrast, some researchers have shown that removal of half the leaves of wheat plants after flowering had no effect on wheat yield. This implies photosynthetic over-capacity in wheat and that increasing grain number, grain weight and grain size would lead to a greater harvest index and higher potential yield. Much effort has gone into identifying quantitative trait loci for these and other yield-associated traits in crop species.

Xing and Zhang (2010) reviewed potential yield in rice. Rice is the model species for cereal genetics because it has a small and relatively simple genome that has been sequenced. It also shares an evolutionary history with the other major cereals, meaning that yield determinants in rice may have similar characteristics to the other grains.

The approaches discussed here are directed at increasing potential yield. However, serendipity occurs in research. CSIRO recently announced that a genetically modified wheat, in which a gene

involved in starch modification was disrupted, has larger than normal seeds and an increase in yield of 30 per cent in glasshouse trials (Ral et al. 2012). These genetically modified wheats are currently in field trials in Australia (Neales 2012).

### **Increasing farmer yield**

Farmer yield can be increased by improving management of pest and diseases and the ability of the crop to cope with abiotic stresses, such as lack of water, too much water, frost, heat and suboptimal soil conditions, including salinity and acidity.

The limit of farmer yield (usually about 75 per cent of potential yield) is governed by financial considerations. For example it is not economically feasible to start controlling pests and diseases until some threshold of crop damage is sustained. Farmers will not knowingly apply excess fertiliser or soil amendments. Research suggests that farmers apply less fertiliser than the amount recommended and that they forgo profit because of it.

One way to reduce the need for farmer intervention in crop husbandry is to breed/develop crop varieties that are resistant to pests and diseases and other abiotic stresses.

### **Abiotic stress**

Unlike animals, which can move location in the face of adverse conditions, plants cannot move and have to adapt to changes in the environment through physiological and morphological responses.

Detection of a change in environmental conditions activates the expression of genes in plants. These genes can encode a variety of proteins. The genes are classified into three categories based on their role in the stress response (Vinocur & Altman 2005; Wang et al. 2003):

- signal sensing, perception and transmission
- gene transcriptional control (regulating messenger RNA production, transcription factors)
- stress tolerance response mechanisms, such as detoxification, water and ion movement and osmoprotection (producing proteins or small molecules to protect against damaging effects of water loss).

These groups of proteins can be involved in a number of metabolic pathways that are interconnected in a variety of ways. As a result, when traits associated with abiotic stresses are investigated, responses to other abiotic stresses are sometimes observed. These effects can spill over to biotic stress traits, such as infection by plant pathogens. Plants are often exposed to many stresses simultaneously, such as heat, drought and nutrient deficiency (Fleury et al. 2010); the responses to these are regulated through an interacting and complex system.

Given the spillover effects, it is likely that a whole suite of genes help a plant cope with drought, and some of these genes may also be involved in other stress responses. Interestingly, the expression of a single gene can be altered by different abiotic stresses. Additionally, other systems of gene regulation may be involved in stress responses. Small non-coding RNAs that exert regulatory control on gene expression have a role in responses to abiotic and biotic stresses (Sunkar & Zhu 2004).

### **Drought tolerance and water use efficiency**

Drought stress results in several responses in the plant, including changes in gene expression, synthesis of specific proteins, accumulation of metabolites, closing of leaf pores and inhibition of

shoot growth. These stress-related responses also affect the plant's ability to grow, which in turn reduces crop yield.

Tolerance to drought is the capacity of a plant to grow, live and reproduce with limited water supply or during periods of water deficit (Fujii et al. 2005). This is different from producing a reasonable crop in less than ideal conditions, which is important for yield. The term water use efficiency is often used interchangeably with drought tolerance; however, these are not necessarily the same. Water use efficiency can relate to a single plant or a whole crop. Crop water use efficiency is measured as the yield of grain per unit of water used. At the single plant level, water use efficiency can be described as the efficiency of water use in photosynthesis.

Overall, the objective in plant breeding is not to turn crop plants into cacti but to let them grow and yield optimally under water-limited conditions.

Improving water use efficiency in plants can be achieved in a number of ways (Glover et al. 2008), including selection for the following traits:

- long emerging shoots (coleoptiles)—enable seeds to be planted deep into the soil so they are better able to access stored soil moisture
- root architecture—assists in the ability of a plant to access water from the soil
- early vigour—in the growing season, early and rapid development of leaf area helps the plant access water, reduces water loss from surrounding soil surfaces and by suppressing weeds, reduces their use of soil moisture
- reduced tillering—fewer tillers (branches) may conserve water for grain filling by reducing water use before flowering; plant's investment of growth and energy freed up for other organs, such as the root and shoots (Richards et al. 2010)
- increased stem-stored carbohydrates—allows remobilisation of these carbohydrates for grain-filling when photosynthesis is inhibited late in the season due to limited water availability (Ehdaie et al. 2006; Reynolds et al. 1999)
- stay-green types—maintain greater green leaf area after flowering; have higher chlorophyll content at all stages of development; more photosynthetically active leaves contribute to higher yields and improved water use efficiency
- waxiness of leaves—associated with reduced day and night-time transpiration and protection of the developing ear (in wheat) and upper leaves from high temperatures (Richards et al. 2010)
- leaf rolling—important trait in maintaining leaf area late into grain filling; Leaf rolling decreases the transpiring surface by reducing leaf area (see Richards et al. 2010)
- improved transpiration efficiency—selection on the basis of differential carbon isotope discrimination has been successfully used in developing wheats with higher yields in rainfed farming systems (Rebetzke et al. 2008)
- polymers of fructose (fructans)—fructans may play a role in providing membrane stability under conditions of water stress (Valluru & Van den Ende 2008)
- other compounds—application of polyamines to plants helps increase plant tolerance to abiotic stresses, such as cold, drought, salinity, waterlogging and heat (Gill & Tuteja 2010); polyamines are involved in many plant growth and developmental processes.

Genetic control of the drought response is complex as it involves genes that are affected by the environment. Many quantitative trait loci have been identified for yield under water stress, but few have been any more useful in breeding than selection based on yield alone. However, quantitative trait loci have been identified for the traits described here and these characteristics have been used successfully in breeding programs. These include quantitative trait loci for stem-stored carbohydrates, carbon isotope discrimination, stay-green traits, leaf rolling, osmotic adjustment and root architecture (measured as canopy temperature).

In some cases molecular markers have been used to follow these traits through breeding programs. For example, the CSIRO used quantitative trait loci to develop the Drysdale and Rees drought tolerant wheat varieties. These varieties perform well where water is available and when it is deficient. Field trials showed that Drysdale yielded 23 per cent more under dry conditions than the widely cultivated Diamondbird variety (Richards 2006).

The drought genetics program at the Australian Centre for Plant Functional Genomics has identified several quantitative trait loci in wheat that are associated with physiological characteristics of yield maintenance under drought stress. Results from preliminary studies indicate these loci could be used in breeding programmes. It is hoped that this improved breeding material will be available for field evaluation in the future.

Recently CSIRO released improved wheat lines into breeding programs that have a lower tillering (branching) potential than current varieties. Low tillering types are more water efficient and this allows them to outyield conventional varieties in areas normally associated with lower yields.

The low tiller breeding material is a good example of a change in breeding objectives to suit the environment. Some breeding programs aim for a maximum potential yield under perfect growing conditions. This is a sensible approach when pest and disease control options and permanent access to sufficient water through irrigation or climate are available. However, this approach may not always be effective in Australia. Plants bred to cope with reduced water availability can also yield at reasonable, but not maximal levels when moisture conditions are nearly perfect. However, these plants have higher multi-year yield averages in the variable climates common to Australian grain regions.

Evidence suggests water deficit can decrease flower fertility in wheat. This may be an area of future research. If variation can be found in this trait, quantitative trait loci analysis may provide a means to develop markers to follow this trait in breeding material.

### **Waterlogging**

In contrast to the Australian drought in the early 2000s, recent seasons have brought higher than average rainfall. Too much rainfall can reduce yields and cause problems such as waterlogging.

Good and/or above average rainfall years or poorly draining soils can lead to plants becoming waterlogged, plant death or yield reductions. Under a changing climate, predicted heavier rainfall events may increase plant stress. In Australia, waterlogging has significantly reduced production and caused substantial crop losses in wheat, cotton, canola and barley in some growing seasons. Crops such as cotton and rice are frequently exposed to conditions of extensive flooding. This phenomenon in rice has been widely studied and molecular markers used to introduce submergence tolerance into rice varieties. Discovery of genes for a range of traits in rice, including those for waterlogging tolerance, may enable scientists to isolate similar genes in other cereals that may serve to increase tolerance to waterlogging.

## Temperature stress

Heat stress is the rise in temperature above the threshold level for a period of time sufficient to cause irreversible damage to plant growth and development (Wahid et al. 2007). Heat stress is often experienced in combination with other environmental stressors, such as moisture deficit. Many traits identified for improving yield under water deficit have been linked to heat tolerance, including early vigour, stay-green, leaf morphology and photosynthetic rate (Glover et al. 2008).

High temperatures and dry conditions often occur late in the growing season for winter crops. Plants that mature earlier in the growing season may be less affected by drought and heat. One method is to alter the flowering time of plants by making the flowering window earlier in the season. However, this raises the possibility of damage by low temperatures or frosts and consequent yield reductions. Pinto and colleagues (2010) identified common quantitative trait loci for drought stress and heat stress under irrigation, suggesting a common adaptation mechanism to these two stresses.

Tolerance to frost is an important breeding target for Australian wheat and barley. These cereals mature during the winter months and their flowering structures are sensitive to frost damage. This can lead to reductions in yield estimated at over \$100 million annually (Hudswell & Collins 2010). Average temperatures are predicted to increase in the future, as are frost events. Australian breeders recently identified the quantitative trait loci for reproductive frost tolerance in barley; scientists at the Australian Centre for Plant Functional Genomics are trying to isolate these tolerance genes. Markers for vegetative frost tolerance have been used in cereal breeding for some time.

## Salinity

Salinity is a major problem in several regions in Australia. Most dryland salinity is in the wheat growing and sheep grazing areas of Western and South Australia. Land clearing, cropping and grazing have resulted in an increase in rain permeating into saline groundwater, raising the water table and bringing salt to the surface (Glover et al. 2005). While recent wetter than normal seasons have mitigated this problem, it is likely to increase again as drier conditions recur.

Salt inhibits plant growth in two ways. It reduces water uptake, which can cause water deficit, and it is toxic to the plant when present in excessive quantities. Tolerance to salt can be achieved through several mechanisms, including osmotic tolerance, exclusion, or compartmentalising salt in specialised plant tissues.

Different crops have varying levels of intrinsic salt tolerance; for example, cereals have a higher tolerance to salt than legumes. Screening of genetic resource collections and wild relatives provides an avenue for obtaining breeding material with high salt tolerance.

CSIRO has found genes for a salt exclusion mechanism. Initially salt tolerance quantitative trait loci were identified in material resulting from a cross between a modern salt sensitive variety and an older salt tolerant type identified from screening of genetic resource collections (Lindsay et al. 2004). A molecular marker found to be very close to the quantitative trait locus was used to increase salt tolerance in modern varieties of durum wheat and, more recently, bread wheat (James et al. 2011).

While the work described involves an exclusion mechanism, tolerance mechanisms are also being transferred to wheat from sea barley grass via traditional plant hybridisation techniques. The initial aim is to develop wheat fodders for very saline soils; in the long term the aim is to develop grain wheats for saline soils. Researchers will use modern biotechnology, including marker assisted selection, to transfer the trait to wheat and remove most barley grass traits.

### **Acid soils (aluminium and manganese toxicities)**

Worldwide, close to half the arable land is affected by acid soils. Australia has naturally acidic soils and this is exacerbated by farming practices. In acid soils, aluminium and manganese minerals dissolve in acidic groundwater and have adverse effects on plants. Aluminium toxicity stunts root growth leading to poor nutrient and water uptake and poor yield.

Some acid soil sensitive plants with stunted roots can show symptoms of water deficit stress even though soil moisture is suitable for growth of plants with normal root systems. Similar results can be seen when roots are affected by pests and diseases.

In some aluminium tolerant cereals, protection occurs at the growing tip of the root apex, through the excretion of organic acids such as citrate, oxalate and malate. These acids bind toxic aluminium cations, rendering them non-toxic to the root tip (Delhaize et al. 2009; Glover 2005). Manganese toxicity affects shoot growth; symptoms are evident in the leaves as stunted growth, chlorosis (bleaching) and necrotic lesions (dead spots) (Kochian et al. 2004).

Rye, a relative of wheat, has inherently a high level of tolerance to aluminium. Researchers at the Australian Centre for Plant Functional Genomics are using rye as a model species to dissect molecular mechanisms underpinning aluminium tolerance in rye. The information will be used to introduce aluminium tolerance in other cereals (ACPF 2009). Wheat has genes that confer aluminium tolerance through the excretion of malate in the presence of aluminium ions; markers have been developed to follow this trait in breeding populations (Raman et al. 2010).

### **Genetic modification for abiotic stress tolerance**

Modern biotechnology offers other effective techniques to discover genes and define their function. Genetic modification is sometimes used to interrupt gene function in plant populations.

In some collections of genetically modified *Arabidopsis* each gene has been disrupted in an individual line. This results in most genes within the species being disrupted in the experimental population. If the whole collection is screened for tolerance/sensitivity to an abiotic stress, any individuals that show enhanced resistance or tolerance can be used to easily isolate the gene responsible for the tolerance/sensitivity.

Technologies including genomics, metabolomics, phenomics, proteomics and transcriptomics are potentially very powerful. Changes in response to any environmental change can be investigated at the level of transcription of messenger RNA from the genome (transcriptomics), translation of proteins from messenger RNA (proteomics) and changes in enzyme activity and metabolic processes (metabolomics). By comparing the messenger RNA, protein and metabolite complements of plants (or cells or tissues) that have been exposed to different treatments (such as drought and adequate hydration), scientists can gather information about the plant's genetic and biochemical responses to the treatments. The science of this analysis is called bioinformatics. These approaches have been used to identify genes that could be introduced into plants to improve their tolerance to abiotic stresses.

Yang and colleagues (2010) reviewed genetic modification approaches for improving drought tolerance in crops. Reguera and colleagues (2012) reviewed genetic modification solutions to improving abiotic stresses in crops. The approaches described in both publications are alike because of the similarity of plant responses to different abiotic stresses. Plants under abiotic stress use common underlying mechanisms to respond to the stresses.

In general, stress induces a set of genes (known as transcription factors) that activate other genes or gene pathways, resulting in a physical/biochemical response to the stress. This

arrangement allows at least two main genetic modification approaches: to turn on response pathway(s) by manipulating transcription factors or to use single genes to elicit a physical/biochemical response. Some pathways are involved in closing leaf pores. Others initiate one or more single gene responses, including the production of:

- sugars and amino acids to protect the water balance of cells
- proteins (chaperones) that stop loss of activity of important proteins, RNA and cell membranes caused by changes in structure caused by stress
- enzymes to deal with highly reactive and damaging compounds caused by the stress.

Both approaches have been successful in field trials of crops species. For example, rice transformed with hormone inducible transcription factors have significantly higher fertility and seed set than control plants under water deficit. Performance under adequate water conditions was similar. The genetically modified plants were better able to recover from dehydration than controls and were more tolerant to salinity stress (Hu et al. 2006).

Manipulating the hormone-induced stress response pathways has been successful in raising drought tolerance in canola (Wang et al. 2009). A genetic modification that is only activated under stress stops certain types of protein modification and in turn makes the pathway more responsive to a stress-induced hormone. The genetically modified canola performed better than non-modified canola over three years of field trials under water stress. When water levels were adequate yields of genetically modified and non-modified lines did not differ significantly.

Other transcription factors induced by water deficit, but not through hormone activation, have been used to increase the yield of maize by 50 per cent under water deficit (Nelson et al. 2007). When water deficit was severe the yield advantage of these genetically modified maize lines was not evident.

In December 2011 the agricultural biotechnology company Monsanto received regulatory approval for the commercial cultivation of genetically modified drought-tolerant corn in the United States. Known as MON 87460, the corn has a bacterial gene for a cold shock protein. Cold shock proteins act to chaperone (maintain integrity) of other proteins during periods of stress. However, given the differences in water availability between US and Australian farming systems, this technology may not be directly transferable to Australian crops and farming systems.

Reguera and colleagues (2012) concluded that while many single genes and pathways have the potential to increase abiotic stress tolerance, most experiments have not tested performance in the field. Field testing would expose plants to the multiple stresses that crops usually experience. Reguera and colleagues (2012) highlighted the importance of focusing on stress tolerance during a plant's reproductive stage (from flowering through to grain maturation) as this is the phase most important to yield.

In Australia, the Office of the Gene Technology Regulator has approved small-scale field trials of several crops genetically modified for abiotic stress tolerance. These trials are investigating water use efficiency, heat tolerance, salt tolerance and waterlogging tolerance. The genes used in these crop trials fall into three main categories:

- genes that control other genes (transcription factors)
- regulating enzymes in metabolic pathways
- cation binding proteins, structural proteins and membrane transport proteins.

The Office of the Gene Technology Regulator has approved field trials for the investigation of resistance to abiotic stresses in genetically modified wheat, barley, sugarcane, cotton and canola. See the Office of the Gene Technology Regulator's website for information about the field trials and the genes involved (OGTR 2013a).

Another approach to improving crop water use efficiency or reducing water deficit is through minimising water loss. Incorporation of herbicide tolerance traits into crops can reduce competition for water by weeds (Passioura 2006). Several genetically modified herbicide tolerant crops are available and more are in development. Monsanto has said that its most important drought resistance trait is rootworm resistance. This is because healthy functional root systems draw moisture from the soil efficiently and any damage to the root impairs this function.

### **Biotic stress tolerance**

Agricultural crops are frequently exposed to pests and diseases such as insects and bacteria, fungi and viruses. In many cases these pests and diseases can result in substantial yield losses. For example, insects cause an estimated 10 per cent to 20 per cent yield loss in major crops worldwide (Glover et al. 2005). Fungal and bacterial diseases are also major contributors to yield loss in some countries.

Modern agriculture systems and practices cope with most pests and diseases primarily through the use of crop protectants, integrated pest management and through plant breeding. For example, the most common genetically modified crop in Australia is Bt-cotton, which protects itself from the cotton bollworm by producing bacterial insecticidal protein toxins in its leaves. These toxins are also available in commercial sprays containing the bacteria; however, spraying would have to be done regularly in order to combat major cotton pests. Genetic modification and plant breeding provide a season-long solution to the control of the major cotton pests. Although the modifications have not led to increases in potential and farmer yield in cotton, they have resulted in fewer inputs of labour and reduced use of synthetic chemical insecticides. These changes in farming practice increase the sustainability of farming systems by decreasing inputs and consequently reducing impacts on the environment.

Biotechnology will have the biggest impact on farming system sustainability in the area of increasing tolerance or resistance to biotic stresses. While biotechnology may also increase farmer yield, these will not be large where other functional systems are in place for control of biotic stresses (for example, synthetic insecticides). However, where these systems do not exist, the potential to increase farmer yield through plant breeding and biotechnology is present. Hence, while biotechnology may have only a small potential to increase farmer yield in modern agricultural systems, it will probably have a large impact on sustainability in these systems.

The growth of crop plants in large-scale monocultures and with fertiliser application makes the yield of these systems vulnerable to competition and destruction by pests. Animal pests result in estimated losses of 10 per cent of global production of wheat, rice, maize, barley, potatoes, soybeans, sugar beet and cotton (Oerke & Dehne 2004); fungal and bacterial infections and weed competition each account for losses of around 10 per cent of global production of these species while viral infection is estimated to cause a 3 per cent loss. These figures are the calculated actual losses under current pest and disease control practices.

### **Insects and other pests**

In modern agriculture, management of insect pests is generally achieved through the application of synthetic insecticides. Effective synthetic insecticides have transformed crop protection and

significantly improved crop production during the green revolution. However, some of these chemicals are becoming less effective because insects have developed resistance to them. In some cases this has led to the resurgence of some pests (Hoffmann et al. 2008). For example, the Australian cotton industry faced major challenges in the mid-1990s when the crop's major pest, the cotton bollworm (*Helicoverpa armigera*), developed multiple insecticide resistance.

In addition to increasing resistance, higher regulatory standards are seeing older insecticides being taken off the market faster than new ones are being developed. These higher standards are driving the trend toward finding more environmentally benign methods of pest control, including better synthetic chemicals and methods such as integrated pest management. Integrated pest management practices for preventing pest damage include monitoring crops for damage, making use of mechanical trapping devices, natural predators (for example, insects that eat other insects), insect growth regulators and mating disruption substances (pheromones) and, if necessary, chemical pesticides. The use of biological pesticides is an important component of the approach; plant-based resistance to insect attack would provide major advantages for integrated pest management.

Besides pyrethroid-based chemicals, other natural compounds are also used as insecticides. The bacteria *Bacillus thuringiensis* produces insecticidal proteins and preparations of this bacterium have been used for insect control both in conventional and organic farming. Agrochemical companies are focusing on natural chemicals for the isolation of new types of pesticides.

Plant defence mechanisms against arthropod (insects and mites) herbivory are complex, not yet fully understood and until recently, have not been a breeding target in crop species (Smith and Clement 2012). The green revolution saw significant increases in plant yield but it was synthetic insecticides that controlled pests rather than incorporation of arthropod resistance genes through plant breeding. Indeed, some argue that the green revolution resulted in modern varieties that are less resistant to arthropod attack than their lower yielding predecessors.

### **Plant-based mechanisms of tolerance and resistance to insect attack**

All plants are resistant to almost all insects. Where plants are attacked the response is similar to that of abiotic stress—the attack is detected, signals to respond are generated and responses to these signals implemented.

Some plants can tolerate or recover from arthropod (such as insects and mites) damage without adversely affecting the growth or survival of the attacking pest. Resistance is where the plant is able to tolerate and recover from the attack but does so by adversely affecting the attacker. Susceptibility is where the attacking arthropod has successfully countered plant defences. Tolerance and resistance in plants is genetically determined and in some respects plant susceptibility reflects the evolution of genes in the pest that overcomes the plant's defences.

Plant resistance falls into two main categories: antixenosis and antibiosis. Antixenosis is characterised by plant morphology or chemicals that adversely affect arthropod behaviour by causing it to delay feeding or reject the plant as a host. Antibiosis is where a resistant plant adversely affects the survival, development and fertility of an arthropod attempting to use that plant as a host (Smith & Clement 2012). Tolerance and the two types of resistance are under genetic control and can be selected in breeding programs and the responsible genes cloned. All three defence mechanisms can operate simultaneously in plants (Fornoni 2011).

Examples of a tolerance response include an increase in photosynthesis after damage and higher growth rates, increased branching or tillering after attack on the primary growing shoot, storage

of carbohydrates in roots and rapid remobilisation to shoots following damage (Strauss & Agrawal 1999).

Examples of antixenosis include the waxes, thickness of leaf cuticles, trichomes (hairs) that may or may not contain chemicals that act to repel pests or make the plant unpalatable. With respect to sucking insects, plant responses that close or reduce sap supply to feeding sites also fall under this class of resistance.

Examples of antibiosis that are a direct resistance response include toxins that kill the pest, chemicals that inhibit growth of larvae or products such as peroxide that can damage pests. Indirect responses include the production of volatile compounds that attract the pest's natural enemies (usually other insects) or changes in the plant's surface that can cause eggs to fall off or not develop.

Modern breeding for resistance and tolerance characteristics

Around 40 arthropod resistant genes and many quantitative trait loci have been recorded in crop species. Of those about 90 per cent are related to varying degrees of antibiosis resistance and antixenosis resistance. Interestingly, only 10 per cent of the genes relate to tolerance mechanisms (Smith & Clement 2012).

Breeding objectives for Australian canola, barley and wheat are abiotic stress resistance and resistance against nematode infections and fungal diseases. Arthropod resistance is probably not a high priority breeding target because synthetic insecticides are still effective and arthropods do not affect yield when controlled properly.

Arthropod resistance breeding has been undertaken in legumes and sorghum. For example, resistance to red-legged earth mite (*Halotydeus destructor*) has been introduced into clover to improve seedling resistance. The mite is also effectively controlled by synthetic insecticides (for example, Timerite) if farmers follow recommendations on timing of application. However, canola and legumes, such as clovers and the grain legumes, are particularly susceptible. Older wild types of the grain legumes show resistance to the mite and may provide valuable resistance in breeding programs. Wheat and other cereals are tolerant of the mite. (Lawrence 2009)

Australian grain sorghum has been bred for resistance to sorghum midge. Before the incorporation of midge resistance, the cost to the sorghum industry was estimated at \$15 million annually. The first varieties had antixenosis resistance and recent breeding material also has antibiosis resistance. The presence of two types of resistance mechanism is thought to reduce the chances of the midge overcoming plant defences (Freebairn 2012).

While plant breeding for natural arthropod resistance is not a priority in our major crops, our understanding of resistance mechanisms relies heavily on modern biotechnology. Quantitative trait loci analysis, genomic and associated technologies and gene silencing technologies are increasing our understanding of how plants respond to arthropod attack. However, genetic modification is the technique that has had a major impact on the development of insect resistant crop plants.

### **Genetic modification approaches to introducing resistance characteristics**

Genetic modification of crop plants with the insecticidal toxins from *Bacillus thuringiensis* (Bt) has been spectacularly successful, resulting in these modified maize, cotton and other crops being planted over millions of hectares every year. In Australia, Bt cotton accounts for over 90 per cent of all cotton grown. Use of Bt toxins is an extreme form of antibiosis.

New forms of Bt toxin may be developed with improved toxicity to pests, but other plant proteins could be used. These include inhibitors of insect digestive enzymes to protect against pests of seeds and grains, and lectins to help protect against sap sucking insects (such as aphids) that are not susceptible to any of the Bt toxins. Other bacteria also produce insecticidal proteins that seem to be more effective than Bt toxins and have a broader target range. Bacterial enzymes that break down cholesterol are effective against insects and avidin, a protein found in eggs that tightly binds vitamin B, is also lethal to some seed-eating insects (Gatehouse 2008).

Another approach is to produce plant secondary metabolites (chemicals) in genetically modified plants that other plants use to resist insect attack. This approach allows plants to produce insect toxins such as cyanide upon insect attack, or manufacture insecticidal compounds such as caffeine and nicotine in their tissues. These types of traits have been produced in experimental plants. Volatile compounds that act as feeding deterrents and as attractors of natural enemies have also been transferred between plants and have been found to be effective in reducing insect feeding or in attracting predators of pests (Åhman et al. 2010; Gatehouse 2008).

A relatively new approach to insect protection in genetically modified plants is the use of a gene silencing technique called RNA interference (RNAi). This technique allows very effective suppression of gene expression using DNA sequences that are specific for the targeted gene. The method of protection uses small RNA molecules in the plant that pass into a feeding insect to selectively suppress essential genes in the insect. In genetically modified plants, RNAi has been shown to be effective in suppressing genes of the major pest groups: caterpillars and beetle larvae (Price & Gatehouse 2008; Terenius et al. 2011) and aphids (Pitino et al. 2011). Commercial genetically modified crops that use RNAi to provide protection against insects are available overseas (Smith & Clement 2012).

### **Reducing the impact of roundworm**

Nematodes (roundworm) can attack plants in various ways. Some species can cause significant losses to production through their effects on plant roots. In Australia these organisms cause significant yield loss, particularly in wheat crops. Resistance genes have been isolated with the use of quantitative trait locus analysis and molecular markers are used to follow these genes in breeding programs. Plant-based RNAi approaches are effective against nematodes that affect agricultural plants (Huang et al. 2006).

### **Disease resistance**

Plants are attacked by insect pests, nematodes, and pathogens such as fungi, bacteria and viruses. The ways in which plants respond to these disease-causing organisms resemble their responses to arthropod attack and to abiotic stresses. Plants need to be able to detect an attack, generate and transport signals to respond and then respond to these signals to defend against infection.

Most plants are resistant to most disease-causing pathogens. The resistance mechanism that makes most plants resistant to pathogenic microbes is difficult to dissect genetically and relatively little is known about it (Mysore & Ryu 2004). However, where some plant varieties within a species show a difference in their ability to resist a pathogen, modern biotechnology can be used to understand the underlying mechanism and to track the traits in plant breeding.

Disease resistance is a breeding target for Australian cereals, canola and legumes. In wheat, molecular markers have been used to follow multiple resistance genes for rust resistance (Bariana et al. 2007). Rust resistance is relatively well understood and control is effective where resistance genes have been deployed in varieties available for use by the agricultural sector.

However, continual breeding is required to match the evolution of new rust pathotypes that can overcome older resistance genes in existing plant varieties. One example is the stem rust pathotype Ug99, which is causing concern worldwide because it could overcome resistance genes in most wheat varieties. Scientists have found resistance to Ug99 in wheat lines in seed banks and are incorporating these resistance genes into breeding material using molecular markers (ACIAR 2012).

At least 15 other fungal diseases and five bacterial diseases affect wheat in Australia. Quantitative trait loci analysis is being used to investigate the nature of some of the resistance genes for non-rust pathogens in Australian wheat (Zwart et al. 2010); molecular markers for these are used in wheat breeding.

Genetic modification for disease resistance follows one of three approaches:

- **direct interference with or inhibition of the disease-causing organism**—this involves modifying the crop plant with genes (from another plant) that are directly responsible for defence response or that activate an antibiotic effect against the target disease-causing organism. For example, an enzyme from rice that degrades fungal cell walls provides improved disease resistance to some fungal pathogens. Enzymes in grapes for resveratrol synthesis have been transferred to cereals to improve disease resistance. Some researchers claim resveratrol, a compound found in red wine, has human health benefits. Genes for synthetic proteins that have antibiotic effects on some pathogens have also been transferred into plants to improve disease resistance (Collinge et al. 2008).
- **regulation of the host plant's natural defences**—uses cell proteins to detect certain strains of pathogen. Plant proteins are transferred from a pathogen resistant related species to enable the receiving plant to recognise the relevant strain of pathogen and mount a defence response against it. Genes that are known to improve the response of inducible defence systems also improve disease resistance in genetically modified plants (Collinge et al. 2008).
- **pathogen mimicry**—used for resistance against viral diseases and the only one of the three approaches to have produced commercial plants resistant to fungal or bacterial pathogens. However, more work is required to ensure complete resistance (Collinge et al. 2008). In experiments where transcription factors were used, increased resistance to some diseases was associated with increased resistance to abiotic stresses; in some cases increased resistance was accompanied by increased susceptibility to other diseases or deleterious effects on plant growth (Collinge et al. 2010).

In 2010 researchers demonstrated that plant-expressed RNAi constructs suppress genes of invading fungal pathogens in wheat and barley. The pathogen was the agriculturally significant powdery mildew (Nowara et al. 2010). This discovery could lead to relatively simple methods for control of major fungal crop diseases.

However, Collinge and colleagues (2010) believe several technical and non-technical issues must be overcome before genetically modified fungal disease-resistant plants are released commercially. Technically, researchers need a better understanding of the mechanisms of resistance so that durable resistance to fungal and bacterial pathogens can be developed. Public acceptance of genetically modified crops that provide benefits to farmers rather than consumers will continue to be low unless consumer benefits are demonstrated (Collinge et al. 2010). Nonetheless, plant breeding using modern biotechnological techniques will continue to improve disease resistance, especially where natural resistance genes are brought into crop species from their wild relatives.

Genetic modification is also being used to bring together natural resistance genes. For example, the genes for stem, stripe and leaf rust resistance in wheat have been identified. These genes are spread across the wheat genome and wheat breeders devote considerable effort to bringing and keeping these resistance genes together in elite breeding lines. Genetic modification can bring all these resistance genes together in one modification event, saving time and effort in breeding new wheat varieties (Michael Ayliffe [CSIRO] pers. comm. 13 September 2012).

### **Virus resistance**

Plant breeders have been exploiting natural virus resistance genes in crop species or their close relatives for many years. Plant viruses are spread by vectors such as aphids and sap-sucking insects. Resistance to vectors can therefore provide indirect protection against viruses. However, breeders tend to use natural plant-based mechanisms to impair the replication (double-stranded RNA recognition) or movement of viruses within the plant.

Plant breeding for natural resistance to plant viruses uses methods similar to those for breeding of other traits. Quantitative trait loci analysis identifies parts of the genome that influence the trait under investigation. Molecular markers close to the genomic regions that provide significant viral resistance are used to follow resistance in breeding populations.

Viral resistance genes can be transferred from close relatives using marker assisted breeding. For example, barley yellow dwarf virus resistant wheat varieties developed using molecular markers have been released commercially in Australia and China (Zhang et al. 2009). The resistance characteristics were first identified using insect vectors and measurement of viral content in plant tissues. The discovery of simple molecular markers (Stoutjesdijk et al. 2001) allowed these resistance genes to be utilised in national and international breeding programs.

Pathogen mimicry for virus resistance has resulted in the commercial use of genetically modified crop varieties in the United States since the mid-1990s. The general approach was to express a part of the virus protein complement to achieve resistance. Today, breeders tend to use the RNAi mechanism to protect modified plants against viral infection. RNAi is the harnessing of a natural plant defence system that recognises double stranded RNA molecules and directs cellular machinery to degrade all molecules with the same sequence. However, because it targets RNA not DNA, RNAi is not as effective in cases where viral plant diseases are caused by DNA viruses.

### **Weed competition**

Competition from weeds poses the largest potential loss of yield from the world's cropping systems. Effective control methods reduce actual yield losses to a level equivalent to those attributed to pest attack and fungal and bacterial diseases. Weed competition is the greatest threat to wheat production, followed by disease (Oerke & Dehne 2004). The most common control approaches include the use of selective and broad spectrum herbicides and genetically modified herbicide-tolerant plants. Although it requires greater spending on inputs, higher planting density can provide better weed control and farmer returns.

Crop plants are bred for better competitive ability because this is an important factor in yield potential, particularly water-limited yield potential, and water use efficiency. Plants that grow quickly when young (early vigour) can quickly develop closed canopies in the field. Closed canopies do two things. They shade weed species under them, thereby reducing competition for moisture and nutrients, and they shade bare earth, which reduces evaporation from the soil surface and results in more water being available for plant growth. Plant breeders select for early vigour and plant architecture that result in early closed canopies.

Plants produce chemicals that influence both plants and animals. These chemicals are known as allelochemicals. Plant allelochemicals are a diverse set of molecules that have been divided into 14 chemical classes each reflecting a different biosynthetic route (Macías et al. 2007). For example, the mango suppresses the growth of grasses under its canopy using compounds found in its leaves. Some researchers suggest using mango leaves as a safe method for controlling purple nut sedge—one of the world’s worst agricultural weeds—which may itself use allelochemicals to suppress other plants (El-Rokiek et al. 2010). Some plant-inhibiting allelochemicals have been used in the development of new herbicides and, while not strong enough in their native form, derivatives have been released as commercial herbicides. For example, the chemical mesotrione, developed from a natural compound found in the Australian bottle brush species *Callistemon citrinus*, is sold commercially as a broadleaf-selective herbicide for use in corn. Other herbicides in this class are being developed for use in sugarcane and corn. Mixing extracts of known allelopathic plants with herbicides has been shown reduce overall weed control costs in Pakistani farming systems (Elahi et al. 2011); however, the approach may not have the same results in Australian systems.

Crop plants can be bred or genetically modified to produce allelochemicals that will allow them to successfully compete with weeds. Initial screening of wheat, rice and barley shows a high degree of variation within the species for allelopathic activity against weeds. This variability means that plants with high allelopathic potential can be selected for inbreeding programs and the genes responsible for the allelopathy marked for breeding and/or identified. Australian researchers have identified quantitative trait loci in wheat associated with allelopathy against annual ryegrass (Wu et al. 2003). A better understanding of allelopathy through genomic and associated technologies will allow the incorporation of suites of allelopathic genes into commercial wheat varieties (Wu et al. 2008).

Traditionally bred and genetically modified herbicide tolerant plants are a mainstay of minimum tillage cropping agriculture worldwide. It is likely that new plant varieties will be developed that are tolerant to the latest herbicides. Modern technologies that have not yet been classified as genetic modification could be used to develop these herbicide tolerant plants. For example, the rapid trait development system has been used to introduce glyphosate (Roundup herbicide) tolerance to flax. Herbicide tolerant grain sorghum developed using this technology is not considered to be a genetically modified organism by US regulators.

## Nutrient use

Farmers can use several methods to improve nutrient use efficiency in crops, including optimising nutrient application through changes in crop management (see Chapter 3) and improving the use of nutrients within the crop plant.

Nitrogen and phosphorus are essential for plant growth and are the main nutrients applied in modern farming systems. Farmers are interested in improving nutrient use efficiency because fertilisers are expensive and the excess not used by the crop can adversely affect the environment. Phosphorus from agriculture can cause eutrophication (depletion of oxygen after excessive algal growth) of waterways and dead zones in oceans. Unused nitrogenous fertilisers are transformed to potent greenhouse gases and can stimulate algal growth in aquatic and marine systems.

Nutrients are often applied in excess. While phosphorus is required early in plant development and can be remobilised in the plant during growth, a high proportion of applied phosphorus becomes unavailable to plants because it is bound to soil constituents.

## Nitrogen use efficiency

Plants have a higher requirement for nitrogen before flowering to build plant tissues and capture light energy through photosynthesis. After flowering, remobilisation of nitrogen, rather than uptake, is most important. For example, 60 per cent to 95 per cent of the grain nitrogen in wheat comes from the remobilisation of nitrogen stored in roots and shoots. Some of the nitrogen applied as fertiliser will not be available for plant uptake because of losses through volatilisation to the atmosphere, leaching of the root zone and incorporation in soil microorganisms.

Plant breeding during the green revolution saw consistent increases in nitrogen use efficiency as measured by the amount of grain returned per unit of nitrogen input. These increases were achieved by selecting for high yield under adequate nitrogen fertilisation and did not concentrate on factors affecting nitrogen use efficiency (Ortiz-Monasterio et al. 2001). The factors, soil uptake and plant utilisation efficiencies, take on different levels of importance during the growing season. It may be possible to improve nitrogen uptake efficiency of cereals from the current level of about 30 per cent. However, the gains in efficiency will be limited by constraints imposed by complex plant physiology. Genes responsible for rapid and efficient nitrogen uptake under low-nitrogen conditions are turned off under high-nitrogen conditions when other genes are activated.

Nevertheless, both uptake and utilisation efficiency are active research areas and targets for plant breeding. Some researchers have found that most quantitative trait loci associated with nitrogen use efficiency and yield are the same under low and high-nitrogen conditions, while other researchers have found more under low-nitrogen than under high-nitrogen conditions. However, plants used in recent research are derived from those selected under high-nitrogen conditions rather than those found in natural conditions. This suggests as yet undiscovered gene variants in wild relatives and ancient types of crop plants could significantly improve nitrogen use efficiency. Nitrogen use efficiency is also related to photosynthetic efficiency as 25 per cent of all leaf protein is found in the inefficient, but rate-limiting, photosynthetic enzyme Rubisco.

Improvements in the catalytic characteristics of this one enzyme could have major effects on nitrogen use efficiency. Root systems are very important with respect to nitrogen use efficiency but are very hard to study *in situ*. The complex nature of nitrogen uptake and use in plants indicates that an integrated research approach combining genetics, physiology and agronomy is needed to provide breeders with better targets to select (using molecular markers) and farmers with better fertiliser management rationale (Hirel et al. 2007).

Genetic modification approaches to improved nitrogen use efficiency have been successful in model plants and are undergoing field trials in crop plants in several countries. Breeders of crop plants have had some success with genes that appear to improve nitrogen uptake under low-nitrogen conditions. Good and colleagues (2007) showed a 42 per cent increase in canola yield under suboptimal nitrogen conditions using barley gene involved in transferring nitrogen within plants. Shrawat and colleagues (2008) showed increases in yield of genetically modified rice when the same barley gene was used. See the Office of the Gene Technology Regulator's website for information on field trials of DIR 111 wheat and barley approved in Australia (OGTR 2013b). In 2012 the CSIRO announced it had licensed nitrogen use efficient technology to a company planning to develop genetically modified nitrogen use efficient wheat in Australia (CSIRO 2012).

Work by Good and colleagues (2007) suggests current yield could be maintained by using much less nitrogen fertiliser—a clear benefit in terms of agricultural sustainability. It is less clear

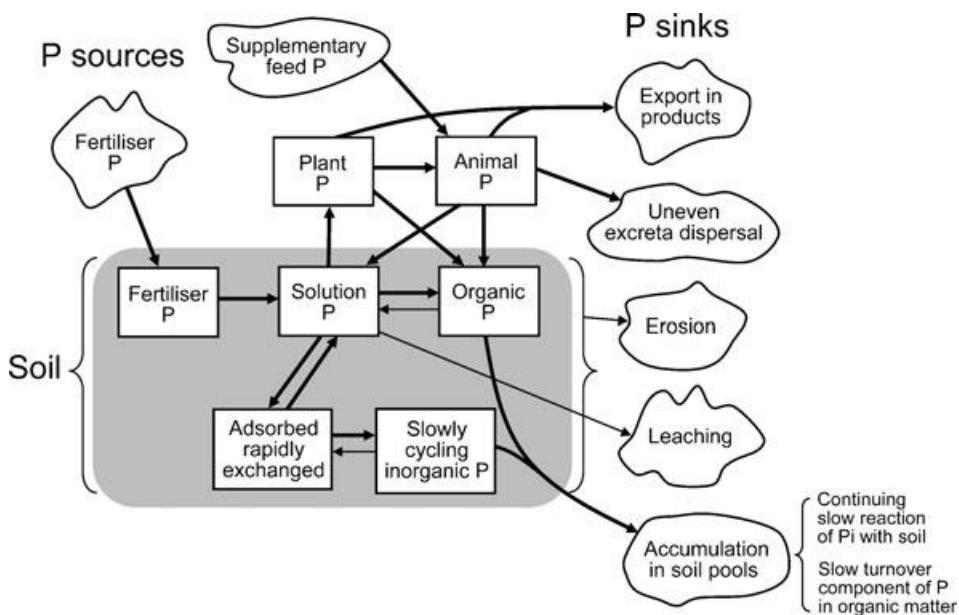
whether yield can be significantly increased by using the same amount of fertiliser applied to non-genetically modified canola.

### Phosphorus use efficiency

Phosphorus is an essential nutrient for plants. It has many functions, including energy metabolism, and is a structural element of cell membranes and nucleic acids (DNA and RNA). Phosphorus differs from nitrogen in that much of it exists in the soil in forms not immediately available to plants. In some cases only 0.1 per cent of phosphorus in the soil is available in a form that can be taken up by plants. Soil pH and the presence of iron and aluminium can affect levels of available phosphorus. Australian soils are naturally low in overall phosphorus and some soils bind phosphorus at high levels.

The sources, sinks and flows of phosphorus in agricultural systems are shown in Figure 4. Plants take up phosphorus from the soil only when it is in soluble form (see Solution P in Figure 4). Phosphorus in solution can also be absorbed by soil particles or be taken up by microorganisms and reside in the organic phosphorus fraction of soil. If solution phosphorus is decreased through plant uptake, additional sources of the mineral can only come from residual fertilisers, from phosphorus stored as organic phosphorus or absorbed by soil particles.

Figure 4 Sources, sinks and flows of phosphorus in agricultural systems



P = phosphorus; Pi = inorganic phosphorus

Note: Soil fraction represents phosphorus present in the proximity of crop plant roots. Movement of phosphorus to sinks shows the fraction no longer available for crop use.

Data source: Simpson et al. 2011

Phosphorus use efficiency can be increased by:

- improving fertilisers and their use (crop management and agronomic practices)
- reducing the movement of phosphorus to sinks
- improving plant ability to acquire or efficiently use phosphorus in the soil (Simpson et al. 2011).
- improving soil microorganism ability to acquire, and make available to plants, phosphorus in the soil.

Modern biotechnology could improve the phosphorus use efficiency of farming systems by improving acquisition of the mineral in plants or through microorganisms, improving the efficiency of use of phosphorus within plants and lowering the amount of phosphorus removed in harvested portions of crops.

Researchers have identified quantitative trait loci for phosphorus use efficiency in wheat (Su et al. 2009), canola (Ding et al. 2012), rice (Wissuwa et al. 2002) and other major crops. Australian researchers are working toward phosphorus efficient wheat and barley and are assessing many lines to determine high and low-efficiency types. This material will be used to develop molecular markers to breed phosphorus efficient cereals (McDonald 2012).

The research uses measures of phosphorus use efficiency such as phosphorus uptake efficiency (phosphorus per unit biomass) and phosphorus utilisation efficiency (grain/biomass per unit internal phosphorus) in combination with yield measurements. These measures are at a high, whole plant level. Richardson and colleagues (2011) describe three approaches to increasing phosphorus use efficiency in plants that concentrate on specific strategies within the plant: improving root and soil mining strategies and breeding plants with better internal phosphorus use efficiency.

Modifying plant root foraging strategies to aid the acquisition of available soil phosphorus may result in fertilised agriculture operating at lower phosphorus input requirements.

Plants could be bred for soil mining strategies that enhance the use of phosphorus found in organic and slowly cycling inorganic pools that plants are not usually able to use. This may mean breeding or genetically modifying plants for the ability to convert phosphorus bound to soil mineral constituents or present in organic components of soils to a form available for uptake. This approach is not considered sustainable in itself because it would be making a one-time use of a finite resource of phosphorus that is already in the soil and currently unavailable to plants. However, in the longer term the approach would improve the use of applied phosphorus in soils that naturally bind high levels of added phosphorus.

Breeding plants with better internal phosphorus use efficiency would help ensure a higher yield per unit of phosphorus taken up through the roots. This approach may enable farmers to grow crops that require less phosphorus while maintaining production.

Richardson and colleagues (2011) reviewed developments in traditional breeding, including quantitative trait locus analysis and genetic modification within the context of the three approaches. They concluded it should be possible to breed crop varieties with phosphorus efficient root traits and better internal phosphorus use efficiency.

In 2012 researchers identified and characterised a gene within a quantitative trait locus for increased phosphorus use efficiency in rice (Gamuyoa et al. 2012). The gene is responsible for increased root mass, root length and root hairs. In phosphorus deficient soils, rice plants with this gene had a 60 per cent higher grain yield than those without it. This gene has already been introduced into elite breeding lines of rice using molecular markers. However, identification of this gene will allow researchers to assess the role similar genes in other crops play in phosphorus use efficiency.

This discussion has covered increasing the phosphorus use efficiency of plants. Other approaches beyond the scope of this report include fertiliser management and design (McLaughlin et al. 2011); managing soil phosphorus levels in different farming systems (Weaver & Wong 2011); and agronomic interventions to improve phosphorus use (Simpson et al. 2011).

## Policy implications

Factors that could limit adoption of biotechnology in the Australian agriculture sector are: research funding, technical constraints and public acceptance of genetically modified crops.

### Research funding

A decrease in funding for scientific research and development will affect the rate of development, and hence adoption, of new and emerging biotechnologies in the agriculture sector. Growth in investment in agricultural research and development has been slowing in real terms for many years (Nossal & Gooday 2009) even though innovation is a key driver of continued productivity growth. The decline in research and development investment is a contributing factor in slowing Australian agricultural productivity growth. Another factor is the large gap between investment in rural research and development and flow-on impacts on industry—25 years can pass between a scientific discovery and a resultant product that is widely adopted in agriculture (Richards 2012). In the context of boosting productivity and production, increases in research and development funding will have a significant lag dependent on the approaches adopted.

If funding were to increase rapidly in the short term, Australia might lack sufficient agricultural or biological science graduates to take up positions in research; low demand has led to a trend of closures of university-level agricultural science courses, and science courses in general (PMSIEC 2010).

### Technical constraints

Phenotype is the composite of an organism's observable characteristics or traits, such as its size and shape, biochemical or physiological properties. The constraint with regard to phenotype information is best described using a human example. Humans are on average 99.5 per cent similar at the DNA level but this can add up to millions of differences in the DNA sequence. Although it is relatively cheap to detect DNA differences between two people, it is difficult to relate each of these genetic differences to the actual physical differences (height, weight, skin colour, disease susceptibility, metabolic rate).

Crop scientists face similar problems with crop species. While it may be easy to find the differences at the DNA level, relating them to the desirable characteristics of a given plant is challenging and expensive. However, the Australian Government, through the National Collaborative Research Infrastructure Strategy program, has funded construction of the Australian Plant Phenomics Facility with modern, high-throughput, plant phenotyping glasshouses (the Plant Accelerator) and laboratories (the High Resolution Plant Phenomics Centre). Researchers will use these facilities to generate phenotypic information that is useful to breeders. Their work is supported by the Grains Research and Development Corporation through the creation of managed environment facilities, which enable field testing of experimental breeding lines that have been developed in controlled environments, using pre-breeding techniques.

While phenotyping in the laboratory and glasshouse can give valuable information about gene function in the context of whole plant development, such information is of little value to commercial breeders unless it has resulted in experimental breeding lines that they can compare with their own advanced breeding lines in the field. In association with the High Resolution Plant Phenomics Centre, the managed environment facilities enable such comparisons and provide novel techniques and instruments for getting detailed phenotypic information across genetically diverse field plots. Such information can be readily referenced to

genetic information from the increasingly fast and inexpensive DNA sequencing technologies now available.

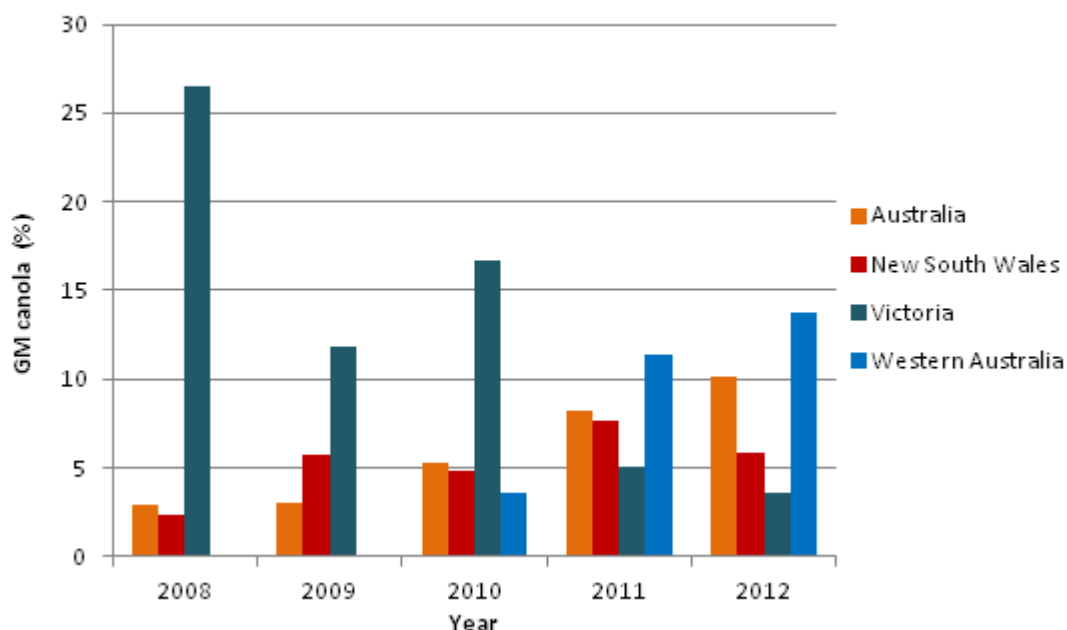
### Public concern

Public concern, in Australia and overseas, about genetically modified crops has slowed the adoption of associated technologies. In Australian states, marketing concerns seem to have delayed the decision to allow commercial cropping of genetically modified (GM) canola. These concerns were about the canola industry's ability to meet customer demand for non-genetically modified products in some international markets when genetically modified canola was also being grown in Australia.

Some Australian states introduced legislation to ensure that marketing and coexistence protocols were in place before allowing commercial cultivation of GM canola. While the rate of adoption of GM canola nationally is increasing, the proportion planted in Victoria has fallen (Figure 5). By contrast, Western Australian farmers have increasingly adopted GM technology since its introduction in that state in 2009.

Different uptake trajectories in different states are related to how the Roundup Ready canola trait fits into farming systems and the profitability of the crop, taking into account segregation and differential transport costs. In Victoria, recent wet seasons have meant that herbicide tolerant canola systems that use pre-emergent herbicides (applied at seeding) are more popular than in-crop herbicide application; this is because wet conditions can prevent timely in-crop herbicide application. In Western Australia, where weed pressure is a major yield determinant and soils are generally well draining, timely in-crop herbicide application is more certain. Only one GM canola trait is available in Australia and most canola plantings are herbicide tolerant varieties that have not been genetically modified.

**Figure 5 Adoption of genetically modified canola, selected states and Australia-wide, 2008-12**



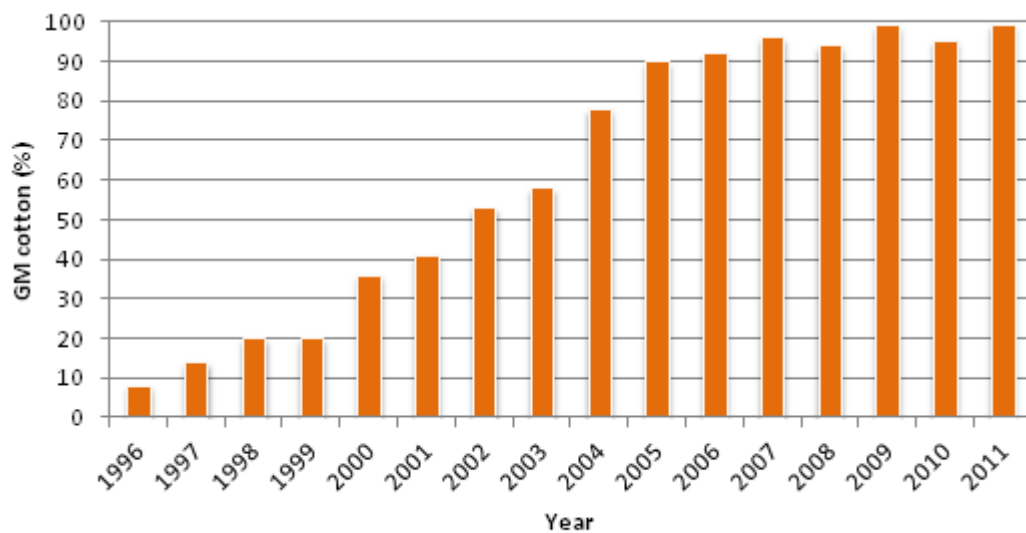
Note: Adoption is expressed as a percentage of the total area planted to canola each year.

Data source: Monsanto Australia, Australian Oilseed Federation

Australian cotton farmers have adopted both herbicide tolerance and insect resistance GM traits so that almost all cotton planted in 2012 had one or more modified traits (Figure 6). When GM cotton was introduced in 1996, only the insect resistance trait was available and an industry imposed a limit of 30 per cent of the total area of cotton planted. Despite this, the adoption rate was approximately twice that of the national adoption rate for GM canola between 2008 and 2012. Two factors may have contributed to the popularity of GM cotton during this period: traditionally bred insect resistant cotton traits were not available and synthetic insecticides were losing their effectiveness.

Farmers aim to maximise profits. Cotton farmers choose varieties based on yield and fibre quality characteristics first and then consider GM trait options (Greg Kauter, [Cotton Australia], pers. comm. 12 September 2012). Similarly, canola farmers choose herbicide tolerant varieties (GM or traditionally bred) that suit their circumstances and maximise profits. Some farmers will not use herbicide tolerant varieties, choosing to manage weed pressure in other ways.

**Figure 6 Adoption of genetically modified cotton in Australia, 1996-2011**



Note: Shows the proportion of the total area of cultivated cotton that had at least one genetically modified trait.

Data source: Greg Kauter, Cotton Australia

Australia ranks twelfth in the world in terms of the area sown to GM crops (James 2011). Some see this as an indication of poor rates of adoption by Australian farmers and an impediment to increased productivity from the technology.

Unlike other leading agricultural exporting countries Australia does not have GM options in its major crop species, wheat and barley. Major crops grown in the United States, Brazil and Argentina include soybean and maize. When GM wheat was close to commercialisation in 2004, the US industry did not support the technology; this may have resulted in withdrawal of the application for its unrestricted use. It is not clear whether industry sees that markets are now more likely to accept GM wheat but this will be the major consideration in any future decision to commercialise it.

## Regulation of new techniques

Governments have a legitimate role in information dissemination. The Australian Government could re-examine the need for balanced scientific information about genetic modification and the benefits and risks of its use in agriculture. Another consideration is that increasing pressure in the global food supply system may mean that we will have to use all safe technologies available.

Since the introduction of the Gene Technology Act in 2001, several new breeding technologies have been developed that challenge the conventional view of gene technology. Lusser and colleagues (2011) discuss these new technologies and their application in the development of plants with new traits. Some of these are close to commercialisation overseas. In Australia, the Office of the Gene Technology Regulator has fielded inquiries from the research community about the scope of the *Gene Technology Act 2000* with respect to these new technologies (OGTR 2011).

Policymakers need to address two questions about these new technologies: Are they covered by existing regulatory systems? If they are not, should they be? Regulatory agencies such as the Office of the Gene Technology Regulator and Food Standards Australia New Zealand are considering these questions. Both agencies participate in international forums where these broad regulatory issues may be discussed. Forums include the Organisation for Economic Cooperation and Development Working Group on the Harmonisation of Regulatory Oversight in Biotechnology and the Task Force for the Safety of Novel Foods and Feeds.

In 2011 the Office of the Gene Technology Regulator made a submission to the Independent Review of the *Gene Technology Act 2000* demonstrates this agency's consideration of the technologies in question (OGTR 2011). The submission also indicates that some of the technologies may not currently be covered under the scope of the *Gene Technology Act 2000*.

Determining whether these new technologies should be regulated may require a public policy discussion. This discussion would be informed by science, but the final outcomes may also be shaped by other factors, including Australian community attitudes, regulatory stances of trading partners and coverage of international instruments such as the Cartagena Protocol on Biosafety.

Discussion and a subsequent decision would give a clearer indication of regulatory and commercialisation pathways for new plant varieties which may be developed using these technologies. Relevant agricultural policy formulation bodies could begin such discussions.

## Key points

Biotechnology can increase food production and improve agricultural sustainability through a range of methods and approaches. Potential yield of crops could be increased by genetic modification or through the application of quantitative trait locus-derived molecular markers for yield in plant breeding.

Genetic modification of photosynthetic processes could increase yield, especially of water-limited crops. However, the technical difficulties are so great that it is likely to be several decades before substantial progress is made.

Biotechnology can increase farmer yield through increasing the crop's ability to withstand biotic and abiotic stresses, thereby reducing the need to apply soil amendments and pesticides. Furthermore, these input reductions can offer cost savings and, by reducing negative environmental impacts, provide a more sustainable future for farming.

## 3 Nanotechnology

In this report, nanotechnology is defined by its focus on materials and objects that are created at the nanoscale. This does not include information technology and biotechnology. In 2008 the Australian Office of Nanotechnology (2008) defined nanotechnology as:

a collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the nanoscale—the size range from approximately 1 nanometre (nanometre = one millionth of a millimetre) to 100 nanometres. The term nanotechnology describes the technologies used to create, manipulate and characterise matter and processes at the nanoscale.

Bawa and colleagues (2005) define nanotechnology as:

*the design, characterization, production, and application of structures, devices, and systems by controlled manipulation of size and shape at the nanometre scale (atomic, molecular, and macromolecular scale) that produces structures, devices, and systems with at least one novel/superior characteristic or property.*

Nanotechnology approaches can be divided into top down and bottom up. The top down approach uses externally controlled equipment to microfabricate nanomaterials or structures. The bottom up approach uses the chemical properties of molecules to create nanomaterials structures by self assembly.

The properties of nanomaterial/structures differ from larger constructs made of similar materials because at the nanoscale the physical forces affecting nano-objects are very different. Surface forces have a proportionally greater effect on nanomaterials and Brownian motion (motion caused by colliding molecules) also has a greater proportional effect at the nanoscale.

Research into nanoscience promises new applications in medicine, food processing and manufacturing. However, relatively few research projects have resulted in applications that increase agricultural production and sustainability (FAO–WHO 2010). These applications, which are described in this chapter, include developments in pesticide (herbicide and insecticide) formulation and delivery, fertiliser delivery, biosensing, remediation and increasing plant productivity.

Terms and definitions around nanotechnology have not been standardised. This results in some publications referring to nanomaterials that, on average, exceed the 100 nanometre threshold mentioned here. In some instances these materials exhibit physical properties or activities that are different from the larger parent material. This chapter will discuss materials with dimensions larger and smaller than 100 nanometres.

### Nanotechnology in agriculture

Nanotechnology is often cited in the media as having applications in the industrial sector and in medicine. The media also covers use of nanotechnology in the food processing sector, a controversial subject within some sectors of the community.

Nanotechnology has potential applications in many areas of human activity, including on-farm agriculture, and in other technologies mentioned in this report. For example, DNA sequencing could be made faster and more efficient. This would be achieved by passing single DNA molecules through nanopores with enzymes attached to the surrounding material so that the DNA sequence of the molecule can be ascertained (Delseny et al. 2010). In the mid-1990s scientists used nanoparticles carrying foreign DNA to create genetically modified plant cells and

more recently nanofibres have been used to achieve the same result. These uses of nanotechnology fall under the biotechnology banner and will not be discussed.

Nanotechnology can provide new tools for disease detection, targeted treatment of water and nutrient application, enhance the ability of plants to absorb nutrients and enhance delivery of disease and pest management.

## **Pesticide application**

The major agrochemical companies are developing new delivery mechanisms for older crop protection chemicals. The patenting of new delivery mechanisms for older chemicals ensures cash flow for agrochemical companies but and provides sustainability and environmental benefits from the more efficient use of chemicals.

Nanotechnology can improve agrochemicals and fertilisers through:

- increased efficacy (same effect with less chemical/nutrient)
- controlled release of pesticides and fertilisers leading to reduction in use
- targeted delivery (reduction in use and or unintended effects).

The four main domains of research activity in the delivery of crop protection chemicals are: nanoclays, nanodispersions, nanoemulsions and nanoparticles (ObservatoryNANO 2010).

### **Nanoclays**

Nanoclays are thin sheets of silicate minerals that are around 1 nanometre thick and 70 to 150 nanometres wide. Although these minerals exist in nature, nanoclays are useful because of their reduced size and the opportunities to modify their surface attributes.

Nanoclays have low toxicity, good biocompatibility and can be used for controlled release applications. The target chemicals are loaded between layers by the use of buffers and pH control. Where the crop protection chemical or nutrient is hydrophobic (repels water), incorporation into nanoclays increases solubility (compared with water alone) and bioavailability. Double layer hydroxides with pesticides, growth regulators, plant nutrients and slow release fertilisers have been developed and tested in the laboratory.

The rate of release of chemicals from nanoclays can be controlled by coating with different polymers and the active ingredients are protected from UV degradation by the structure of nanoclays (ObservatoryNANO 2010). Application of nanoclays can be found in drip irrigation lines. These plastic hose lines slowly release herbicide (incorporated as nanoclays), preventing roots growing into underground water emitters for 50 per cent longer than lines without nanoclay additions (Ruskin 2004). These types of irrigation lines are commercially available in Australia.

These nanotechnology approaches may provide safer, more efficient methods for administering pesticides, herbicides, and fertilisers by controlling when and where they are released. They also act to increase a chemical's activity by increasing its concentration in water.

Nanoparticles have also been investigated for their ability to enter and be transported through plants and to release chemicals carried in the nanostructures (ObservatoryNANO 2010).

Nanotechnology could be used to:

- introduce pesticides into plants and then release them selectively upon attack by herbivores (Bhattacharyya et al. 2010)
- introduce RNAi molecules that effect changes within the plant, herbivores and diseases (Nair et al. 2010; Rai & Inge 2012).

### **Nanodispersions**

Nanodispersions are suspensions of nano sized particles of insoluble compounds in fluids. They are sometimes referred to as nanosuspensions. Nanodispersions have qualities similar to those of a real solution where a substance is dissolved in the fluid (ObservatoryNANO 2010). Sasson and colleagues (2007) believe nanodispersion methodology is the most significant of the nanotechnology approaches for agrochemistry because of the relatively low production costs and reduced environmental impact. Chemicals that may have not been used in certain situations because of poor dispersion characteristics could find new uses through formulation as a nanodispersion (Whitehouse & Rannard 2010).

Chin and colleagues (2011) describe a new, straightforward preparation method for nanosuspensions. Using a poorly soluble insecticide, carbofuran, these authors showed that a nanosuspension had the same effect with a lower amount of insecticide on a common agricultural pest than the commercial microsuspension of the insecticide. Decreasing the size of particles to the nanoscale (~60 nanometre) increased efficacy by about 14 per cent. It was also stable for two years. The nanosuspension had better suspensibility and dispersion, but higher viscosity, meaning that it may be harder to apply than normal preparations. The affect of this on commercial manufacture was not discussed.

Anjali and colleagues (2010) demonstrated a sixfold increase in efficacy of an insecticide nanodispersion stabilised with natural plant extracts on mosquito larvae when compared to the bulk insecticide. While these authors described their preparation as a nanosuspension the mean particle size was around 150 nanometres.

### **Nanoemulsions**

Nanoemulsions, which are mixtures of two immiscible (for example, oil and water) liquids, may have uses where a crop protection chemical cannot dissolve in water. These chemicals have to be dissolved in organic solvents that can be toxic or environmentally damaging. By using surfactants, specific solvents and other chemicals, nanoemulsions of crop protection chemicals dried to leave nanoparticulates that can then be suspended in water just before application (ObservatoryNANO 2010).

Some insecticides have been incorporated in nanoemulsions on an experimental scale (Wang et al. 2007) and the Roundup herbicide, glyphosate, has been made into nanoemulsions using simple methods and ingredients (Jiang et al. 2012). Jiang and colleagues (2012) claim that one of the nanoemulsions, with a particle size of 150 nanometres (a microemulsion) had better efficacy than the normal herbicide preparation. They also tested a nanoemulsion with an average particle size of 50 nanometre but this was no more efficient than the normal herbicide preparation.

The lack of understanding of the formation and the control of properties of nanoemulsions makes their use in agrochemical product formulation much more complicated than for emulsions in the micrometer range (microemulsions). To be successful, agrochemical

production will require new techniques for manufacturing nanoemulsions and specialised additives to stabilise products.

Some commercial microemulsion formulations of herbicides, fungicides, insecticides and plant growth regulators are available in Australia.

### **Nanoparticles**

Nanoparticles are particles measuring 100 nanometres or less. Hollow, silica-based, nanoparticles are biocompatible and can be manufactured with different pore diameter and shell thickness. The pore size and shell thickness of the particles determines the rate of release of chemicals within the particles. Although research into silica nanoparticles started in the pharmaceutical sector, the technology is being applied to agrochemicals and fertilisers (ObservatoryNANO 2010). Some agrochemicals are rapidly degraded by ultraviolet radiation and incorporation into silica nanoparticles can protect them from degradation.

Other types of silica nanoparticles have insecticidal properties due to the physical nature of the particle rather than chemical toxicity. Debnath and colleagues (2011, 2012) showed insecticidal activity of silica nanoparticles against the larvae of rice weevil (a stored grains pest) and the oriental leafworm, (a leaf-eating crop pest). It is thought that in these cases the nanoparticles pierce the cuticle of insect larvae and lead to death through desiccation.

Manufacture of nanoparticles of crop protection chemicals (not contained in a silica nanoparticle) can affect the solubility of the chemicals in water and hence its activity (Joseph & Morrison 2006). Grinding chemicals into smaller sizes can take advantage of the changed physical characteristics of materials at the nanoscale. The simplest change is an increase in the surface area (relative to volume) and this can boost potency, accelerate uptake and reduce or eliminate the risk of settling and separation in the spray tank. Greater potency and faster uptake could mean lower application rates and consequently less run-off and fewer non-target impacts.

Lipids (fats) can be made into nanoparticles with the use of stabilising molecules to maintain particle integrity. Drugs and/or agrochemicals can be dissolved in the fats before manufacture. Yang and colleagues (2009) used garlic oil and a stabiliser to make nanoparticles of garlic oil that gave 80 per cent control of red flour beetle after five months compared with 11 per cent control for untreated garlic oil.

Nanoparticles of silver and copper compounds restrict the growth of fungal and bacterial plant pathogens in the laboratory, glasshouse and field (Lamsal et al. 2011; Rai & Ingle 2012). Titanium oxide nanoparticles reduce the incidence of some crop diseases in the field (Owolade & Ogunletti 2008).

### **Nanofertilisers**

Using nanotechnology it may be possible to deliver precise amounts of fertilisers to crops while minimising wastage caused by leaching from the root zone, mineralisation by bacteria or binding to soil constituents that render the fertilisers unavailable to plants.

DeRosa and colleagues (2010) outline areas of research in this field. Plant nutrients could be encapsulated in nanotubes to affect controlled release. The nanoscale nutrients could be coated with a protective polymer film or delivered as nanoemulsions or nanodispersions or as coatings on other fertiliser products. Ideally, these nanotechnology delivery systems should be able to synchronise the release of the nutrient with uptake by the crops, thereby reducing the leaching or conversion of nitrogen fertilisers to gases. This would be achieved by immobilising nutrients so that they do not interact directly with soil water or microorganisms until needed by the plant.

Although research has shown controlled release in nanotubes and double layer hydroxides they have yet to show a release that coincides with plant nutrient demand. DeRosa and colleagues (2010) suggest that functional nanoscale films may allow the development of such materials in the future. However, this will require development of a nanobiosensor to recognise chemical signals in the soils that indicate when plants require nutrients.

Examples of research approaches include using a nanoscale zinc oxide covering over nitrogen and phosphorus fertiliser particles (Milani et al. 2010) and introduction of soluble nutrients into chitosan nanoparticles (Ghormade et al. 2011; Nguyen et al. 2012). Chitosan, which is derived from the shells of crustaceans, has favourable environmental characteristics.

Zeolites are natural minerals made of oxides of aluminium and silicon. The porous structure of zeolites give them a high internal surface area, which makes them useful in a wide range of industrial and other applications. Natural zeolites are used in controlled release fertilisers, but the formation of synthetic nanozeolites may improve performance. The pores and channels in zeolites and nanozeolites can be loaded with nutrients; the type of nutrients and the strength at which they are bound can vary by zeolite type and be modified with the use of surfactants.

Nanozeolite fertilisers can release nitrogen at a slower rate than untreated fertiliser, doubling nitrogen use efficiency (Subramanian & Rahale 2010). The use of surface modified zeolites for slow releases of phosphorus suggests that nanozeolites could have similar uses in controlled release fertiliser applications.

Zeolites, particularly synthesised nanozeolites, can be used to bind and release charged molecules (ions) to remediate contaminated soils and water.

### **Using nanotechnology to improve plant growth**

Some reports indicate that nanomaterials enhance plant growth. In field trials, the application of titanium dioxide nanoparticles increased the yield of cowpea (Owolade & Ogunleti 2008) and barley (Moaveni et al. 2011). It appears that these titanium nanoparticles protect against diseases and increase photosynthesis. These field results follow those of Zheng and colleagues (2005), who found that titanium nanoparticles improve the growth of spinach seedlings by up to 50 per cent through effects on photosynthesis. While only a few scientific publications deal with enhanced plant growth using titanium nanoparticles, the approach is covered by at least one patent (Choi 2012).

Tripathi and colleagues (2011) have also demonstrated positive effects of carbon nanotubes on chickpeas, with shoots and roots showing improved growth. The researchers also observed better water uptake in chickpea plants as a result of the carbon nanotubes penetrating the root surface and entering cells in the root associated with water transport throughout the plant. These experiments with carbon nanotubes were performed in the laboratory in nutrient solution.

Yuvakkumar and colleagues (2011) have shown that silica nanoparticles increased the growth of maize plants in both laboratory and field experiments. The silica nanoparticles were prepared from the ash of burnt rice husks and were found to increase growth and yield in field studies. In laboratory experiments the silica nanoparticles increased seed germination and water use efficiency.

While promising, the results with carbon nanotubes and silica nanoparticles need to be demonstrated in large field trials where plants are grown under accepted agronomic practices.

Several reports show that nanoparticles made of various metals have negative effects on plants, particularly at higher concentrations. Khot and colleagues (2012) have reviewed the negative effects of nanoparticles on plant growth, regulatory considerations of nanomaterial use in agriculture and potential nanobiosensing applications for pesticide residue and pathogen detection.

### **Biosensing**

Nanotechnology could be used to make biosensors that have applications in many fields, including agriculture. Some biosensors have been developed specifically for the food industry. Agricultural biosensors could be used to detect diseases and/or pests and pollutants such as pesticides.

Nanosensors can detect diseases and toxins rapidly and could become relatively inexpensive to use. For example, nanosensors can detect the presence of the disease-causing organism *Salmonella* (Junxue et al. 2008) and viruses such as ebola and smallpox (Yanik et al. 2010). These systems rely on the use of target-specific antibodies attached to a nanostructure that can transmit signals to electronic equipment.

The system designed by Yanik and colleagues (2010) has two nanostructured detection plates, one with an antibody attached and the other acting as a reference plate. Both plates are exposed to light. When antigens from the organism are attached to the antibodies on the analytical plate, the wavelength of the light passing through it increases, indicating the presence of the targeted organism. This system could be used for detecting disease-causing organisms in imported agricultural produce or for determining food safety attributes at the farm gate. However, antibodies are expensive to produce and are prone to non-specific effects and denaturation.

Cheap nanosensors may help growers make better decisions and respond faster to potential problems; they could help monitor soil moisture, temperature, pH, nitrogen availability and measure crop growth (Robinson & Morrison 2009). They could even help growers detect diseases before symptoms are visible or help them carry out microbiological tests very rapidly (Khot et al. 2012).

### **Remediation of degraded agricultural land**

Organic pollutants such as pesticides can be degraded and detoxified by photocatalysis facilitated by the chemical's interaction with metal oxide nanostructures (Baruah & Dutta 2009). The US company Verutek has developed green chemistry methods that use plant oils and citrus extracts to produce nanoemulsions containing metal nanoparticles. These can be used for the remediation of pesticides in soil and groundwater. Similar technologies are also available to remove pesticide contaminants and fertiliser runoff from wastewater streams (Mueller & Nowack 2009). Products designed for the remediation of soils containing diesel and other hydrocarbon contamination may have direct use on farms.

Nanotechnology products for remediation of soils and wastewater streams containing heavy metal contamination are available and research is continuing in this area (Mueller & Nowack 2009). Soils that are currently unsuitable for agriculture could be brought into production through soil remediation of heavy metal contamination using these technologies. Biosolids from sewage processing are unsuitable for application to agricultural lands because they have high nutrient and organic carbon content and high levels of heavy metals meaning. Nanotechnology may someday be used to remove a range of contaminants from waste streams so they can be used in agriculture.

## Policy implications

Nanotechnology has applications in a range of industries, including agriculture. The technology is mostly identified with the industry sector, with many manufacturers of consumer products claiming nanotechnology is used in their products (Wijnhoven et al. 2009). This technology has potential applications in agriculture.

Despite the considerable promise of nanotechnology, research and regulation issues must be addressed before the benefits can be realised at the farm level. More research is needed to understand the fate of nanomaterials applied in agricultural situations or the agricultural products exposed to them, and their effect on the environment. This research will give regulatory authorities valuable information to judge the safety of such products and harmonisation of regulatory approaches to nanotechnology will allow more rapid and consistent application of this technology across global agriculture.

The OECD is examining technical aspects of the regulation of nanotechnology. Some countries, including Australia, have adopted the OECD's working definition that restricts the term nanotechnology to materials that have at least one dimension less than 100 nanometres. Some authors of scientific literature have yet to adopt or recognise this definition. They continue to publish papers in the nanotechnology domain about materials that are larger than 100 nanometres. This causes confusion around an already controversial technology. It also indicates that materials larger than 100 nanometres can have physical and chemical attributes similar to nanoscale materials. However, Australian regulatory agencies assess new materials with small particle sizes on the basis of the danger they pose even if the particles are larger than 100 nanometres.

Regardless of whether particles are larger or smaller than the 100 nanometre threshold, regulatory authorities need to be equipped to measure and assess the risk of small particles that have novel characteristics. Ludlow and colleagues (2007) have analysed the Australian regulatory framework with respect to nanotechnology and identified that changes will be required in the longer term. The Australian Government's National Enabling Technology Strategy has funded the development of detection/measurement techniques for nanomaterials (nanometrology) and supports appropriate coverage of enabling technologies in policy and regulatory frameworks. The Australian Pesticides and Veterinary Medicines Authority (APVMA) is likely to assess veterinary medicines and agricultural chemicals using nanotechnology and has developed a strategy for dealing with nanotechnology (APVMA 2009; Centre for International Economics 2011). The strategy outlines how APVMA is preparing for the regulation of future nanotechnology products for use in the agriculture sector.

Food Standards Australia New Zealand (FSANZ) has investigated the use of nanotechnology in the production and manufacture of foods. Food substances, including food additives, processing aids, novel foods and nutritive substances that involve the use of nanotechnology, will require premarket approval if they are potentially unsafe. FSANZ amended its *Application Handbook* in December 2008 to ensure that appropriate information is provided on the use of nanotechnologies that could introduce novel characteristics into food or food ingredients and ensure these are taken into account as part of the risk assessment process.

A popular futurist concept in agricultural nanotechnology involves wireless nano-sized sensors sending farmers automatic notification when their crops are experiencing low water, low nutrient or disease pressures. Nanosensors, linked by communications technology, are seen as the vehicle for these early warning systems. Nanosensors that respond to changes in abiotic and biotic stress factors are already available, but information and communications technologies

that can enable nano-sized sensors to communicate wirelessly with other farm management systems are not yet available. Nevertheless, it appears that developments in precision agriculture (see Chapter 4) will use nanobiosensors and other sensors in monitoring instruments that communicate wirelessly with farm management systems.

## Key points

In the future we may see applications of nanotechnology that improve potential yield by increasing photosynthetic efficiency (for example, titanium dioxide nanoparticles). Farmer yield could be improved by making the application of pesticides cheaper and more effective or by providing better and earlier information to farmers through biosensors so that pests can be better managed. Environmental sustainability benefits may be achieved through more targeted pesticide application and the use of nanomaterials for remediation.

## 4 Communications and information technologies

Information technology has changed many industries, including agriculture. It will increase farmer yield and promote increasing efficiency in the use of agricultural inputs. The use of performance information from farming equipment and allied sensing systems has the potential to improve farmer yield, sustainability and profitability. An enabling technology is an invention or innovation that can be applied to drive radical change in the capabilities of users. Communications and information technologies have driven radical changes in many areas. They may also do so in agriculture.

This chapter will examine existing and potential applications for information and communications technologies in precision agriculture. This includes the use of imaging technologies, the internet, remote sensing and satellite navigation for vehicles.

### Communications technology

The internet and modern mobile telephony will continue to have an impact on farming operations. Applications include beyond-farm-gate sales and marketing and better communication within farming operations and with regional peers. Farmers and others see the benefit of access to mobile telephony and allied services such as email and SMS; for example, some Australian agronomists SMS their clients with advice on planting times, fertiliser use and alternative pesticides for particular pest problems.

However, communications technologies by themselves have little direct effect on increasing farmer yield or sustainability of production systems. Communications infrastructure, such as the internet and satellites, will be crucial for the efficient transfer of information as precision agriculture becomes more commonplace in Australian production systems.

### Information technology

#### Crop modelling

Australian scientists have developed software that simulates cropping systems. This work has attracted significant interest domestically and internationally. While it is predominantly used by crop scientists, attempts have been made to make it accessible to farmers.

The Agricultural Production Systems Simulator (APSIM) is a modular modelling framework that simulates the biophysical processes in farming systems and allows users to explore management options and their effects on input use and outputs. APSIM can also be linked via a web interface to other software such as Yield Prophet which can provide grain growers with real-time information about their crop and integrated production risk and monitoring decision support down to the paddock level. For example, Yield Prophet, taking into account rainfall and weather already experienced in the growing season, can predict yield and the effects of additional nitrogen application on final yield and overall paddock profitability. APSIM has modules for a wide range of broadacre and horticultural crops.

The CSIRO-developed GRAZPLAN suite of decision support tools can be used in a range of grazing applications. GRAZPLAN was originally developed for temperate grazing systems (which APSIM did not initially cover) but has been expanded to service large mixed cropping and/or grazing enterprises.

APSIM and the GRAZPLAN group of decision support tools are used by researchers and extension organisations to provide information and advice to farmers. Some progress has been made in getting suitable tools to farm-level decision-makers through products such as Yield Prophet (APSIM) and LambAlive and GrazFeed (GRAZPLAN).

APSIM has been used to model the effects of a new water use efficiency trait under development by plant breeders. It is being used to assess the potential performance of the new trait and which management practices might suit it best. Kirkegaard and Hunt (2010) modelled management scenarios for growing a new water use efficient wheat variety in the Victorian Mallee. This wheat can be sown deeper in the soil and earlier in the season in order to access stored soil moisture earlier. The management scenarios modelled included contemporary conservative management practices of farmers and more advanced management practices. The model predicted that in the millennium drought years, and using the advanced management techniques, the new variety would have produced a 38 per cent higher yield than normal varieties.

The same authors (Hunt & Kirkegaard 2011) used APSIM to model the effects of conservation of summer rainfall on wheat yields across the Australian wheat belt. Complete control of weeds in summer fallow is the best option to conserve soil moisture in the period between harvest and sowing. The results indicate that, in some areas, stored summer rainfall could account for 72 per cent (2.0 tonnes per hectare) of yield of the following wheat crop, while in others it could account for as little as 3 per cent (0.1 tonnes per hectare). The result highlights the importance of summer weed control in some areas and also points to the importance of this management practice in the future given trends of increasing summer rainfall in the Australian wheat belt.

Whelan (2012) suggests that the integration of crop/pasture simulation into precision agriculture systems is an area of research that may provide benefits for the broadacre cropping industries. Crop modelling may also have a role in crop insurance products (Hatt et al. 2012) and in other forms of risk management on farms (Loch et al. 2012).

## Precision agriculture

Many of the technologies that underpin recent advances in Australian agriculture practices come under the banner of precision agriculture. Precision agriculture is an ongoing process that involves the observation, impact assessment and timely strategic response to fine-scale variation in causative components of an agricultural production process. Precision agriculture uses information technology, guidance systems, variable rate application, and zone management.

In Australia, precision agriculture is predominantly used in broadacre cropping. Precision agriculture approaches can be simple or complex. An example of a simple approach is the use of tractors with guidance systems that give left-right directions to the operator who steers the machine on a predetermined bearing. Minimal guidance systems offer sustainability and economic benefits because they prevent overlap in seeding and spray operations. Some farmers have estimated cost savings of 8 per cent to 10 per cent during seeding by just using GPS guidance (SPAA 2008).

Precision agriculture hardware, particularly GPS guidance systems, vary in accuracy and price and farmers adopt different systems depending on their needs. For instance, farmers with little variation in yield across paddocks may adopt low-price, low-accuracy systems. This level of guidance offers financial and environmental benefits because it allows farmers to avoid overlap in sowing and the application of agrochemicals. This entry-level technology can also facilitate controlled traffic farming where machinery and implement traffic is restricted to permanent

traffic lanes, which are normally untilled and unplanted. The benefits of controlled traffic farming include:

- improved yields of 15 per cent in a wide range of soil types, mainly through better root growth and increased water availability to plants
- reduced costs of fuel, seed, fertiliser and agrochemicals
- lower tractor power requirements
- improved timeliness of operations
- greater accuracy of placing inputs
- improved control of erosion and waterlogging
- improved efficiency and effectiveness of all operations.

Bowman (2008) modelled the environmental impacts of the adoption of controlled traffic farming in southern Queensland and concluded that their use can result in a 90 per cent reduction in soil loss, a 60 per cent reduction in fuel use and reductions in nitrogen and carbon loss of 90 per cent and 60 per cent respectively. Bowman found that producers could increase yield, reduce labour costs and increase their gross margin by 68 per cent, even when the costs of moving to controlled traffic farming machinery were taken into account.

Fuchsbichler and Kingswell (2010) modelled the effects of controlled traffic farming on a standard Western Australian farming system and found that profitability could be increased by 50 per cent. This would be driven primarily by increased yields and grain quality, but reductions in farm inputs, including agrochemicals, also contributed substantially to increased profitability.

While controlled traffic farming has many benefits in terms of increased farmer yield and environmental sustainability, other types of precision agriculture also promise immediate benefits and will be the platform for further improvements.

Farmers who see relatively high variation in yield across paddocks under uniform management conditions are likely to get benefits from higher accuracy machinery with variable rate technologies.

### **Site-specific crop management**

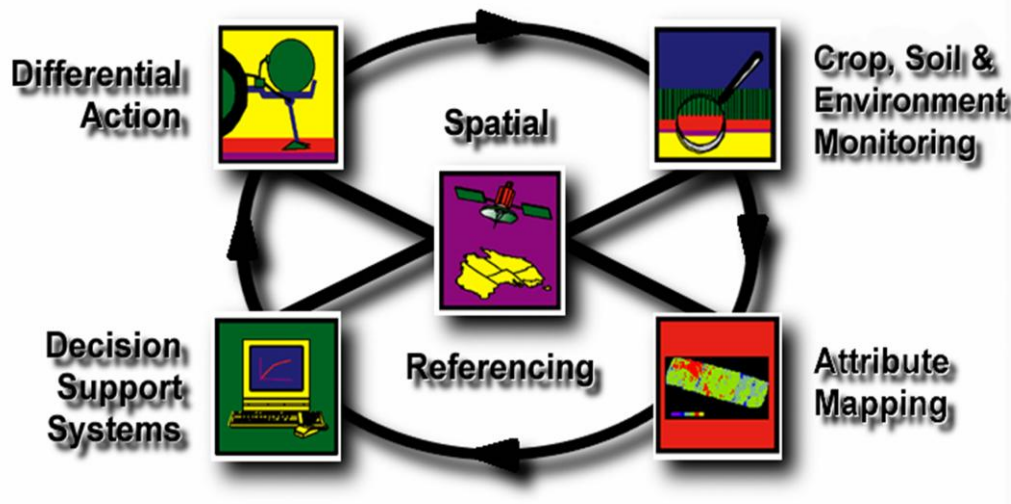
A common approach to precision agriculture is site-specific crop management. This is a form of precision agriculture where decisions on resource application and agronomic practices are improved to match soil and crop requirements as they vary in a field. The effect of site-specific crop management is to apply different treatments to specific areas of a field rather than apply a uniform treatment across the field, as was standard practice in the past (Whelan & Taylor 2010).

Site-specific crop management is a cyclical process facilitated by (Figure 7):

- spatial referencing (identifies where things are)
- crop, soil and environmental monitoring systems (identifies what is happening and where conditions vary)
- attribute mapping (maps variation in a form accessible to both farmers and machinery)

- decision support (allows farmers to determine the best management options for observed variation in the field and assign management prescriptions to those areas)
- differential action by machinery that can apply inputs at variable rates (applies material at different rates according to information from decision support systems).

Figure 7 Site-specific crop management cycle



Source: Whelan and Taylor (2010)

### Spatial referencing

Spatial referencing is simply knowing where things are. Measurements from remote sensing platforms, such as satellites and aeroplanes, are matched with global positioning system coordinates to allow features to be compared. Farmers can use spatial referencing to measure and map soil parameters, yield and weed presence at many different points in their fields. Autosteer technology controls machinery so that operators only have to manage manoeuvres at the end of rows and then only to place the machine in a rough orientation to the intended direction. Autosteer systems then direct machinery with  $\pm 2$  centimetre accuracy.

### Crop, soil and environmental sensing

Crop, soil and environment monitoring systems enable farmers to collect data for site-specific crop management. Farmers can choose from a suite of sensing and monitoring systems that gather information such as crop biomass, crop vigour and indicators of crop stress. Real-time sensors monitor soil attributes such as moisture content, pH and conductivity throughout the season. Grain flow through a harvester can be measured to determine yield in real time. Remote sensors include those mounted on satellites and on aircraft. Proximal sensors are mounted on tractors, other farm equipment or low flying manned and unmanned aircraft; included in this group are *in situ* monitoring systems, such as wetting front detectors, which are important in modern irrigation systems.

Developments in sensing technologies, particularly in proximal sensing systems, continue to increase the range of crop/soil/environmental characteristics that can be measured and subsequently managed through differential actions by farmers.

### **Attribute mapping**

The large sets of data generated by sensing systems need to be collected, cleaned and presented on a map as attributes of the farming system. This requires information technology features that enable farmers to create high quality maps of, for example, yield, soil type, crop vigour or nutrient status. Continued development of software is making attribute mapping easier.

### **Decision support**

Once attribute maps have been developed, software modules help farmers decide on the best management responses to any observed variation within their fields. These software systems help in the formation of management zones, each of which will have a set of management actions designed to maximise the potential crop yield from each zone while minimising waste of inputs and effort. Commercial decision support systems for precision agriculture are available to farmers.

### **Differential action**

Once decisions have been made about different treatments across management zones, GPS-guided machinery with variable rate technology can implement different treatment regimes. Variable rate technology machinery can deliver different amounts of seed, fertilisers, crop protection chemicals and soil ameliorants, such as lime, in response to inputs from decision support software systems. While differential management does not require variable rate technology, it makes complex management operations much easier. Variable rate technology machinery can also take information from real-time sensors for the delivery of agrochemicals at different rates.

## **Components of precision agriculture**

Farmers use a range of communications and information technologies in precision agriculture, including satellite imagery, robotics and geospatial tools.

### **Hardware**

Farming landscapes generally consist of a mix of landforms from flat to hilly. On any one farm, or even in one paddock, soil type, soil depth, drainage patterns, nutrient content and water holding capacity vary and this has an effect on how crops perform. Older crop management techniques treat each farm or paddock as a uniform unit and the same management treatments are applied across them; however, because of underlying variation, crop production in these areas is also variable. Farmers have understood this for a long time, but until recently few tools were available to address or react to this variation.

### **Global navigation satellite systems**

Global navigation satellite systems (GNSS) are satellite-based navigation systems that provide autonomous geospatial positioning with global coverage. The most well-known of these systems in Australia is the United States NAVSTAR Global Positioning System (GPS). GPS and its Russian equivalent GLONASS were developed for military use. GPS has been in public use for many years but its more advanced features did not become available until 2000. GLONASS, which is currently being upgraded, had its public launch in 2007 and the European Union's Galileo system will come into service in 2015.

All three global navigation satellite systems have orbiting satellites and ground-based control stations. Users access the system via receivers. The auto-steer functions of farm machinery need high quality receivers and/or a local base station to give accuracy between one and five

centimetres. This level of accuracy facilitates planting between the rows of stubble from the previous year's crop (inter-row planting).

### **Hyperspectral and multispectral imaging**

Digital cameras create digital images that can be processed, compressed and stored on computers and then printed or otherwise manipulated. Agricultural utility comes from images captured by satellites, planes, drones and digital cameras mounted on machinery or in processing plants.

Digital imaging captured by specialised cameras can be extended to the electromagnetic spectrum outside the range of human vision, including infrared and ultraviolet. Multispectral imaging is produced by sensors that measure reflected energy within several specific bands of the electromagnetic spectrum. Typically three to 10 bands are measured by multispectral sensors.

In hyperspectral imaging, narrower and more numerous bands are measured. In some instances as many as 200 spectral bands are measured and while this allows for greater analytical power, it also requires significantly more processing. The practical difference between the two processes is that multispectral analysis can map vegetated areas and hyperspectral imaging can identify different species of plant in the same vegetated area.

### **Machine vision**

Machine vision is the use of digital cameras and computing power to capture images and extract information in order to control a process or activity. Machine vision forms part of many potential robotics applications in agriculture.

### **Robotics**

Robots are usually employed to save labour costs or to perform tasks that carry inherently high levels of risk for humans. Robotics marries engineering with computing technology and sometimes machine vision to create machines that can autonomously perform tasks. While industrial robots are common, researchers are trying to develop robots for agriculture. Potential applications of robotics are discussed in this chapter.

### **Material flow and physicochemical sensing**

Information technology has allowed the development of sensing instruments that are now robust and small enough to be deployed on agricultural machinery and specialised sensing platforms. For example, sensing instruments measure soil parameters such as electrical conductivity, and gamma radiation in real time, and in georeferenced form. Other instruments measure crop characteristics such as chlorophyll, biomass and ground cover. Other sensors detect the amount of grain moving through harvesters so that yield can be determined over the field in real time. Moisture or grain protein content (a major quality characteristic that determines final price) can be determined in real time by using measurement devices on harvesters.

### **Software**

Software options for precision agriculture can be applied to different aspects of farm data information management. Many machinery manufacturers supply precision agriculture software to integrate the use of their products. Some software can monitor resource use and automatically request material from suppliers, as well as monitor machine performance and communicate problems to the manufacturer or local service agent.

## Artificial intelligence

Artificial intelligence is the study and modelling of human mental functions by computer programs. The control of modern machines, particularly robots, requires appropriate intelligent software. Specialists in machine vision, mechanical engineering and artificial intelligence collaborate to produce systems that have agricultural applications.

## Site-specific crop management in action

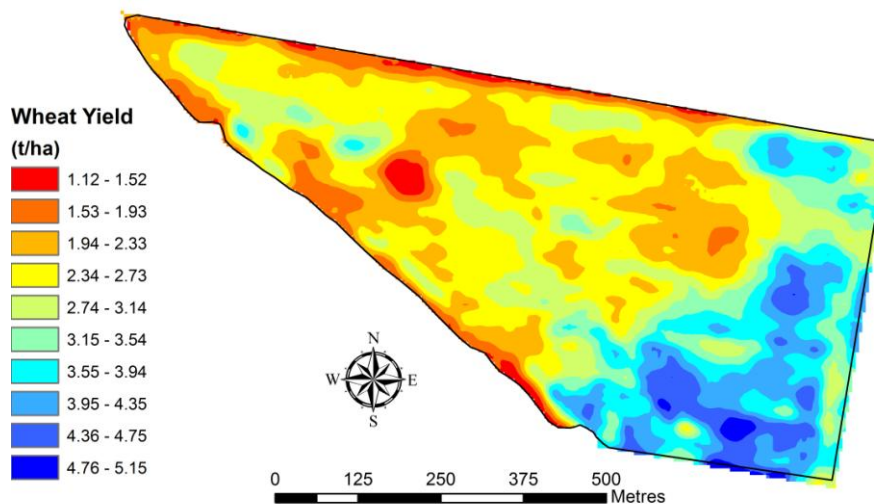
Site-specific crop management aims to manage the variability of the farming system to maximise the efficiency of input use. This leads to better profitability, less waste and fewer off-site effects. A key technology for site-specific crop management is variable rate technology.

After ensuring large-scale agronomic factors such as soil pH and weed management have been optimised, the first step in site-specific crop management is to determine the amount of variability in yield within a paddock. This is usually done by mapping yield variation through yield monitoring during harvest (Figure 8).

The variation in yield can be caused by factors including soil characteristics or nutrient status. The usual practice is to look for possible causative factors and then assign areas of similar yield to management classes or zones. Examining field characteristics such as elevation or soil characteristics or soil electrical conductance and gamma radiation signatures can give indications of drainage direction, soil texture, clay content, water holding capacity and salinity. Figure 9, Figure 10 and Figure 11 show soil electrical conductance, elevation and two potential management zones for the field shown in

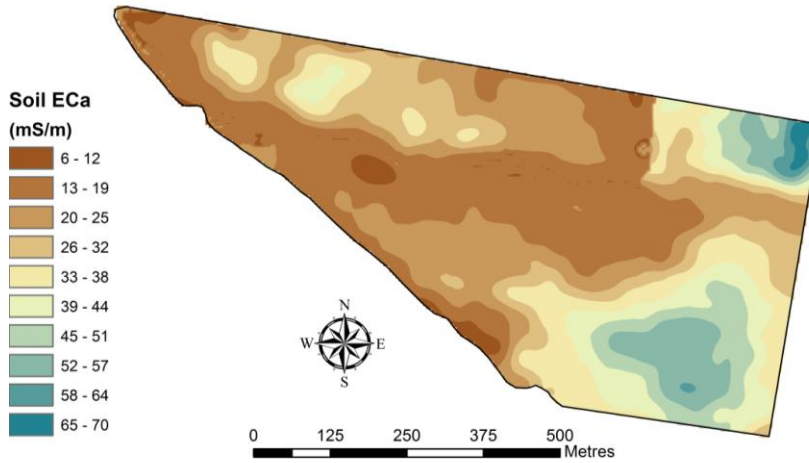
Figure 8. Maps such as these can guide soil sampling and the analysis of soils can give further information on factors that may be responsible for constraining yield. Soils analysis allows field-level electrical conductance measurement to be associated with the different soil types present.

**Figure 8 Yield map showing variation in wheat yield over a 42 hectare field**



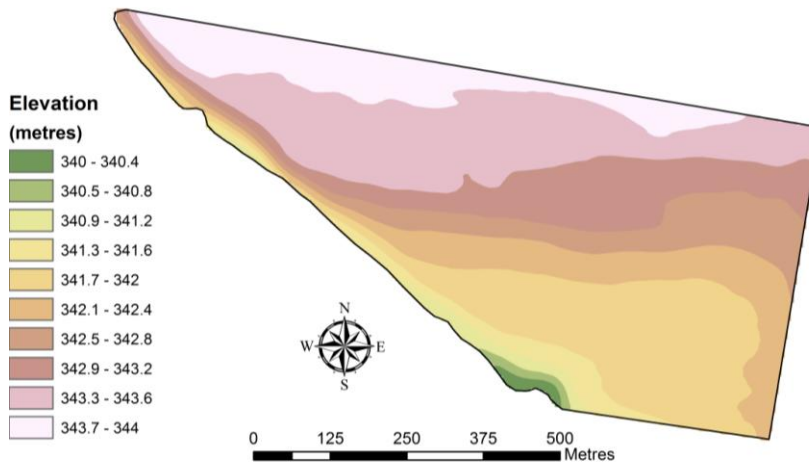
Data source: Whelan and Taylor (2010)

Figure 9 Soil conductivity map of 42 hectare field depicted in Figure 8



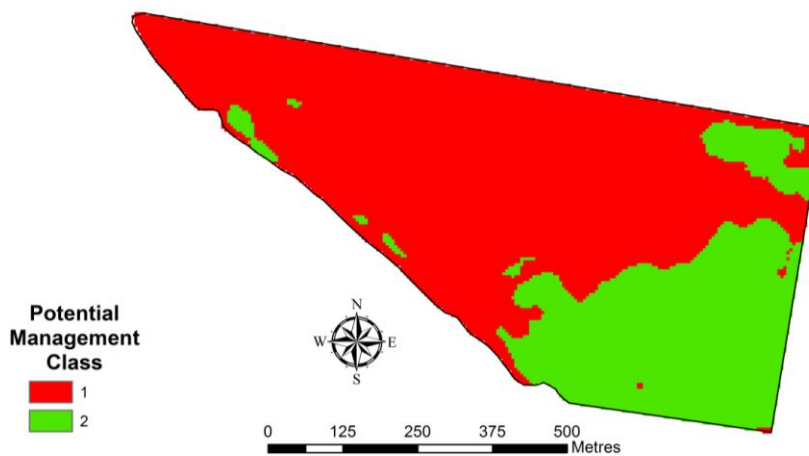
Data source: Whelan and Taylor (2010)

Figure 10 Elevation map of 42 hectare field depicted in Figure 8



Data source: Whelan and Taylor (2010)

Figure 11 Potential management classes for 42 hectare field depicted in Figure 8



Data source: Whelan and Taylor (2010)

Once management zones have been established, experimentation can begin with major inputs such as nitrogen and phosphorus to determine the yield response to different levels of these nutrients in the zones. Using this information it is possible to determine the optimal amounts of N to apply to the management classes by marginal cost analysis. This approach will maximise efficient use of nitrogen or other inputs. The total amount of nitrogen used across the paddock may increase or decrease depending on the relative size of each management zone. Nevertheless, use of nitrogen by crops will be maximised meaning the off-site effects of unused nitrogen will be minimised. Gathering data and relating it to maps, has many other uses. For example, farmers can measure yield and grain protein content during harvest to determine the amount of nutrient removed in the harvest and use this information to determine fertiliser requirements for the next crop. It can also guide harvesting over seasons so that high protein grain is separately harvested. Segregating on quality characteristics in this way can maximise returns from the paddock. Inputs can be applied in real time when on-the-go sensors are used.

Rather than applying all fertilisers at sowing, some farmers split the application of costly inputs such as nitrogen to manage the risks of poor rainfall or they apply nitrogen during optimal growth periods to maximise utilisation efficiency. Proximal sensors that measure reflected light of different wavelengths can be used to determine the amount of chlorophyll and biomass in the crop. Usually a calibration strip is required in the field where nitrogen was applied at rates that do not limit crop growth and yield. Once calibrated, nitrogen can be applied on-the-go at different rates depending on reflectance measurements. Map-based prescriptions can be superimposed over this on-the-go approach so that different maximum application rates are set for different management zones.

Weedseeker is another example of on-the-go variable rate technology that uses reflectance measurement technology. This is an automated spot spraying system where spray nozzles are activated when a green plant is detected. Weedseeker could be used for inter-row weed control, especially where the crop is a herbicide tolerant variety; genetically modified and traditionally bred herbicide tolerant crops could be used.

In situations such as the spraying of weeds in fallow, the use of this technology can result in reductions in herbicide application of up to 90 per cent, which has both financial and environmental sustainability benefits. The control of weeds in fallow conserves soil moisture which can be used by crops that are planted subsequently. Used in row crops like cotton and soybean, Weedseeker reduces herbicide costs by up to 50 per cent. In these situations shielded spray units are used to prevent injury to crop plants but unshielded units could be used with herbicide tolerant plants. Weedseeker technology can also be used for the application of insecticides or foliar fertilisers (application on plants rather than soil).

However, this technology cannot yet record georeferenced information about where in the paddock weeds are occurring. Weeds usually grow in patches in the same area from season to season and knowledge about their likely location would have benefits.

Other advances in spraying equipment include independent activation of sections, or of individual nozzles, of a boom spray in response to GPS and prescription map inputs. This technology has environmental benefits in terms of spray drift and run-off because it reduces agrochemical use, especially on areas without crop plants.

**Figure 12 Lentil crop sown between rows of the previous crop**

Photograph: Newag Consulting 2012

Inter-row sowing is the practice of sowing the new crop between the rows of stubble of the old crop (Figure 12). This practice has been facilitated by the use of high accuracy ( $\pm 2$  centimetres) autosteer GPS guidance. Inter-row cropping, when compared with slashed or burnt stubble, has been shown to increase yield and herbicide efficacy in some crops in South Australia. Sowing wheat between rows rather than in rows of a previous wheat crop gave yield advantages because of the lower incidence of wheat pathogens in the inter-row areas (McCallum 2007). Researchers made similar findings in New South Wales and South Australia where inter-row planting resulted in significant yield advantages (Daniel et al. 2007; Knight 2012).

Other benefits of stubble retention include less spray drift (Woolf 1999), reduced wind and water erosion, improved water infiltration and water storage in soils, reduced spread of disease and increases in soil organic carbon and earthworms. Disadvantages of stubble retention include interference with older machinery, disease carryover, reduced herbicide efficacy in some situations, nutrient immobilisation and yield loss (Scott et al. 2010). The benefits and drawbacks of stubble retention vary across Australian cropping zones and are not necessarily associated with standing stubble and inter-row sowing.

The costs associated with high accuracy GPS systems may be decreasing because of the introduction of continually operating reference stations (CORS). CORS can facilitate the use of high accuracy GPS systems because farmers do not need to, as individuals or local collectives, purchase their own base stations with a range of 20 to 30 kilometres. With a CORS network the correction signals needed for high accuracy are delivered through the internet on mobile phone networks. Surveyors and engineers have used these systems in urban areas for many years.

CORS networks in rural areas have expanded in recent years with all of regional Victoria covered by the Victorian Government's GPSnet. Other government and/or private systems have been deployed and deployment is planned in the other states.

## **Benefits of site-specific crop management**

The overall aim of variable rate technology is to maximise production and input use efficiency. The application of the technology in Australian broadacre cropping systems has provided significant financial and environmental benefits, mostly in better fertiliser and spray delivery.

The environmental benefits of precision agriculture and variable rate technology have been recognised in government funded programs. For example, the Reef Rescue program funds projects that improve farming practices to reduce the amount of soil, fertiliser and pesticide run-off into the inshore waters of the Great Barrier Reef. The program funds projects that help farmers move from old farming practices to best management practices that involve the use of GPS-guided controlled traffic practices and variable rate technologies.

## **Future directions**

Although variable rate technology is delivering benefits to some farmers, it is constrained by technical limitations in sensing capability and speed and delivery capability. Further developments in these areas over the next decade will offer significant sustainability benefits.

Rapid developments in sensing technology will lead to increased use of variable rate technology. Developments in on-the-go sensing are likely to change current practices significantly. On-the-go soil measurement of total nitrogen, organic carbon and moisture content using a visible and near infrared spectrophotometer has been demonstrated by Kuang and Mouazen (2011). Systems for rapid in-field soil nutrient testing are under development (Lobsey et al. 2010). Other soil sensing systems, such as electrical conductivity, are already used in the field for measuring soil texture and moisture content.

New sensing technologies are also being developed to detect plant diseases and pests. Systems that will be able to work on-the-go will most likely be based on advanced imaging techniques or will analyse particular parts of the light spectrum (Sankaran et al. 2010). Machine vision systems designed for identifying weed species are also being used to identify insects in agricultural situations (Solis-Sánchez et al. 2011). Systems that both identify and then spray insects have not yet been developed.

European researchers are developing machine vision systems that will recognise a suite of 20 or more weed species in real time and apply herbicide(s) from spray systems with the capacity to carry three or more herbicides. Cerberus is a camera controlled sprayer that reacts automatically to weed images taken by onboard cameras, selects the appropriate herbicide and application rate and then spot sprays while moving steadily across a field. Trials over 800 hectares in Europe showed that the Cerberus system can reduce in-crop herbicide requirement by 67 per cent in winter wheat, 39 per cent in malting barley and 52 per cent in sugar beet.

In this research area there is a trade-off between the accuracy and the speed of weed identification. Systems that can identify several weed species in particular crops work on-the-go, but sensing systems that identify a wide range of weeds in different cropping situations do not yet operate fast enough to allow on-the-go operation. For example, it may take an hour for the processing of digital images to allow discrimination of a wide range of weed species from the crop. While imaging and spraying can be achieved in a two-pass operation, this option may not be competitive with other weed control options. Advances in computing speed and image analysis may allow real-time detection and response systems in the future.

European researchers are working on smaller GPS-guided robots that can identify individual weed species and apply concentrated herbicide directly using ink jet technology (Midtby et al. 2011). Hassal (2010) reports that European researchers see a trend in the development of

autonomous equipment that allows finer scale crop management with smaller scale robots applying inputs and harvesting crops, and larger vehicles following tramlines to transfer chemicals and collect harvested crops. Slaughter and colleagues (2008) conclude that robotic weed control systems will be a reality when robust weed detection and identification systems are developed.

Automated or robotic weeding systems are physical hoeing systems. They rely on machine vision recognition of crop plants or high accuracy georeferencing of seed placement to guide machinery around individual crop plants. Accurate control of seed placement can also be used to create crop patterns that are amenable to physical weed control by machinery that can make perpendicular passes across the crop (Nørremark 2010; Piron et al. 2011).

Infection of plants with fungal pathogens causes biophysical and biochemical changes within plant tissues. These can be detected using a range of techniques such as thermography, fluorescence measurements and hyperspectral analysis. However, in terms of diagnosis of infection, these techniques suffer from co-measurement of changes that are not related to infection. For example, thermal images and fluorescence measurements vary according to water stress or other abiotic stresses. Despite this, progress is being made in both the remote and near-range detection of plant diseases and pests.

Mahlein and colleagues (2012) suggest that the future of precision crop protection will be sensor fusions. This incorporates information from more than one set of sensors into images where complex analytical techniques can be used to detect combinations that are diagnostic of disease infection. However, automated disease diagnosis is only the first step. Once identified, crop protection decisions have to be made and these will be determined in large part by the characteristics of the pathogen.

Chavez and colleagues (2012) showed that latent asymptomatic bacterial disease in potato can be detected by examining particular wavelengths of reflected light and applying analytical techniques to the reflectance data. The detection of asymptomatic plants will allow early detection of the disease and therefore an opportunity to limit its spread and impact on yield.

Research into variable rate technology methodology and machinery is extensive and will result in many products to fill diverse niches. However, it is likely that the technologies will increasingly rely on high accuracy georeferencing, which is currently restricted to high-end guidance systems. It is also likely that variable rate technology will become financially more attractive to farmers who currently do not use it, leading to wider adoption of high resolution GPS systems.

Precision agriculture, variable rate technology and associated whole-farm management software could have applications in managing and recording the carbon and nitrogen status of farmland. Soil carbon and standing biomass could be recorded through remote and proximal sensing systems with year-to-year variation in these attributes tracked by farm software. Such systems may help verify carbon accumulation or loss from individual farming systems (PARG 2009).

### **Adoption of precision agriculture technology**

While precision agriculture is bringing benefits to farmers through profitability and to the environment through the reduction or more efficient use of inputs, adoption of the technology is slow in some sectors, including cereal cropping.

The actual rate of adoption of precision agriculture systems is not easy to estimate. Robertson and colleagues (2012) state that adoption of precision agriculture in cereal cropping was about

four per cent in 2004. McCallum (2008) estimated that in South Australia 30 per cent of broadacre crops are planted and sprayed with GPS technology but less than 1 per cent of the crops are managed with variable rate technology. Other estimates vary across regions. GPS guidance is relatively common, with 70 per cent adoption in New South Wales, the Victorian Wimmera/Mallee and Western Australia.

Variable rate technology has been adopted by about 20 per cent to 30 per cent of farmers in the Wimmera/Mallee and Western Australia, but only five per cent in New South Wales cropping regions (Whelan, [University of Sydney], pers. comm.. 6 March, 2011). Robertson and colleagues (2012) surveyed farmers in all Australian cereal cropping areas and found the adoption rate of variable rate technology averaged 20 per cent but this varied between 35 per cent in the Victorian Mallee and 11 per cent in the Wimmera.

Edwards and colleagues (2012) surveyed farmers across Australia's 14 agro-ecological zones and reported similar trends for the use of GPS guidance and variable rate technology. They also reported an average 20 per cent adoption of controlled traffic farming across Australia. Bramley (2009) noted that take-up of precision agriculture in the sugarcane industry was low when compared with grain cropping and viticulture in Australia.

Hardware compatibility and technical complexity of both equipment and software are limiting the adoption of precision agriculture, and in particular variable rate technology. Most farmers are aware of variability in their fields and agree that variable rate technology could be beneficial for them but few have implemented the technology. This has been attributed to technical complexity and to the relative difficulty in acquiring professional advice specific to farmers' circumstances (Mandel et al. 2011; Robertson et al. 2012). Mandel and colleagues (2011) identified hardware compatibility as a constraint to adoption. Adoption of the ISOBUS (ISO117893) standard by manufacturers was meant to solve these problems.

According to Robertson and colleagues (2012) increased adoption of variable rate technology requires the development of:

- capacity within the grains industry to market, deploy and service precision agriculture equipment and provide services. This should include targeting of training and education of consultants, whose presence is a factor in early adoption
- rapid and cheap methods for diagnosis of the causes of yield variation, particularly those that account for seasonal effects
- simple approaches for on-farm trialling, including the interpretation of results.

Given the wide awareness of precision agriculture and variable rate technology, the provision of more general information about it is unlikely to be effective in increasing adoption rates.

## Policy implications

State governments and the private sector have created or are creating CORS networks to service the agriculture sector, as well as several other sectors that use high accuracy georeferencing. Existing mobile phone networks are used by machinery to accurately determine its position.

With developments in modern machinery and sensing systems, modern farming operations will generate large amounts of data. This will create a need for mechanisms to transfer this data from the farm to service providers who can extract relevant information from the data and return their recommendations to farmers more quickly than is currently possible. Improvements in

internet speed and capacity will enable rapid transfer of information between farmers and remote advisors. These improvements may result in greater adoption of precision agriculture and variable rate technology in the cropping sector by addressing the three priorities for variable rate technology identified by Robertson and colleagues (2012). Such improvements could also facilitate adoption of precision agriculture in other areas such as livestock production and farm-scale carbon accounting. Better internet capability could improve machinery servicing through data and audiovisual connections to manufacturers and service centres. It could also support farm safety through vehicular rollover sensors that can alert others to accidents.

The National Broadband Network is a key technology for a demonstration project developed by the University of New England and the CSIRO. These organisations are demonstrating the concept of sustainable, manageable and accessible rural technologies (SMART) farming at the University of New England farm in Armidale, New South Wales. The university (PARG 2012) believes that SMART farming:

will increase crop and pasture yields through better targeting of water and/or fertiliser inputs and increase livestock production through improved animal management and increased pasture utilisation. SMART farming also offers the means to achieve improved environmental outcomes through highly efficient use of resources; spatially enabled technologies can reduce the water and carbon footprint of farming.

Precision agriculture could significantly improve productivity, input-use efficiencies and sustainability across diverse farming systems. Controlled traffic farming, autosteer guidance and variable rate technology are already providing financial benefits to farmers. The public also benefit through more efficient use of inputs on farms. Further developments in information technology and precision agriculture could add to the benefits already evident, especially in the non-grain sectors.

## Key points

Examples of enabling information technologies, such as precision agriculture and crop modelling, will continue to offer significant benefits in the profitability and sustainability of Australian cropping, horticulture and livestock production systems. In the cropping sector these technologies will have two effects. Firstly, crop production will use inputs such as fuel, fertilisers and agrochemicals more efficiently, resulting in greater sustainability of farming systems. Secondly, farmer yield may be improved by better and timelier management of factors that reduce potential yield, such as soil constraints, weeds, pests and diseases.

## 5 Conclusion

Greater food production and long-term improvements in sustainability are possible through investment in agricultural research and development. However, the lag between the purchase of research and delivery and adoption of a product by farmers is, by some estimates, 25 years. This poses important questions for policymakers:

- What will our food production needs be in 25 years?
- What increases in production and sustainability are required?
- How much do we need to spend now to achieve greater food production and environmental sustainability?
- What is the role of government?

The technologies discussed in this report have real and potential benefits for increasing food production and the sustainability of farming systems. This report gives examples of relevant outcomes from biotechnology, nanotechnology and information and communications technologies. Of the technologies discussed, information technology and biotechnology are likely to have positive effects in the near future while benefits from the applications of nanotechnology in agriculture are more distant.

With respect to biotechnology, genetic modification technologies have played a positive role in increasing farmer yield around the world, particularly in less developed countries. For example, in developed nations genetically modified cotton, which brings significant reductions in pesticide application, has made cotton farming more sustainable. Such genetically modified crops contain relatively simple modifications; a single herbicide tolerance gene or perhaps two related insecticidal genes. The modifications work by producing one or several new proteins within the plant that have a direct affect, such as killing insects or working in the presence of a herbicide.

Quantitative traits (such as water use efficiency and frost tolerance) that are under the control of many genes are much harder to introduce into plants by genetic modification. This is because the genes responsible have not yet been identified, the ways in which the genes and their products operate in the plants are not yet known, and the number of genes involved in the trait may be so large that transfer of all genes to a new species may be beyond the current technical limits of genetic modification. It is likely that marker assisted breeding (facilitated by quantitative trait loci analysis) will be used to improve complex traits in our crops species for the foreseeable future. However, genetic modification will have a role in improving relatively simple traits in crops. Genetic modification could be used in the near future to introduce resistance to some diseases or pests, herbicide resistance and tolerance of some abiotic factors.

Other areas of science also offer significant potential benefits for increasing food production and sustainability of farming systems. Agronomy (the science and technology of growing plants) and extension services are important areas. Better understanding of the biological constraints to production (cryptic root pests and diseases) along with improvements in the way fertilisers are designed and delivered are two research areas that could provide significant increases in production and more efficient use of resources.

It will be a challenge to integrate new developments from many fields into Australian farming systems. This challenge will fall to farmers and agricultural extension services. However, policymakers must act now to consider the nature and needs of Australian farming in 25 years.

Other sectors of importance to the Australian and global food supply (such as livestock and horticulture) may see productivity and sustainability benefits from the applications of the technologies discussed in this report.

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