
# Decadal Plan for Australian Agricultural Sciences 2017-26

## Final Consultation Draft

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Prepared by the Australian Academy of Science National Committee for Agriculture, Fisheries and Food

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# Executive summary

Agriculture has played a central role in the history of humankind. It is the fundamental catalyst that allowed the development of civilisations and through productivity gains has made possible all other areas of human endeavour, including the sciences. Agriculture's importance to civilisation will continue into the future, yet its success has allowed it to play a largely unnoticed part in modern, urban life. To the casual observer much of agriculture may appear unchanging. Seen from a passing car, crops and grazing livestock seem almost timeless. Yet in reality agriculture is a highly dynamic industry regularly adopting recent innovations.

The Australian agricultural sector has a keystone position in the structure and functioning of the country as a whole. Producers have stewardship of more than 60% of Australia's land mass, and the industry directly employs more than 307,000 workers—the biggest employer in rural and regional Australia. About 1.6 million Australians are employed in the complete agricultural supply chain including food manufacturing and processing, distribution and retail. Agriculture supports population decentralisation, provides the 'life-blood' and social fabric of inland Australian settlement, and the industry acts as a source of skilled labour for mining and other industries.

The core purpose of this Decadal Plan for Agricultural Sciences is to identify and define responses that will position Australia to take advantage of the likely major scientific and technological advances occurring over the coming decade. It aims to:

- provide strategic direction to Australia's future investment in agricultural science by identifying relative strengths and shortfalls in scientific capacity that needs to be developed or maintained to ensure Australia is strong, prosperous, healthy and food secure
- enhance the value of Australia's research investment to ensure future economic prosperity and wellbeing by providing a strategic framework with which researchers can align and coordinate their efforts to leverage greater impacts
- identify workforce needs and strategies that enhance career pathways for graduate and postgraduate scientists from all fields that contribute to the agricultural sciences.

Chapters 1 and 2 outline how fundamental science and agricultural research will contribute to Australia's successful agricultural future. Chapter 1 discusses the fundamental framework of drivers influencing agriculture. Chapter 2 identifies specific research areas that present strong opportunities in the medium to long term and opportunities to coordinate those.

Chapter 3 shows that, to realise the future that Australia is capable of, we need to enable our researchers to achieve those solutions through education, career development, and retention of top-class researchers. Chapter 4 argues how it is essential to coordinate Australian research to prioritise and stabilise its funding so that it is commensurate with the nature of the challenges that face agriculture into the future.

Finally, Chapter 5 recommends solutions for the challenges identified in previous chapters to consolidate Australia's role in the future of agricultural sciences.

All parts of the sector share the responsibility for ensuring that Australia's agricultural future is as bright as it can be: to achieve national priorities, to clarify and implement efficient funding arrangements, to manage research over the scales and timeframes that are commensurate with the challenges, and to nurture and safeguard our agricultural research capacity.

## Findings and recommendations

The National Committee for Agriculture, Fisheries and Food (NCAFF), which is responsible for this plan, is widely representative of its disciplines and is supported by the Australian Academy of Science recommends that:

1. The Australian Government creates a National Agricultural Research and Innovation Council, or an equivalent body with similar functions, to provide a central point of coordination for agricultural research and its applications. Its functions should be to:
    a. coordinate the priority-setting exercises of all publicly funded research organisations and funding agencies and to strongly urge public research organisations towards simplified and transparent funding interactions between them
    b. directly manage a modest but influential collaboration incentives program with the intention of filling strategic research gaps and forming teams around nationally important challenges or unexpected shocks that unite the most suitable experts regardless of their location, and over timeframes that are commensurate with the research challenges
    c. conduct rolling identification of national agricultural research priorities (reporting triennially) and assessment and forecasting of Australia's research capacity requirements (offset reporting at a similar frequency), including both human and infrastructural capabilities
    d. coordinate Australia's involvement in international research programs, to align programs where appropriate, and to address any fragmentation of international engagement effort that may be found.

2. The Australian Government establishes a National Agricultural Research Translation and Commercialisation Fund, to address gaps in the national research priorities and to strengthen the parts of the innovation system at which agricultural innovations fail to translate into commercial products. The fund should be managed according to the following principles:

a. The fund must be governed by a priority-setting cycle that keeps pace with the rate of change in the sector, but that provides the stability necessary to undertake large-scale endeavours. Triennial reporting from the National Agricultural Research and Innovation Council would provide a suitable information base for such priority-setting over the medium to long term.
b. The fund should address the most pressing gaps in the innovation system that present barriers to uptake at the time. It will not diminish the essential existing roles of current research agencies or reduce the need for them, but rather reinforce them all by strengthening the system in which they all operate.
c. Stable funding arrangements must be aligned with the long-term, complex nature of research translation, commercialisation and uptake.

3. The academic, industry and government sectors partner to create a doctoral training and early career support centre for the agricultural sciences. Its functions should be to:
   a. administer a substantial and targeted PhD top-up scholarships program that can compete with other options available to professional agricultural scientists. This would partially reduce the current financial barrier that prevents professionals from returning to study or bringing on-farm experience back to the research sector
   b. run an agricultural enterprise engagement program to provide graduate students with ongoing exposure to the working farm systems that are relevant to their research, and to encourage research towards the challenges that the National Agricultural Research and Innovation Council identifies as being on the horizon.
   c. manage an early- and mid-career support network to maintain connections between PhD cohorts and provide opportunities for early- and mid-career researchers to connect with mentors, each other, and a wider range of agricultural systems than would otherwise be possible.

4. The agricultural research community engages strongly with infrastructure planning processes at all levels to enable agricultural research to benefit from, and contribute to, shared national capabilities, including emerging data-infrastructure and maintaining the pool of skilled technicians that unlock value from national infrastructure capability.

5. All organisations in the agricultural sector need to do more to understand and engage more effectively with the public on social acceptance of agricultural science and the enterprises it supports. This also applies to understanding that agriculture reaches far beyond the farm gate.

# 1 Introduction

*Agriculture has played a central role in the history of humankind. It is the fundamental catalyst that allowed the development of civilisations and through productivity gains has made possible all other areas of human endeavour, including the sciences. Agriculture's importance to civilisation will continue into the future, yet its success has allowed it to play a major but largely unnoticed part of modern, urban life.*

*Agriculture is vitally important to Australia's economy and social fabric, and contributes to global health and wellbeing. It faces a range of challenges across biophysical, economic and social arenas. Opportunities for technological and production improvements are continuously being identified from scientific research. However, to attain step change improvements into the future will require integrated multidisciplinary research underpinned by a well-resourced science research pipeline. Vital to any assessment of future needs and capacity in agriculture is an understanding that agriculture sits within a web of interacting and overlapping science and technology linkages.*

## 1.1 Scope and focus

Agricultural research is not a core scientific discipline in its own right. Rather it is the confluence of many different scientific disciplines and endeavours, from which it holistically integrates and applies a range of developments to achieve improvements in profitability, productivity and sustainability. Primarily, agricultural science is an integrator of advances in enabling scientific disciplines in which research may have been carried out without an explicit end-point application. Traditionally, this has involved taking advances in sub-components of the basic disciplines of botany, zoology and soil science including *inter alia* genetics, chemistry, biochemistry, plant physiology, microbiology, soil nutrition and statistics. More recently the range of contributing disciplines and associated sub-components has broadened rapidly—partly on the back of the substantial advances flowing from molecular biology, but also from technologies associated with engineering, robotics, automation, weather forecasting, informatics and 'big data' manipulation together with a vision of agriculture as a source of renewable feed stocks replacing fossil-fuel derived components in industry (Fig. 1.1). Understanding the position of agriculture is vital to any long-term assessment of its future needs and capacity requirements.

In setting the boundaries for this plan we have deliberately chosen to narrow our focus to terrestrial systems and, within these, narrow the inclusion of forestry to farm forestry activities including its contribution to sustainability and integrated farm management. Standard production forestry, aquaculture and fisheries are excluded—not as any reflection on these important areas of production or the industries they support, but rather to avoid reducing such an expansive canvas to

broad generalisations, and thereby diluting the strength of any recommendations. Furthermore, the marine sciences are the subject of a recently released national plan[1]. Similarly, we do not cover the entire business chain from 'paddock to plate'[2]; rather as a boundary we have loosely used the separation provided by pre- and post-farm gate, concentrating on the former. Notwithstanding this, we recognise and include research areas and targets that may be driven by interests further down the supply chain where legitimate responses can be achieved through on-farm application of science. Thus, for example, changes in the nutritional content of grain (e.g. reduced anti-nutritional factors and enhanced bio-fortification) are considered. On the other hand, issues associated with transport logistics (a major export cost) are not.

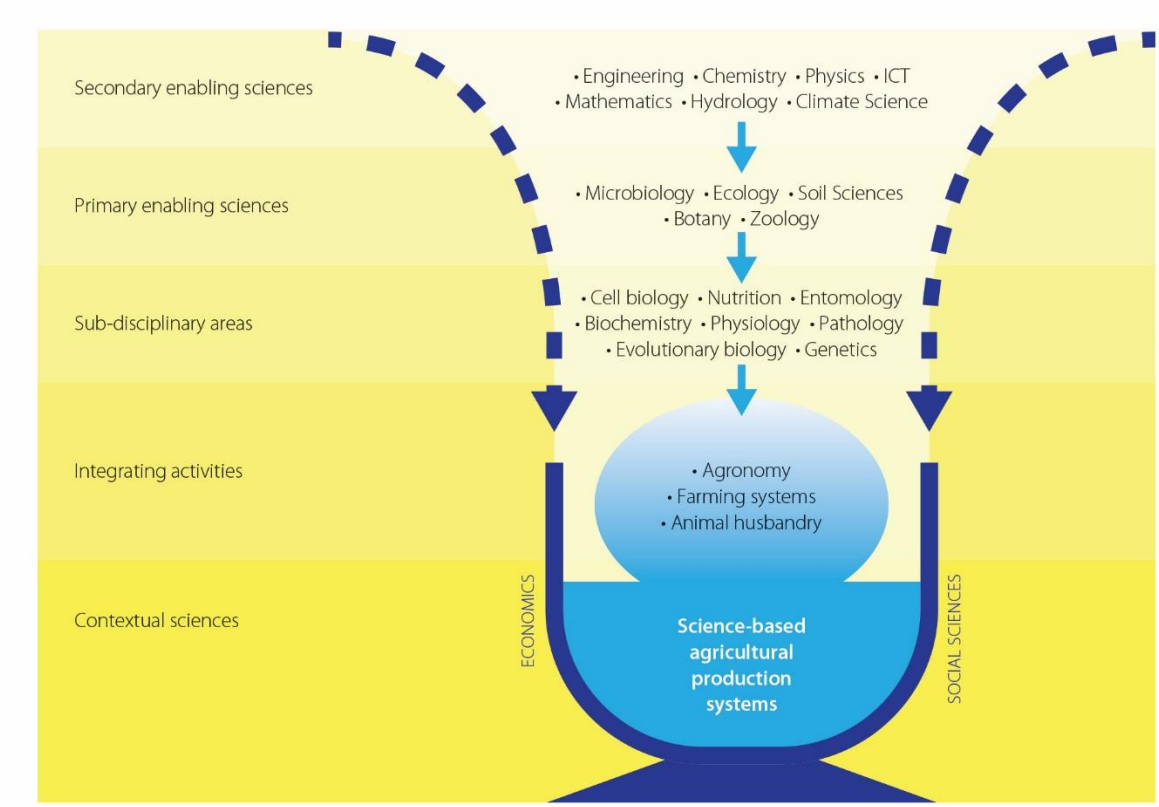


Figure 1.1: Discipline and sub-discipline inputs into the integrating crucible of agricultural sciences.

Quality Research, Development & Extension (RD&E) that responds to immediate problems or leads to constant small but important incremental gains will always be

[1] The Academy recently endorsed the National Marine Science Plan 2015–2025: Driving the development of Australia's blue economy, developed by the Australian Institute for Marine Science.
[2] Food and Fibre: Australia's Opportunities (2014). Report of a study by the Australian Academy of Technological Sciences and Engineering (ATSE).

needed. However to access step changes in productivity and profitability it is essential to identify innovations, new technologies and approaches that will come from melding biological disciplines that have traditionally underpinned agriculture with different approaches from other areas including biotechnology, ICT, mathematics, chemistry, physics and engineering. The core purpose of this Decadal Plan is to identify and define responses that will position Australia to take advantage of the likely major scientific and technological advances occurring over the coming decade. This involves establishing routes whereby 'high-promise niche' technologies can be transformed into general-purpose technologies with clear sight of opportunities in agricultural industries; ensuring infrastructure needs are identified and met; and ensuring the best talent of the current generation can be attracted to agriculture as a worthwhile, exciting and profitable career path. The plan is cognisant of trends in the agriculture enterprise, changes in land use, extensive versus intensive production, emerging technologies versus labour, irrigated versus dryland systems and the means to ensure that decisions are integrated and shared between the Australian Government and state governments, the research community and the various faces of the private sector.

## 1.2 Aims

The aims of the Decadal Plan for Agricultural Sciences are to:

- provide strategic direction to Australia's future investment in agricultural science by identifying relative strengths and shortfalls in scientific capacity that needs to be developed or maintained to ensure Australia is strong, prosperous, healthy and food secure
- enhance the value of Australia's research investment to ensure future economic prosperity and wellbeing by providing a strategic framework with which researchers can align and coordinate their efforts to leverage greater impacts
- identify workforce needs and strategies that enhance career pathways for graduate and postgraduate scientists from all fields that contribute to the agricultural sciences.

## 1.3 The decadal plan in the context of recent reports

Over the last decade or so several government white papers[3,4], reports and position statements from learned societies[5,6], advisory bodies[7,8] and industry-based economic assessments[9] have considered aspects of the current and future challenges facing Australian agriculture at various points along the production and marketing supply chain. Collectively, these reports have stressed the international competitiveness of agriculture and the major, but transitory, opportunities for Australia that are possible, provided productivity momentum in Australian agricultural industries is restored. They broadly recognise that for Australian agriculture to have a vibrant and exciting future a range of issues along the entire business/supply chain must be addressed. Post-farm gate, these include aspects of transport infrastructure and port terminal congestion; pre-farm gate, issues include aspects of productivity, technology uptake, availability of high-speed internet connections, social issues associated with ageing and competing employment prospects, and general societal expectations regarding environmental stewardship. Together these reports underline the importance of developing connected and mutually reinforcing areas of high capability to ensure the best possible outcomes. This document contributes to the wider conversation around Australian agriculture by focusing strongly on the research that underpins our future agricultural success, and the scientists that will deliver it.

## 1.4 Structure of the decadal plan

The Decadal Plan for Agricultural Sciences is divided into five components. Chapter 1 provides an overview of the R&D industry that contributes to agricultural research, the current and future challenges facing agriculture, the necessity of ensuring research is applied on farm and how science investment is linked to fundamental economic drivers. In Chapter 2 we identify the primary areas that researchers across

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[3] Commonwealth of Australia 2015. *Agricultural Competitiveness White Paper*, Canberra.

[4] Commonwealth of Australia 2015. *Our North, Our Future: White Paper on Developing Northern Australia,* Canberra.

[5] Australian Academy of Technological Sciences and Engineering 2014. *Food and Fibre: Australia's Opportunities*, ATSE, Melbourne.

[6] Daly, J, Anderson, K, Ankeny, R, Harch, B, Hastings, A, Rolfe, J and Waterhouse, R, 2015. *Australia's agricultural future. Report for the* Australian Council of Learned Academies, www.acola.org.au.

[7] Rural Research and Development Council 2011. *National Strategic Rural Research and Development Investment Plan*, Department of Agriculture, Fisheries and Forestry, Canberra

[8] PMSEIC 2010. *Australia and food security in a changing world*. Prime Minister's Science Engineering and Innovation Council, Canberra.

[9] ANZ Insight 2012. *Greener pastures: the global soft commodity opportunity for Australia and New Zealand*. Issue 3, October 2012.

Australia agreed were the most likely to contribute significant step changes in productivity, profitability and sustainability in the next decade. These cover specific basic research areas as well as a number of outcome or implementation foci. Chapter 3 assesses the current and future state of university training programs and their ability to develop researchers and other workers to ensure the vitality of agricultural research into the future. In Chapter 4 we discuss funding opportunities for the future of Australian agriculture. Finally, Chapter 5 recommends solutions for the challenges identified in previous chapters to consolidate Australia's role in the future of agricultural sciences.

## 1.5 The context of Australian agriculture

### 1.5.1 The current place of Australian agriculture

In Australia the agricultural sector has a keystone position in the structure and functioning of the country as a whole. Producers have stewardship of more than 60% of Australia's land mass; the industry directly employs more than 307,000 workers and is the biggest employer in rural and regional Australia. About 1.6 million Australians are employed in the complete agricultural supply chain including food manufacturing and processing, distribution and retail. Agriculture supports population decentralisation, provides the 'life-blood' of settlement of inland Australia and the industry acts as a source of skilled labour (e.g. heavy machinery operators) for mining and other industries. Furthermore, while agriculture no longer has the dominant position as a generator of GDP that it did in the first half of the 20th century, direct farm-gate production still constitutes 2.3% of GDP[10], while post farm-gate this production is a major component of support for the food and beverage sector. Agricultural exports in 2012-13 accounted for 15.5% of Australian merchandise exports[11].

### 1.5.2 Australian agriculture as an innovative industry

To the casual observer much of agriculture may appear unchanging. Seen from a passing car, crops and grazing livestock seem almost timeless. Yet in reality agriculture is a highly dynamic industry regularly adopting recent innovations. Over the last hundred years the proportion of the global population directly involved in farming activities has fallen dramatically while those being fed has risen from about 1.5 billion in 1915 to more than 7 billion today. The extent to which the size of the

[10] National Farmer's Federation. Farm-Facts. www.nff.org.au/farm-facts.html [Retrieved on 23rd June 2016].
[11] Australian Government Department of Foreign Affairs and Trade. Trade and investment topics. www.dfat.gov.au/trade/topics/pages/agriculture.aspx [Retrieved on 23rd June 2016].

agricultural workforce has changed is strongly linked to economic development: more than two-thirds of the population in many less industrialised countries are still directly engaged in agriculture while less than 5% of the population is involved in agriculture in highly developed countries[12]. High productivity increase is the primary driver for these differences.

Australian agriculture has embraced this trend of continued adoption of innovation. In recent times management systems have changed radically in:

- the shift from ploughing to conservation agriculture
- the types of crops and animals produced
- the use of genetics and the associated dramatic shift in marker assisted selection, whole genome breeding, and GM traits which have variously resulted in major gains in quality, yield and protection from pests and diseases
- the use of automation in many areas of harvesting and production.

However, productivity growth in Australian agriculture has slowed in recent times[13] and over the past 50 years has been less than many of the countries we compete with in global markets (Figure 1.2).

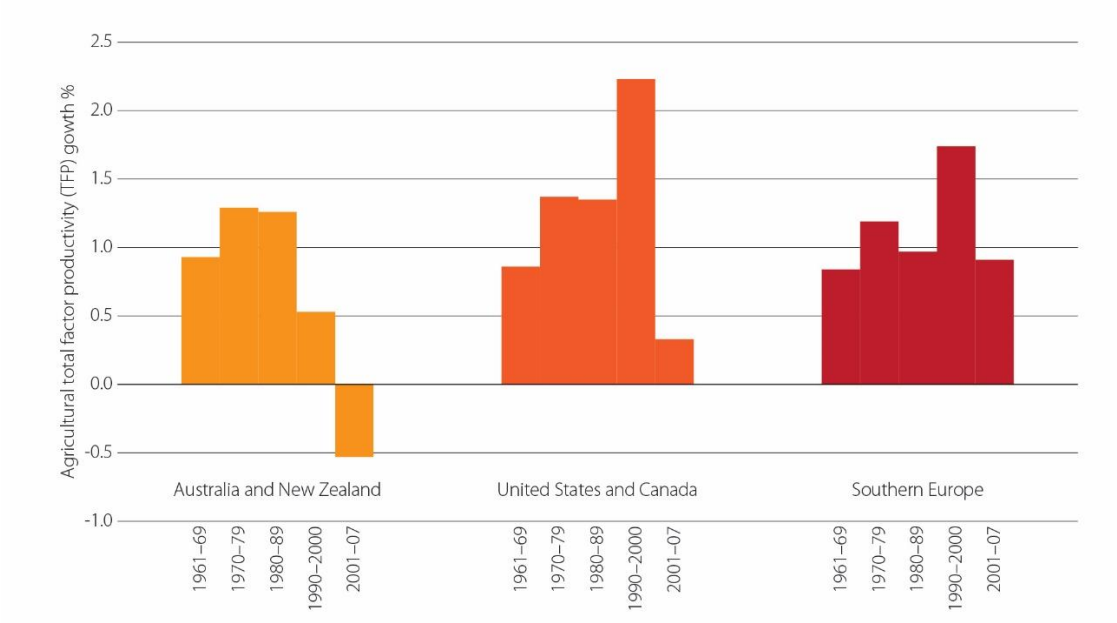


Figure 1.2: Agricultural productivity growth for three selected regions over the decades.[14]

[12] Roser, M 2015. Agricultural Employment. Published online at OurWorldinData.org. Retrieved on 1st November 2015 from: http://ourworldindata.org/data/food-agriculture/agricultral-employment

[13] http://data.gov.au/data/warehouse/9aap/2014/apgpfd9abp20140220/AgProdGrthPstRfmFtrOppsv1.0.0.pdf

[14] Alston, J. Babcock, B. Pardey P, The Shifting Patterns of Agricultural Production and Productivity Worldwide (2010). CARD Books, Book 2, Data from Table 4.7

The appetite of producers for innovation varies from industry-leading rapid adopters who are repeatedly testing the value of recent ideas through groups who show considerable enthusiasm once they are provided with practical local evidence of benefit, to those who for a variety of reasons are less inclined to change existing practices. Overall though, producers rapidly make complex risk/reward assessments to inform significant financial decisions on the basis of the productivity, profitability and/or sustainability gains that new approaches will deliver. Producers themselves are amongst the biggest innovators especially when it comes to farming practices and the design of equipment that address particularly pressing problems. A good example of this is seen in the Harrington Seed Destructor designed to reduce weed seed load[15].

For scientists it is vital to understand the producer's perspective, especially the complex decision matrices they face. It is in this context that the current Decadal Plan for Agricultural Sciences is set. In essence, the process of integrating research breakthroughs into an overall farming context, via enabling systems approaches, is vital.

## 1.6 Australian agriculture into the future

The challenges and opportunities facing agriculture in Australia range widely from physical and biological to economic and social and their effects are very real. They either limit the ability of agriculture to respond to new market opportunities, or provide expanded opportunities for greater volume, changed quality or novel products. It is essential that both challenges and opportunities receive consideration in determining how science can benefit Australian agriculture in the future. This is summarised in the following sections.

### 1.6.1 Global population growth leading to increased demand

The world's population continues to expand and is predicted to increase by more than 40% to surpass 9.5 billion people by 2050. Associated with the consequent increased demand for food, there will be a disproportionate increase in demand for protein in line with burgeoning numbers in the middle classes of many of the most populous countries such as China, India and Indonesia. Filling this protein demand through increased animal production places a disproportionate demand on agricultural production. It has been calculated that to meet this requirement, cereal

[15] Walsh, MJ, Harrington, RB and Powles, SB 2012. Harrington Seed Destructor: A new non-chemical weed control tool for global grain crops. *Crop Science* 52: 1343-1347.

production world-wide will need to increase by 50% by 2050 with almost half this increase being used to feed livestock[16].

### 1.6.2 Market globalisation

Agriculture is increasingly a global business. For commodity crops the balance of supply and demand is driven by events occurring across the globe such that prices obtained by Australian farmers are driven less by the size of the local crop and more by production levels in other major exporting countries. For example, prices realised for wheat by growers in Australia are highly dependent on production conditions in North America, the European Union and Ukraine. Furthermore, changing patterns in rainfall, heat and cold stress around the globe as a consequence of climate change all have the potential to affect cereal production either positively or negatively against a backdrop of stimulated crop growth resulting from increasing concentrations of $CO_2$. The extent to which these effects differentially translate into changes in the relative efficiency of production by Australian growers and our international competitors has the potential to affect the economic viability of some Australian production systems.

Increasing the productivity of agriculture in the face of its many challenges is a non-negotiable necessity, and while Australia will never be the 'food bowl' for Asia, considerable opportunities exist for increasing volume and quality. However, Australian producers can expect to experience continuing and intensifying competition in global commodity markets for many of our major farm products: beef, dairy, lamb, cereals, oilseeds, cotton, sugar, horticulture and wine.

### 1.6.3 Product differentiation

Increasing concerns about the cost of an ageing population and the obesity epidemic, together with a broader consumer awareness of the effects of poor diets on individual health outcomes, are driving a strong focus on the quality of human nutrition at both consumer and public policy levels. Food is an important factor which affects individuals through their choices, and populations through public policies regarding access and pricing. Some food crops can be enriched to contain higher nutritional or medicinal content that can command a price premium when people are aware of the benefits. Examples include various grain crops which can directly affect health through reductions in obesity, heart disease, colo-rectal cancer and micro-nutrient deficiencies and can be marketed or mandated as such, which increases their value. However, this type of impact is likely to be highly variable

[16] Hubert, B, Rosegrant, M, van Boekel, MAJS, and Ortiz, R, 2010. The future of food: Scenarios for 2050. *Crop Science* 50: S- 33-50.

across industries. In many commodity crops, maintaining (and slowly improving) quality is essentially a defence against discount penalties although some market sub-division (e.g. wheats with specific noodle-making qualities) can generate premiums. However, in other plant and animal products, quality traits can generate significant benefits (e.g. premiums and discounts for wool quality attributes such as fibre diameter, staple length and staple strength). In other circumstances it is possible that quality changes can drive new sub-divisions in production—as is likely to occur when omega-3 canola is brought to market.

Product differentiation can also be based on traceability and product provenance. The knowledge that agricultural products come from production systems that are 'clean and green', meet minimum residue limits, are free from other biotic or abiotic contamination, are environmentally sustainable, have been produced in ethical and humane ways and have clear mechanisms documenting food-chain integrity en-route from producer to consumer are all criteria whereby competition and price-point differences may occur. Achieving these outcomes raises a number of challenges in different production systems—for example, removal of antibiotics from some animal production systems, fungicides and pesticides in horticultural and wine industries or a switch from caged to free-range egg production systems may have spill over consequences within the same or to other agricultural sectors.

### 1.6.4 Social and consumer challenges

***Social issues*** – Australia has a highly urbanised population (~89% in 2011; with ~82% living within 50kms of the coast in 2011[17]) that has little understanding of farming or the issues involved in the production of reasonably priced, safe food. Rising consumer and government scrutiny of produce in domestic and international markets with respect to food safety, pesticide-free production, ethical animal treatment and processing practices, as well as emerging biosecurity and environmental protection priorities, are increasingly imposing a range of societal expectations that must be met. Negative consumer responses to GM technologies, for example, and the consequent reaction by many food manufacturers and retailers, provides a strong salutatory message regarding the importance of consumer education and engagement.

***Workforce issues*** – Agriculture is increasingly embracing high levels of technology that require a significant expansion of skills and expertise in both its on-ground practitioners and its research workforce. Combined with Australia's ageing workforce and until recently a relative lack of appeal of agriculture to the young as a

[17] Hugo G, Feist H, Tan G, Australian Population and Migration Research Centre (2013), Population change in regional Australia 2006-11. Vol. 1, No. 3.

career path, this suggests a future that will be increasingly reliant on a flexible workforce (for example transitioning of mid-career scientists in and out of agricultural research) and adoption of increasingly sophisticated automation processes and mechanisation. This in turn means that appropriate training and education is a very high priority for the future.

### 1.6.5 Physical environmental challenges

A wide range of challenges to the physical environment, and the role of agriculture within it, are predicted to increase dramatically over the decades to come. Universally applicable challenges include:

***Global climate change*** – The associated and combined effects of climate change require urgent and considered attention. In particular:

1. rising temperatures
2. changing rainfall patterns
3. uncertainty about our future climate patterns
4. increasing carbon dioxide concentrations.

For agriculture, the diverse consequences may include shorter growing seasons with more abrupt finishes, increased heat stress, abnormal frost events and a permanent reduction in water available for irrigation associated with both animal and plant production. In many animal production systems the impact of climate change will be felt through changes to the productivity of rangelands and other grazing systems. Together these changes pose significant challenges for the productivity and reliability of existing production systems and in a broader context, to the size, distribution and commodity mix of future production areas. It is highly likely that some production systems will cease to be viable in some regions. There is also a pressing need to identify change scenarios and plan accordingly so Australia can maintain an efficient agricultural system that can predict and adapt to changes in real time—not maintaining production in the face of climate change is simply not an option in a world with a growing population.

***Greenhouse gas emissions*** – Agriculture is a major source of anthropogenic greenhouse gas emissions. Even without the impact of land clearing, agricultural production accounts for just under a quarter of global emissions [Smith et al. 2014]. Manufacturing nitrogenous fertilisers via the Haber-Bosch process alone accounts for approximately 2% of global emissions. As the world increasingly recognises and embraces the need to control and reduce emissions it is inevitable that agricultural businesses and practices will come under greater pressure to improve performance, for example by decreasing emissions intensity through greater efficiency.

***Competing resource use demands*** – alienation of land for alternative uses is affecting all agricultural sectors including horticulture (urbanisation), and cropping and grazing (mining and conservation). Similarly, competing alternative demands for environmental resources and ecosystem services such as water and biodiversity lead to direct reallocation of such resources to non-agricultural uses, novel pricing structures that substantially alter the economics of production, or to changes aimed at accommodation of ecosystem benefits and agricultural production through better integration of land use. In a drying environment in particular, where the absolute availability of water may well decline, competition for its use will continue to intensify.

### 1.6.6 Biotic threats

Increasing globalisation is not just an issue concerning market competition; rather the greater mobility of people around the world and significant increases in the volume of trade constantly challenge Australian agriculture's clean, green credentials. Effective and efficient biosecurity measures that identify and manage risks before they occur require great vigilance—many agricultural industries are only a single disease away from catastrophe (for example, an outbreak of foot and mouth disease would severely affect Australian meat and livestock producers[18]). At the same time, quarantine regulations face competing pressures: strict conditions designed to prevent entry of unwanted pests and diseases can also affect business efficiency and slow scientific advances by lengthening the time taken to introduce novel germplasm for breeding programs and research (although the application of appropriate precautionary principles is to be applauded).

### 1.6.7 Technological opportunities

Some technology changes, such as robotics and automation, are directly applicable to farming operations changing the efficiency and productivity of animal and plant production systems. Others, while not directly applicable to farming systems, create new capabilities that provide novel opportunities for changes in the way agricultural operations are executed. Wi-Fi and broadband technology have already transformed some farming operations; greater spatial data coverage and reliability is a critical feature underpinning the continued expansion of many aspects of precision technology and the on-farm use of extensive, integrated datasets. The extremely rapid changes currently occurring in the efficiency of renewable energy generation—particularly photovoltaics—and even more importantly energy storage

[18] Buetre, B et al. 2013, Potential socio-economic impacts of an outbreak of foot-and mouth-disease in Australia, ABARES research report, Canberra

technologies, are rapidly building the possibility that many agricultural enterprises will be energy self-sufficient. The ramifications of low-cost energy on demand (apart from initial capital costs) have yet to be fully explored but, for example, horticultural systems could experience major changes in the extent of environment-controlled production systems.

## 1.7 Ensuring delivery and uptake

### 1.7.1 Balance between leading scientific research and adoption

Much of the rationale for agricultural science is to integrate knowledge and developments from across a wide range of contributing disciplines in such a way as to increase the productivity and sustainability of farming systems. To do this requires a focus on impact and delivery beyond that typically seen in more academic disciplines. Agricultural scientists generally recognise this imperative even if the research they are conducting is fundamental. Furthermore, the need for practical application imposes a series of selective hurdles for adoption. Adoption will only occur if the resultant change leads to greater economic return, efficiency or sustainability, and has a much better chance of occurring if the end user is consulted and engaged along the R&D process.

Despite the necessary focus on adoption, it is also imperative to recognise the importance of fundamental science as the source of new insights that ultimately find their way into applied systems. Research that aims to deepen our understanding of the way plants, animals or Earth function (e.g. modification to rumen microbiology to reduce $CH_4$ emissions; $C_3$ to $C_4$ photosynthesis systems) is inherently risky and may ultimately find applications only after multiple setbacks. Research setbacks are disappointing, but it is on the back of 'failures' and the knowledge they impart that major breakthroughs are often eventually achieved.

### 1.7.2 The effect of regulatory requirements and a social licence to operate

Agriculture is an increasingly high-tech business. Satellite technologies and GPS underpin precision agriculture. GM technologies and genomic approaches have spread widely through plant and animal breeding. Near infra-red scanning is used to measure grain quality. Rapid advances in milking technologies have revolutionised dairy production. These innovations are just the forerunners of a wave of technological changes that are recasting almost all agricultural practices. Many of these changes (for example, the use of antibiotics and pesticides; GM traits) engender controversy or are subject to a range of regulatory controls that can

prevent or slow uptake dramatically or escalate the cost of uptake to an unsustainable level. For example, regulatory requirements associated with ensuring the efficacy, targeting precision, lack of toxicology to non-target organisms, environmental safety, rapid breakdown and safety to human and animal life substantially raises the total cost of bringing new pesticides or new crop varieties carrying certain DNA insertions to market. For example, average total costs per trait for the discovery, development and authorisation of new biotechnology-derived crop traits in the period 2008–12 were $136 million, of which more than 25% was attributed to the direct cost of regulatory compliance[19]. Regulatory costs vary according to crop size, market size and geography, but are particularly high in cases involving crops with extensive international markets.

In setting research agendas it is important to be aware of regulatory requirements and the public attitudes underlying them, as these inevitably influence if and when new advances, however economically attractive or environmentally sustainable they may be, are adopted[20]. In the current Australian agricultural setting, where the private sector is playing an increasingly dominant role, changes based on high tech applications or even more traditional approaches will only occur if a business case demonstrating clear return on investment can be developed.

While there is considerable merit in applying precautionary principles, the ability of agriculture to respond to the challenges of the 21st century and deliver the triple bottom line requirement of profitability, productivity and sustainability may be significantly impaired if technologies that can revolutionise production are sidelined. Box 2.1 shows how GM technology in the form of Bt insect resistance genes has greatly benefited the Australian cotton industry, leading to greater profitability and a marked reduction in environmental pollution by pesticides.

While the application of GM technology in agriculture is a particularly high profile activity, public interest and concerns about many agricultural activities (e.g. the balance between water used in agriculture and that available for environmental flows; biodiversity conservation; animal welfare; the contaminant-free production of foodstuffs) are potentially powerful forces that can reduce market demand, lead to changes in the regulatory environment or drive innovative change. It is vital that agriculture takes a proactive approach to these concerns by working with

[19] Phillips McDougall. 2011. *The cost and time involved in the discovery, development and authorization of a new plant biotechnology derived trait: A consultancy study for CropLife International*. Midlothian, UK: Phillips McDougall.

[20] Daly, J, Anderson, K, Ankeny, R, Harch, B, Hastings, A, Rolfe, J and Waterhouse, R, 2015.Securing Australia's Future - *Australia's agricultural future*. Report for the Australian Council of Learned Academies. Chapter 5: Australian agriculture's social and political context.

consumers to maintain a social licence to operate by generating mutually beneficial and acceptable change.

### 1.7.3 Making information available on-farm

Ensuring scientific advances are converted into practical outcomes is a constant and vital part of the application of science to agriculture. Legitimate concerns about a potential neglect of research delivery and extension have troubled the industry for some time—this component is becoming more important as the contributions made by science become increasingly complex and sophisticated.

A major consequence of the growing availability of 'big data'[21] and its integration with mathematics and statistics, computing science and ICT is the potential, through meta-analyses, to generate additional insights with both theoretical and practical outcomes—helping guide research on the one hand, and increase the efficiency and productivity of farming operations on the other. Considerable investment will be required to ensure that producers have access to appropriately processed data presented in a readily-understandable form, for example as clear decision-support tools. Failure to do so will result in significant lost opportunities. Data privacy and ownership remains to be resolved in some cases: as with other demographics, producers display a natural reluctance to pay for information that they have provided despite data-processing being essential to unlocking its usefulness and profitability.

## 1.8 Globalisation of science and engaging with private sector research

Agriculture in Australia is not unique. Many issues we face need locally based research in which solutions are tailored to a particular set of environmental circumstances, but it is important to recognise that as one moves along the research, development and extension (RD&E) continuum from locally applied science to fundamental science, the geographic focus of that work changes substantially. Thus, work to encourage adoption of research solutions (extension) has to be done locally; the adaption of fundamental scientific advances and their integration into production systems (development) is best achieved at the regional level; while much basic curiosity-driven research (research) can be executed wherever the necessary critical mass of researchers exists (i.e. at a global level).

[21] Datasets that are so extensive or complex as to make traditional processing approaches inadequate. In the context of agriculture the complexity of such datasets is often associated not only with size but the need to meld together disparate information sources (e.g. soil nutrition, plant growth and reproduction, weather variables, genetics).

International collaboration is essential, given the costs associated with leading scientific research, the innumerable demands on funding and the global commonality of many problems, and has delivered major advantages for Australian science. For example, Australia participated in genome sequencing projects for many of our major crops and livestock (beef, sheep, barley and wheat) that could not have been undertaken alone. Having a 'place at the table' in major paradigm-shifting projects such as that for $C_4$ rice or the International Wheat Yield Partnership (IWYP)[22] provides access to major comprehensive projects that would be unlikely to receive sufficient funding in Australia alone. Indeed, consortia such as the IWYP bring together investment from both public and private research organisations from around the world and use this to draw on and integrate the efforts of skilled groups.

Major multi-national life science companies increasingly dominate research in many areas of agriculture, particularly plant-based systems where the opportunity to obtain a commercial return on investment is best developed. The $5+ billion invested annually by these companies in a broad sweep of research dwarfs the combined capability of Australian public investment. Only these companies have the financial resources to cope with the high regulatory costs involved in bringing GM as well as new pesticides and herbicides to market. In reality, the biggest issues regarding research conducted by the life-science companies are the speed and cost at which it is made available in Australia.

## 1.9 Linking science investment to its fundamental drivers

In agriculture, there is very clearly a creative tension between curiosity-driven research in the plant and animal sciences and the practical realism imposed by the need to ensure that any scientific or technological development can be implemented in a cost-effective manner to improve profitability or sustainability. While producers are willing to support fundamental research, there is an expectation that its core rationale is to positively contribute to their triple bottom line. They will not adopt research advances that do not do so.

The allocation of resources across the RD&E spectrum inevitably involves choices, trade-offs and compromises. Not all activities can be supported but examination of the different routes whereby productivity can be maximised—through reducing losses to pests and diseases; better matching existing genetics to available environmental resources; or through fundamental changes in the genetic capability of plants or animals—provides a strong guiding framework for investment decisions. A simple but effective way of considering the various routes to increase productivity

[22] International Wheat Yield Partnership @ iwyp.org. [Retrieved on 5 November 2015].

and decrease losses is to examine the relationships between input risks and output rewards (Fig. 1.3).

Within the limitations imposed by a given set of genetic resources, the limits to productivity are set by a complex interaction of the available physical environmental resources (e.g. water, nutrient, temperature) thereby generating an existing productivity limit band. Vertical differences (Point A, Fig. 1.3) in the current potential productivity band reflect season-to-season changes in uncontrollable factors such as an excess or deficiency of water, or temperature extremes. Horizontal changes are largely controlled by the producer and are driven by their appetite for risk. In reality, few producers actually operate at the potential yield limit of their environment. Even for the most enthusiastic producers, the declining incremental rewards obtained through increasingly greater input costs imposes too great a risk considering the inherent unpredictability of the Australian environment. In more protected systems producers may find it easier to aspire to maximise returns although even then not all risk can be avoided as unexpected changes (for example in market demand) are impossible to predict. The realised productivity outcome (Point B, Fig. 1.3) slides up or down the current productivity limit band depending on the producer's appetite for risk.

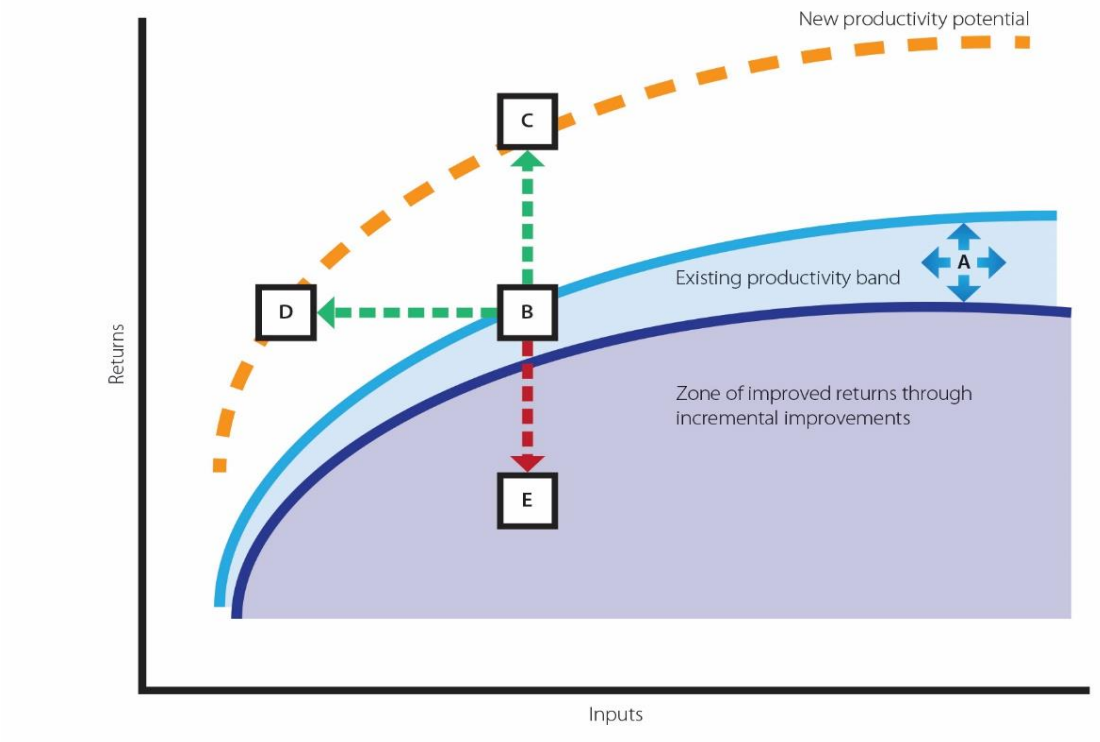


*Figure 1.3: Schematic of the different pathways whereby science innovations may contribute to the overall productivity and profitability of farming systems.*

*Note: See text (section 1.9) for explanation of the various scenarios (modified from Keating et al. 2012)*[23].

A step change in the way plants or animals interact with the environment will move the overall productivity of a system to a new potential high (or low, if a pest or disease is introduced or makes a major change in infectivity or aggressiveness). Examples include an increase in the efficiency of rubisco, an enzyme critical for the capture of energy during photosynthesis, or the release of major heterotic advantage in hybrid systems. Similarly, the shift may occur through cost structure changes in off-farm operations, such as automation and robotisation in abattoirs, or through major reductions in nutrient costs. Under these circumstances, benefits may be realised either through increased productivity for the same level of inputs (Point B → Point C) or through sustainability gains achieved through maintaining productivity while using fewer inputs (Point B → Point D).

Examples of recent significant gains following both these pathways exist. Thus 15–30% increases in nitrogen use efficiency demonstrated in rice and canola following insertion of particular genes using technology owned by Arcadia Inc.[24] follows B → D; while the pathway B → C can be represented by whole genome breeding technologies that are driving major improvements in dairy cattle and other animal breeding programs[25] or by a range of transgenic, drought tolerant traits that provide a yield advantage of 10–20% in several crops[26]. Successfully identifying, developing and deploying the next generation of game-changing scientific advances remains an active and ongoing challenge.

Plant and animal production is always under pressure from a broad range of biotic agents—pests, weeds, diseases and parasites—that reduce productivity, quality or both (Point B → Point E). Here the aim of science and technology must be to block this pathway to give producers the best possible output. Much of the pest control base currently achieved is under constant threat as selection favours resistant biotypes of micro-organisms, insects, fungi, weeds, and animal parasites. An

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[23] Keating, B, Carberry, P, Thomas, S and Clark, J. 2013. Eco-efficient agriculture and climate change: Conceptual foundations and frameworks. *Issues in Tropical Agriculture Eco-Efficiency: From Vision to Reality*. International Center for Tropical Agriculture.

[24] Field Trials of New Nitrogen Use Efficient Rice Show Increased Productivity, Leading to Increased Food Security and Reduced Fertilizer Dependence. 2013. Arcadia Biosciences. http://www.arcadiabio.com/news/press-release/field-trials-new-nitrogen-use-efficient-rice-show-increased-productivity-leading.Development of Commercial Nitrogen Use Efficient Canola Varieties Shows Early Development Success. 2007. Arcadia Biosciences. http://www.arcadiabio.com/news/press-release/development-commercial-nitrogen-use-efficient-canola-varieties-shows-early-develo.

[25] Van Eenennaam AL, Weigel KA, Young AE, Cleveland MA and Dekkers JCM. 2014. Applied animal genomics: results from the field. Annual Review of Animal Biosciences **2**: 105-139.

[26] Waltz E 2014. Beating the heat. *Nature Biotechnology* **32**: 610-613.

example of the step changes needed is the resistance of cotton to the cotton bollworm (*Helocoverpa punctigera*), which was achieved through the insertion of *Bt* genes from *Bacillus thuringiensis* and provided near-complete protection. Bt cotton allows near-zero insecticide use and provided both production and environmental benefits[27].

In Fig. 1.3 it is easy to equate 'returns' with productivity, yet added returns or benefits may be achieved in other ways. Advances that improve or radically change quality may lead to substantially higher returns for the same or even lower yield. For example, modification of canola to produce significant levels of omega-3 fatty acids (a current CSIRO–GRDC–Nufarm venture[28]) could generate a distinctly different market from that of mainstream canola. Perhaps more difficult to value are changes that substantially enhance sustainability, as the real benefit of these technologies is typically reflected in environmental gains (for example less erosion, greater soil quality, reduced eutrophication of water courses) that benefit production across multiple systems and years.

Economic drivers are not the sole determinant of science investment decisions. Community expectations about ethical food production, the desire for quality, nutritious foods that reduce or eliminate the risk of allergenic reactions or reduce the levels of known dietary villains, or concerns about controversial technologies (for example, GM traits in plants and animals) all have an impact on science investment decisions. In some cases these considerations may slow or even prevent further research, while in others cases community demand may drive research into products seen as beneficial (for example low gluten barley; high fibre wheat). Similarly, social and environmental concerns about the sustainability of particular farming practices and their off-farm effects may drive investment decision-making. The impact of sediment, nutrient and farm chemical loss to surrounding or downstream environments may drive investment into research focused on reducing losses and allowing individual producers or even entire industries to continue to operate. A case in point here is the impact that pollutants are having on the viability of the Great Barrier Reef and the response this has engendered in the sugar industry.

[27] Knox OGG, Constable GA, Pyke B and Gupta WSR. 2006. Environmental impact of conventional and Bt insecticidal cotton expressing one and two Cry genes in Australia. Australian Journal of Agricultural Research **57:** 501-609.

[28] Petrie, JR, Nichols PD, Devine M, and Singh, SP. 2013. Engineered oilseed crops with fish oil DHA levels. Inform 24: 648-652.

## 1.10 Summary

Agricultural improvements have been driven, and will continue to be driven, by prevailing challenges in the industry. Recognition of the complex inter-relationships between societal, economic, environmental and technological challenges is required to drive future science solutions for change. Strong working partnerships between scientists and producers, which operate in both directions, are vital to increasing the impact of R&D outcomes. Overall, the needs imposed on science can be generally regarded as innovations or breakthroughs to reduce losses (either yield losses or degradation of the resource base) while simultaneously improving the maximum productivity limit. These dual demands also operate on a range of scales; individual growers require strategies to help close the gap between realised and potential yields, whereas entire sectors require breakthroughs in fundamental research to forge new frontiers in potential yields. Strategies that help to close the gap between realised and potential yields (the 'zone of improved returns through incremental improvements'; Fig. 1.3) are important for individual producers. This will require fundamental research to develop new technologies, and for them to integrate with different technologies to lift potential yield frontiers significantly in single steps. This is the context in which this decadal plan aims to identify how the agricultural sciences are placed to respond to the demands placed upon them. Opportunities and approaches to achieve both incremental and step changes are presented and discussed in the next chapter.

# 2 Science solutions of the future

*"We cannot solve our problems with the same thinking we used when we created them".* – attrib. Albert Einstein.

*Widespread consultation across core and enabling science disciplines for agriculture identified six specific research areas that are most likely to contribute, either individually or more likely in collaboration, to the advancement of Australian agriculture:*

1. *development and exploitation of genomics*
2. *agri-intelligent technologies*
3. *big data analysis*
4. *sustainable chemistry*
5. *coping with climate variability and change*
6. *metabolic engineering.*

*Future opportunities for each of these six research areas are presented in this chapter. Integration of these activities will see four major science-based outcomes:*

1. *increased productivity through integrated farming systems*
2. *enhanced biosecurity*
3. *maintenance of a sustainable resource base*
4. *increased value through quality and market advantage.*

In scientific research and innovation it is increasingly clear that single-discipline approaches are unlikely to be successful. Nowhere is this truer than in agriculture where the successful translation of fundamental breakthroughs to application and adoption is highly reliant on systems with porous borders. Collaboration along the discovery–delivery pathway is paramount. Indeed, a very broad range of science—from plant and animal studies to mathematics, climatology, electronics and chemistry—has the potential to contribute to the development and implementation of new approaches in agriculture (Figure 1.1). Such contributions range from small changes that generate incremental gains resulting in continuous, slow but vital improvements, to individually more significant 'step changes' that can result in marked improvements in profitability, productivity and/or sustainability.

Over the past 50 years, advances in genetics, mechanisation, integrated management practices and the use of agrochemicals have all driven productivity increases[29]. Continued application and industry penetration of advances to date will provide additional future incremental benefits but significant steps forward will

[29] Daly, J, Anderson, K, Ankeny, R, Harch, B, Hastings, A, Rolfe, J and Waterhouse, R, 2015. *Australia's agricultural future*. P. 92. Report for the Australian Council of Learned Academies.

require new breakthrough technologies and practices that often arise from fundamental research[30]. However, given the complexity of farming systems with their constant interplay of genetics and management against an environmental backdrop that incorporates both fixed and highly variable elements, the introduction of novel approaches of major effect rarely, if ever, occurs without a range of other effects. These foreseen or unforeseen consequences may reduce or enhance immediate benefits or cause other longer-term changes in the system.

While for convenience we might consider the contributions of individual areas separately, they cannot and must not be seen in isolation to one another if lasting benefits are to be extracted from novel advances. Agriculture involves biological entities—crops, livestock, weeds, pests and diseases—as well as complex bio-physical elements such as soils that may change detrimentally (for example through increases in salinity) even if they do not co-evolve. This propensity for the broader environment to change in response to agricultural practice changes presents a particular set of constraints and opportunities that are not encountered in many other disciplines (Box 2.1). For these reasons, integrative approaches have a major role in the contribution science can make to agricultural production.

**Box 2.1:** ***Planning for unforeseen consequences***

Unforeseen consequences to the introduction of novel practices in agriculture may occur well after the initial stimulatory change and, in doing so, may markedly reduce the net value of the original innovation.

A good example of this phenomenon is seen in the flow-on effects arising from the widespread adoption of minimum-till technologies in Australia. Minimum-till has been highly important in the management of Australia's soils, primarily through reductions in soil erosion and water losses. However, a consequence of adoption of this approach has been the loss of time-proven weed control mechanisms associated with tillage and the increased dependence on high efficacy herbicides for weed control. This dependence, however, has resulted in over-use and poor management of key chemicals resulting in the build-up of resistance across several modes of action herbicides by numerous weeds, particularly annual ryegrass. Of particular concern is the rise in incidence of resistance to the herbicide glyphosate which is a fundamental component of the minimum-till farming system. The risk to glyphosate had been heightened by the development of crop varieties with glyphosate tolerance. This has increased the dependence of farming on a single herbicide by increasing its use and changing it from a non-selective pre-plant herbicide to an in-crop broad spectrum selective herbicide. The future of glyphosate in Australian tillage systems is being questioned, there is no suitable replacement on the market at present and the impact on conservation farming could be devastating. While scientists have for many years been aware of

[30] ATSE Submission to House of Representatives Standing Committee on Agriculture and Industry Inquiry into Agricultural Innovation. 2015.

resistance to glyphosate emerging in weed populations, and have devised ways to manage it, the risk remains high as the number and spread of glyphosate-resistant weeds continue to increase. This example highlights the need for forethought of the longer-term consequences of changes in production systems and the need for education in the implementation of new technologies in farming systems. Without such forethought there will be erosion of productivity, profitability and environmental gains associated with the initial innovation.

In contrast, forethought leading to modification of farming systems to protect the benefits of technologies can ensure durability and result in greater benefits in the longer term. Australian agriculture has one of the best examples of such an outcome as seen in the introduction of *Bt* insect resistance technology into the cotton industry and its continuing success two decades after its initial deployment in 1996. At the time of its introduction, the industry's viability was greatly threatened by increasing pesticide resistance in the cotton bollworm (*Helocoverpa punctigera*) and significant environmental issues associated with the high reliance on insecticides. However, recognition of the vulnerability of the protection afforded by single-resistance genes led to the development of a long-term pre-emptive insect resistance management strategy designed to reduce the selective pressure imposed by the *Bt* gene on the insect—use of resistance-free refuges, defined planting windows, limits on the total area sown to *Bt* cotton, and strategies to eliminate over-wintering pupal survival. Implementation of these strategies was also made easier by commercial realities with stewardship of the technology in the hands of a single company and annual seed distribution through a grower-owned cooperative. Additional *Bt* genes have since been deployed (two- and three-gene combinations in 2004 and 2015 respectively) and wider benefits have been achieved through the integration of the *Bt* technology into integrated pest management (IPM) systems. With pre-emptive resistance management to protect the technology, modest changes to the additional control approaches have ensured the long-term durability of plant insect resistance while maximising the economic and environmental benefits accruing from reduced pesticide use.

An extended process of consultation with a broad representation of researchers from across core and enabling disciplines that feed into agriculture led to the identification of several distinct areas of particular promise. These areas are perhaps best envisaged as a matrix in which numerous individual research frontier areas intersect with a smaller number of broader themes in which the integrative nature of much agricultural research comes to the fore (Table 2.1). The major issues associated with each of these specific research and theme areas are considered individually but in no order of priority.

Table 2.1: Specific research frontiers and theme areas identified as being major areas of focus and contributors to agriculture in the coming decade

| Specific research areas | Outcome/implementation areas | | | |
|---|---|---|---|---|
| | **Increased productivity through integrated farming systems** | **Biosecurity** | **Sustainable resource base** | **Increased value through quality & market advantage** |
| **Development & exploitation of genomics** | • Genomic prediction<br>• Targeted genetics<br>• Novel crops & livestock<br>• Manipulating the soil and gut biome | • Rapid diagnostics<br>• Pest & weed control<br>• Gene drives | • Identification tools<br>• Resilience<br>• Complex ecosystem analysis | • Changed/enhanced quality<br>• Altered nutritional values |
| **Agri-intelligent technology** | • Remote sensing & real-time monitoring<br>• Harvest scheduling<br>• Pesticide application | • Targeted control methods<br>• Remote surveillance | • Remote surveillance<br>• Phenomics research<br>• Intelligent sensors | • Reduced post-harvest losses<br>• Reduced pesticide use<br>• Product traceability<br>• Defined provenance<br>• Differential harvesting-grapes and fruits |
| **'Big-data' analysis** | • Integrated management<br>• Soil microbiome functional analysis | • Holistic risk profiles | • Catchment management<br>• NRM monitoring and analysis | • Product traceability<br>• Production systems management |
| **Sustainable chemistry** | • Novel nutrient production<br>• Novel pesticides & herbicides<br>• Biopolymers<br>• Real-time nutrient measurements<br>• Waste utilization and value adding | • Targeted control methods | • Reduced environmental contamination | • Product provenance |
| **Coping with climate** | • Seasonal forecasting<br>• Managing extreme events<br>• Carbon capture<br>• Water storage<br>• Managing $CO_2$ responses | • Invasive threats<br>• Changing distributions | • Carbon capture<br>• Resilience<br>• Water storage<br>• Mid-range, short & localized predictions | • Improved animal welfare & quality of animals and produce<br>• Targeted planting, fertilizer use<br>• Targeted harvesting |
| **Metabolic engineering / Synthetic biology** | • Biofuels & industrial feedstocks | • Targeted control methods | | • Novel products<br>• Toxin-free products |

The table illustrates the matrixed nature of research with development in the more fundamental research areas feeding into multiple broader outcome areas through which on-farm impact is achieved. A representative but non-exhaustive set of significant topic areas within this matrix provides an indication of the diversity of areas in which change is likely to occur.

## 2.1 Specific research areas

### 2.1.1 Development and exploitation of genomics

***Areas of application:*** breeding (genomic prediction); farming systems management; plant-soil interactions; biosecurity; pest and disease control; bio-industrial feedstocks; food quality and personalised nutrition; traceability; crop diversity conservation; sustainability.

***Contributing disciplines:*** plant and animal biology; bio-medical sciences; bioinformatics; computing and data analytics.

The McKinsey report[31] recognises next generation genomics as a truly disruptive technology with continuing rapid improvements in efficiencies and novel approaches leading to increasingly diverse applications. While medical science is at the cutting edge of these advances, agriculture is following closely. Improved technology and infrastructure is predicted by the next decade[32] to see routine human genome sequencing carried out at a cost of $100 within the hour. This technology will also have massive effects on agriculture. Genomics and post-genomics technologies, including transcriptomics, proteomics and metabolomics, are driving conventional and transgenic plant and animal breeding, making complex bio-engineering processes involving whole enzymatic chains possible, and providing ever-increasingly precise tools for use across the entire agricultural spectrum.

The extent of the changes likely to result from the application of molecular technologies is virtually unlimited. Here we highlight a limited number of areas in which this revolution will have an increasingly significant impact as well as some bottlenecks that will have to be resolved in order to extract the full value of the genomics revolution. The dynamism of this overall field of research makes it inevitable that many other areas of potential application will rapidly arise and underscores the potential benefits to be had from research investment in the area.

*a) Genome to phenome*

Until recently, the major bottleneck in the development of genomics and its applications was the high cost of sequencing and its relative slow speed. Today, next-generation sequencing technologies are generating a flood of data and the

[31] Manyika J, Chui M, Bughu J, Dobbs R, Bisson P and Marrs A. 2013. Disruptive technologies: Advances that will transform life, business and the global economy. McKinsey Global Institute report.
[32] Derek Thompson, 'IBM's killer idea: The $100 DNA-sequencing machine,' The Atlantic, November 16, 2011.

bottleneck has shifted to data handling and analytical procedures (bioinformatics) and the problem of linking individual gene sequences to the phenotype they underpin. To meet this challenge there has been a surge in automated screening technologies so that, in plants, large numbers of individuals in segregating populations can be rapidly screened under glasshouse or field conditions for characteristics such as canopy leaf temperature that are linked to traits of agronomic importance such as drought tolerance ('plant phenomics').

As sequencing costs continue to fall and genome sequences for all the major crop and animals become available, identifying the function of individual genes will become easier and faster. For example, in both plants and animals it will be possible to screen large numbers (say in the order of 10,000) for their individual phenotype (for several traits of interest) and then compare these data with full genome sequences for all 10,000 individuals. The size and heterogeneous nature of such combined datasets reinforces the need for further investments in bioinformatics and 'big data' processing (see Section 2.1.C). This linking of genome to phenome, and increasing predictive skills regarding the phenotypic identity of specific gene sequences, is highly dependent on understanding biochemical processes and pathways within the target organism (metabolomics, proteomics), the traits that are important for productivity (e.g. energy efficiency conversion rates—photosynthesis and animal metabolic rates), and the extent to which expression of the genotype is influenced by different environments—that is, linking genomics with crop and animal physiology, animal husbandry and plant agronomy.

*b) Changing breeding technologies*

Genetic modification is a key research tool for advancing knowledge of gene function as it enables the introduction of genes of interest or the reduction in expression of endogenous ones. Recent exciting developments collectively called genome editing offer significant opportunities for the analyses of plant and animal genomes through the ability to make precise changes at specific genomic locations via gene insertions, gene replacements, or insertions or deletions that disrupt the function of a specific gene[33]. At this stage, use of this technology requires a precise knowledge of the sequence of the target gene[34], although its power to alter

[33] Lawrenson T, Shorinola O, Stacey N, Li C, Østergaard L, Patron N, Uauy C, Harwood W. 2015. Induction of targeted, heritable mutations in barley and *Brassica oleracea* using RNA-guided Cas9 nuclease. *Genome Biology* **16**, 258. doi:10.1186/s13059-015-0826-7

[34] Further demonstration of the importance of the genome-phenome association.

agriculturally important traits has already been demonstrated in hornless cows[35], pigs that are resistant to swine fever[36] and plants resistant to disease[37]. Clearly, the practical implications of the widespread application of gene editing to plant and animal breeding programs are substantial. The list of traits that could be addressed when sequence information is available is extremely large. However, there is a range of ethical and consumer acceptance issues that will need resolving.

At the same time, whole genome selection[38]—a form of marker-assisted selection in which genetic markers covering the whole genome are used—has become widely used due to the efficient genotyping of large number of single nucleotide polymorphisms discovered by genome sequencing. Implementation of genomic selection has already had major impacts on animal breeding (e.g. milk production in dairy cattle) and is now being widely introduced into plant improvement programs.

Plant and animal breeding has traditionally relied primarily on commercial varieties and breeds, heritage breeds or landraces or, in plant breeding, more distant relatives as sources of variation for improvement programs. In addition, ionising radiation, chemical mutagens, soma-clonal variation and the introduction of genes from other species (usually representatives of different kingdoms) by genetic engineering have supplied additional levels of resources. More recently, epigenetic changes have been recognised as having considerable potential as a further source of variation for germplasm enhancement programs. Epigenetic traits differ from other sources of variation in that the stably inherited phenotype results from changes in a chromosome without alterations in the DNA sequence. This is achieved through modification of the activation of certain genes, but not the sequence itself. The role of epialleles in developmental gene regulation, response to the environment, and in natural variation of gene expression levels strongly suggests that there is the potential for epigenetics to play a role in crop improvement

[35] Carlson DF, Lancto CA, Zang B, Kim E-S, Walton M, Oldeschulte D, Seabury C, Sonstegard TS, and Fahrenkrug SC. 2016. Production of hornless dairy cattle from genome-edited cell lines. Nature Biotechnology 34:479-481.

[36] Lillico SG, Proudfoot C, King TJ, Tan W, Zhanbg L, Mardjuki R, Paschon DE, Rebar EJ, Urnov FD, Mileham AJ, McLaren DG, and Whitelaw BA. 2016. Scientific Reports 6:21645. Doi:10.1038/srep21645

[37] Li, T, Spalding MH, Weeks DP, and Yang B. 2012. High-efficiency TALEN-based gene editing produces disease-resistant rice. Biochemistry – Faculty Publications. Paper 110. http://digitalcommons.unl.edu/biochemfacpub/110

[38] Goddard ME, Hayes BJ. 2007. Genome selection. *Journal of Animal Breeding and Genetics* **124**, 323-330.

strategies[39]. New breeding technologies, including gene editing using CRISPR/Cas9, will further enhance the range of technologies available to breeders.

### *c) Wider ripples of the genomics revolution*

Molecular tools are already routinely used in a broad sweep of animal and plant studies, including breeding, pest and disease control, soil biome structure and function, biodiversity in agricultural landscapes and future scenario settings. Thus in integrated pest and disease control highly specific molecular diagnostics play a vital role in management programs through direct detection of plant and animal pathogens in the environment, the identification of infected asymptomatic hosts and in more basic studies aimed at understanding sources of variation within parasite populations and their interactions with host animal and insecticide resistance. Even more sophisticated approaches—using, for example, gene-drive technology—offer the real possibility of elimination of pest organisms, for example some plant and animal viruses through targeting of vectors with genetic changes that prevent transmission[40]. Similarly, molecular tools are also proving of great value in studies aimed at understanding the structure and function of the microbiomes in water, soil, rumen and gut where the inability to culture many species, their great diversity and overlapping functions and associated potential redundancy have proven major stumbling blocks in the past. Application of molecular tools in all these areas will revolutionise progress on many previously intractable problems.

## Future opportunities

International science efforts will make many of the critical discoveries and fundamental breakthroughs that will power agriculture. However, ***to remain internationally competitive and attractive to international public and private science efforts, and to respond to the diverse and rapidly changing needs of Australia's diverse agriculture sector, a focus of funding needs to remain on post-genomic science research.***

[39] Springer NM. 2013. Epigenetics and crop improvement. *Trends in Genetics* **29**, 241-247.

[40] National Academies of Sciences, Engineering, and Medicine. 2016. *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values*. Washington, DC: The National Academies Press. doi: 10.17226/23405.

### 2.1.2 Agri-intelligent technology

***Areas of application:*** on-farm management (crop and livestock production, management and processing); precision feeding (animals); harvesting; early disease detection; sustainability management.

***Contributing disciplines:*** engineering; robotics; automation; mathematics; computing/IT; agronomy; animal husbandry.

A new wave of innovation in agriculture is being triggered by the unification of information derived from big data analysis [see 2.1.C], integrated assessments of individual agronomic and animal husbandry processes [see 2.2.A] and the deployment of key technologies related to robotics, autonomous systems and remote sensing[41] including state-of-the-art active learning decision support systems.

The following areas of research in agri-intelligent technology all have the potential to make significant contributions to the development of truly integrated farming systems approaches.

*a) Agricultural cybernetics*

The ability to make decisions and sequentially hone their accuracy through time using systems capable of receiving, storing and processing information has the potential to have a major impact on field-based agricultural production. However, such systems depend on feedback which, if not properly handled, may result in limitations in action effectiveness or even undesirable outcomes. Currently the broadest application of agricultural cybernetics is in controlled environment-grown horticultural crops where decisions for controlling nutrient and water availability, pest and disease control and energy input are integrated.

By drawing on a significant body of relevant cybernetic science that has already been developed in the fields of applied engineering and finance, it will be possible to extend these approaches to field crops with concomitant significant gains in resource use efficiencies.

*b) Sensors and sensor networks*

The use of sensors and sensor networks with their delivery of information used in decision-making is already well established in agriculture (e.g. canopy temperature sensors; individual animal monitors in dairy systems; irrigation flow gauges linked to soil monitoring sensors). Differences in the spatio–temporal characteristics of the

[41] Perez, T. 2016. Digital agriculture - opportunities & challenges. Landwise 14th Annual Conference, Havelock North, New Zealand, 25-26 May 2016.

different target processes inevitably requires networks of different spatial dimensions, different sampling frequencies and different response times. Already intensive irrigated cropping industries use many remote sensing networks. This will continue to grow into the future as an ever-increasing array of sensors become available. The scope of their use will be controlled simply by imagination and the ability to identify an appropriate 'signature cue' from targeted plants or animals that provides the basis for an effective measure of the trait or feature of interest.

Into the next decade, the cost of sensing technology is likely to continue to trend downwards, opening up additional real-time applications and the opportunity to link incoming data into virtually all aspects of farm management. Examples might include soil nutrition sensors at the head of a tractor controlling variable fertiliser release in a towed unit; sensor identification of weeds in crops enabling precision herbicide treatments in-crop; the health of free-ranging cattle being determined via real-time measures of residual nutrient composition of dung or parasite infestation rates; and highly automated horticulture harvesting equipment.

### *c) Robotics and autonomous systems*

Robotics and autonomous systems are making a significant impact in operations of multiple sectors of the economy. In agriculture, early stages of automated systems (e.g. laser leveling; GPS guidance) are well established but we anticipate that robotic and autonomous systems will be developed specifically for agriculture, particularly with respect to robot-enabled sensing, decision making ('thinking') and acting (Fig. 2.1). In this regard, robotic applications in the typically more spatially structured controlled-environment horticulture are already advancing. For typical grazing and cropping systems though, the big challenge is to develop effective robotic operations for largely unstructured environments although robotic milking already provides a clear picture of future possibilities

Unlike fixed or dedicated sensor networks, robot-enabled sensing can be flexible and adaptive in space, gathering a variety of data that can be analysed for decision-making and discovery purposes. The flexibility of robot-enabled sensing is the key to adaptive sampling and could be deployed in pest and disease detection. With appropriate research investment, most of the tasks shown under robot-enabled sensing in Figure 2.1 could be occurring in at least some agricultural systems in the next ten years.

Robot-enabled 'thinking' refers to the gathering and analysis of information and its use in decision-making. In the next decade, agricultural systems will see a significant increase in the application of automation in sensing and routine management

decisions. As this continues to develop, robotic technology and thinking will be used to generate likely scenarios with their associated uncertainties to assist human decision-making (essentially an application of agricultural cybernetics). We already see applications for robotic dairy cow nutrition, milking, weed management, pest control agent application, and harvesting of certain horticultural crops.

Table 2.2: Robotics and autonomous systems in agriculture

| |
|---|
| **Robot-enabled sensing** |
| • Weed detection & classification |
| • Crop yield estimation |
| • Soil characteristics |
| • Flower & fruit detection and localisation |
| • Pest and disease detection & monitoring |
| • Feeding and reproduction behaviours |
| • Grading and quality assessment |
| **Robot-enabled thinking** |
| • Making sense of data – data analytics |
| • Risk-informed decision support – from data to decisions |
| • Improved strategies for spacio-temporal application of inputs |
| • Improved strategies for weed and pest management |
| • Harvest scheduling optimisation |
| • Workforce scheduling |
| **Robot-enabled acting** |
| • Herbicide application |
| • Alternative weed destruction |
| • Pest control agent application |
| • Nutrient application |
| • Seeding |
| • Pollination |
| • Harvesting |
| • Irrigation |
| • Pruning |

Perez, T. 2016.

The third wave of the application of autonomous systems will be seen in robot-enabled acting in spatially complex environments. This application incorporates

sensing of target features in the environment, analysis of the resultant data inflow, simple to complex decision-making based on that information, followed finally by execution of remedial action (see Fig. 2.1). Despite the apparent simplicity of some of the target applications, this area of research is still in its infancy.

#### Future opportunities

As agriculture moves into the digital age there are tremendous opportunities to be realised in greater use of integrated autonomous operations that are also more directly linked to down-stream logistics and marketing. For this to occur, ***resources must be made available to promote continuing development of the software and hardware of autonomous robotic systems to provide the base for smart delivery of many aspects of integrated decision support systems. The training of engineers and IT specialists needs to go hand in hand here as does support for small, high tech businesses in regional areas.*** This is an area ripe for strong public–private engagement.

### 2.1.3 Big data analysis

***Areas of application:*** on-farm management (crop production, management and processing); catchment management; sustainability.

***Contributing disciplines:*** mathematics; statistics; computing; information and communication technology.

Big data[42] analysis is more than simply efficiently analysing individual datasets, however large. Rather, big data analysis aims to get the best possible value from nested analyses of multiple data sets gathered for a variety of reasons in a variety of ways. Big data is characterised by its *volume*, the *velocity* with which it can be acquired including near real-time, and its *variety.* It refers to multiple different characters reported in all sorts of formats from numeric information in structured datasets to unstructured text documents[43]. The variety of information being handled can add great complexity because of the need to devise data handling methodologies that link across different systems and enable enhanced decision-making, insight discovery and process optimisation.

Essentially, the primary value of big data comes from the insights, products and services that emerge from analyses. In agriculture, the integration of large datasets from a broad diversity of areas—including crop and animal breeding, farming systems, climatic information and soil nutrient maps—may uncover fundamental

[42] See Chapter 1 for definition.

[43] *Laney, Douglas.* "The importance of 'Big data': A definition". *Gartner*.

relationships. These can then be used to guide effective decision-making and support innovations to improve productivity, efficiency and sustainability. Many precedents in other sectors of the economy support this contention; however, realising those benefits requires significant shifts in how data supports decisions and product/service innovation[44].

*a) Discovery from data*

The analysis of big datasets in agriculture is in its infancy. Where such datasets exist or can be compiled, data can be analysed to discover new insights and increase situational awareness. However, this requires the development of analytical techniques and application of specialised frameworks, models, and artificial intelligence for pattern recognition. A major complication is that important agricultural processes range in scale spatially from the individual to the landscape, and temporally from within-day patterns to yearly aggregating values such as yield. Furthermore, interacting processes can involve relatively slow or fast-changing abiotic factors (such as soil chemistry and precipitation patterns respectively), growth patterns in biotic components (crops and livestock) and complex feedback loops that induce evolutionary change in pests, weeds and diseases. Currently the relative availability of these differently 'grained' data is very variable but is changing rapidly.

Undoubtedly the next ten years will see an increase of spatio–temporal data in farming systems as well as along the value chain. To ensure maximum value is extracted from these data[45], agriculture will require the use and specialisation of technology for big data analytics already used in other sectors of the Australian economy such as sociology, national security, finance and insurance.

*b) Informed decision-making*

Big data analysis extracts and integrates information from a diversity of data sources to assist in reducing uncertainty in decision-making. The management of agricultural production systems involves repeated decision-making by humans, autonomous agents or a combination of both, in the context of varying levels of uncertainty. Selection of an action from a set of potential alternatives must take into account the consequences of potential outcomes. In turn, these depend not only on the action taken, but also on various attributes that are often uncertain at the time. This uncertainty makes decisions difficult. Uncertainty can be reduced by learning from

[44] *Davenport TH, Dyché J.* Big data in big companies (2013).

[45] Bennett JM. 2015, Agricultural Big Data: Utilisation to discover the unknown and instigate practice change. *Farm Policy Journal* **12**, (1) 43-50.

purposefully collected data combined with sophisticated mathematical models to extract information: analytics.

Assisting farmers, managers and SME service providers to collect, merge, and analyse large amounts of data, as well as to extract valuable information in the context of their decisions, communicate uncertainty and appreciate the full range of potential consequences, are areas in need of much development in agriculture. To reduce decision-making risks in all aspects of agricultural production systems it is essential to ensure investment in the development of agriculture-friendly analytics that extract relevant information from the increasing amounts of data now available. A good example of the steps being taken by governments elsewhere is seen in the recently launched Agrimetrics Centre, established with a £11.8 million contribution by the British government to support a joint venture between Rothamsted Research, the University of Reading, Scotland's Rural College and the National Institute of Agricultural Botany[46].

As noted in Chapter 1 (Section 1.4.3), issues regarding the ownership of big data and its availability from both on- and off-farm sources (e.g. processors, shipping agents) will have to be resolved equitably if the potential value for this approach is to be fully realised. Similarly, the on-farm value to be derived from the analysis of big data will often be highly dependent on the availability of efficient, reliable high-speed internet connections.

### Future opportunities

The merging and analysis of diverse, large and complex datasets is generating novel insights across multiple sectors of the economy. In agriculture such analytical tools offer great opportunities in guiding decision-making in multiple areas and will increasingly underpin integrated farming systems advances. ***It is essential to support research that utilises the best of tools developed in other sectors of the economy and shapes and develops these for use with complex agriculture-related datasets.***

[46] Agrimetrics: http://www.agrimetrics.co.uk/

### 2.1.4 Sustainable chemistry

***Areas of application:*** real-time measurement of soil nutrient status; real-time measurement of feed; onversion rates; biopolymers for crop production; novel pesticides and herbicides; waste recovery.

***Contributing disciplines:*** chemistry; computing/IT; biochemistry.

The potential contribution of sustainable chemistry applications to plant and animal production is yet to be fully imagined let alone realised. However, in several areas, significant contributions are already occurring while in others there is clear potential.

There is increasing sophistication in IPM (weeds, insects, fungi) programs. The absolute need to increase the sustainability of agricultural activities means that greater emphasis is being placed on the development of a new generation of agro-chemicals that combine greater efficacy towards target species with near-zero toxicity to non-target ones.

Polymer and other coatings are already in use to reduce evaporation and frost effects or increase temperatures during critical early growth phases of some annual crops. Further development of encapsulation systems for use in measured, sustained release of plant (e.g. slow release nutrients; pesticides) and animal (e.g. encapsulation of oral vaccines, helminthicides) therapeutics will continue the drive towards reduced unintended evolutionary impact on the soil microbiome and other bacteria more intimately associated with animal production. They will also assist in reducing off-farm effects of excess nutrient contamination of waterways.

Finally, development of many potentially valuable sensors for use in animal and plant production depends on identification of real-time or near real-time sensory clues that allow the development of effective measures of critical criteria. For example, real-time measurement of soil macrontrient and micronutrient concentrations, if fitted to the leading edge of a spray or injection rig could provide vital input to one-pass detection and remediation technology. Similarly, autonomous robot-mounted ‘e-nose’ sensors are needed to monitor faeces for gut parasite infection rates, feed energy conversion rates and general herd health status.

### Future opportunities

We highlight here a few areas in which sustainable chemistry already has or will have a significant impact on plant and animal production; it is inevitable that ***many other areas of potential application will rapidly arise, underscoring the potential benefits to be had from research investment in the area.***

## 2.1.5 Coping with climate variability

***Areas of application:*** national and regional climate scenarios and local within-season climate prediction; on-farm and catchment management.

***Contributing disciplines:*** physics; mathematics; climatology; computing science; meteorology; climate science; ecological and evolutionary sciences.

Australian agricultural systems already have to cope with considerable variability in seasonal conditions within and among years. Variability in the timing of the autumn break, in the occurrence of cold stress during flowering, or in the rate at which conditions dry and heat up during crop maturation all introduce significant unpredictability into agricultural operations and decision-making success. Many management practices and genetic responses have been developed to counter these effects—but the actual productivity achieved is still often significantly constrained.

Exacerbating the challenge of climate variability is climate change, which is altering the background on which climate variations occur. Changes are expected in patterns of precipitation, evaporation and temperature, along with increases in some severe weather events including heatwaves. In many cases, the tools needed to cope with climate change can be developed through the development of better management strategies for climate variability. In other instances, climate changes may be so drastic that completely new practices are required.

Generic climate forecasts of rainfall and temperature have limited utility in helping guide decision-making in agriculture. Extensive research is now underway in tailoring these products for individual needs. For example, predictions can be made for frost risk in cotton, heat stress on cereals, or pasture growth in rangeland grazing. Timescales vary from days to years: from those needing to know whether to harvest this week or next, out to whether to reduce stock this year to conserve pasture quality ahead of a good year in the next. As the skill of weather and climate

models continue to progressively increase[47], so will its ability to provide this information with more certainty in the coming decade.

### Future opportunities

To be of real value to producers, regional level climate modelling and weather forecasting information needs to be integrated with farming systems approaches to guide better decision-making about how best to adapt to variations in climate and prepare for extreme weather events. Achieving this will require ***continuing investment in the development of increasingly accurate forecasting systems and the real-time integration of these with plant and animal production models.***

## 2.1.6 Metabolic engineering/synthetic biology

***Areas of application:*** novel products from plants; renewable industrial feedstocks; reuse of waste and by-products.

***Contributing disciplines:*** molecular biology; chemistry; biochemistry; computing; mathematics.

Significant metabolic engineering in plants has only become possible because of advances in molecular technologies that make over-expression or suppression of endogenous genes, or the cloning and transfer of alien genes, increasingly routine. In general terms the traits targeted for engineering can be placed into three broad groupings:

1. crop protection traits
2. plant growth, nutritional quality or environmental benefit traits
3. renewable industrial traits[48].

Early metabolic engineering approaches that focused on resistance to pests or herbicides clearly demonstrated the contribution that GM technologies could make to both agricultural production and environmental health (reduced pesticide use) through the incorporation of single genes (e.g. insect resistance conferred by the *Bt* gene from *Bacillus thuringiensis*). Those successes have been followed by a variety of different approaches, ranging in complexity from the insertion of single genes to the discovery (from unrelated wild plants and microalgae), introduction and

[47] Charles AN, Duell RE, Wang X, & Watkins AB. 2015. Seasonal forecasting for Australia using a dynamical model: Improvements in forecast skill over the operational statistical model. *Australian Meteorological and Oceanographic Journal* **65**, 3-4.

[48] The line between metabolic engineering for direct production benefit or industrial feedstocks and food nutritional quality and health traits is inevitably fuzzy. In the latter area successful outcomes may be achieved through both conventional or GM approaches.

coordinated expression of transgenes encoding an entire biosynthetic pathway comprising five discrete enzymatic conversion steps. In this case, nutritionally important omega-3 LC-PUFA, EPA and DHA are produced in seed oil with additional potential environmental benefits of reducing the impact of fish farming on wild fish stocks.

In other studies, genes for the production of spider silk protein, and of various fatty acids found naturally in insects have been expressed in plants. These successes underline the potential for the use of plants to produce renewable industrial feedstocks that are currently only available through the processing of fossil fuels.

While metabolic engineering approaches to date have already generated exciting changes in the fundamental quality and value of some crop species, these changes are dwarfed by the potential of synthetic biology which, by using rapid developments in DNA sequencing, gene editing and synthetic technologies, is likel to radically change some aspects of agriculture in the future[49,50]. For example, by designing entirely new bacteria it may be possible to provide intimate nitrogen-fixing capabilities to non-leguminous crop species, while the range of novel plants capable of producing complex industrial feedstocks will increase dramatically.

The great potential of this research area to contribute to the future of agriculture is currently tempered by a combination of commercial and social considerations. Somewhat like renewable energy research, practical application of the results of metabolic engineering research has to confront short-term commercial considerations where replacement of existing feedstocks will only occur if plant-derived alternatives are available at a comparable price. As fossil fuels are typically the main or only source of many of these compounds, low oil and gas prices present a major impediment. Social considerations revolve around ongoing concerns about the safety of GM approaches, especially if the proposed products may enter the food chain at any point.

[49] Biotechnology Industry Organisation. Current uses of synthetic biology for Renewable Chemicals, Pharmaceuticals, and Biofuels. 2013

[50] Kelley, NJ, Whelan, DJ, Kerr, E, Apel, A, Beliveau R, Scanlon, R. Engineering biology to address global problems: Synthetic biology markets, needs and applications. Industrial Technology, June 2014. DOI: 10-1089/ind.2014.1515

### Future opportunities

Given broad global recognition of the extent of the problem posed by increasing levels of $CO_2$ in the atmosphere and the demand for materials and compounds with novel properties, ***the potential to access unique or highly unusual compounds and replace fossil-fuel derived plastics, polymers and other products with ones that are essentially carbon-neutral is an area of research that must continue to be actively pursued.***

## 2.2 Outcome implementation areas

Individual scientific breakthroughs resulting from fundamental research in underpinning disciplines are hugely important to the generation of rapid and sustainable gains in the productivity, profitability and sustainability of agricultural systems. However, agricultural systems are also extremely complex and such innovations, and the production systems into which they may be deployed, have to be adapted to each other to generate the best possible outcome while minimising the potential for negative foreseen or unforeseen consequences. In this regard, agricultural production systems are becoming increasingly more complex and sophisticated as information technologies, in particular, are more broadly applied[51]. Indeed, it is likely that multiple emerging technologies will be used in combination, reinforcing each other and driving greater impact.

### 2.2.1 Increased productivity through integrated farming systems

Changes in farming systems have been amongst the biggest drivers of productivity gains in Australian farming in the past 50 years. The source of these gains is diverse—ranging, for example, in the case of minimum-till from better moisture management, reduced soil erosion and compaction to lower disease incidence and, importantly, early crop seeding to maximise growing season length. However, in all farming systems the extent of the gains realised are environment-dependent (e.g. soils, climate) and as detailed in Box 2.1 even the most apparently simple changes can bring with it the seeds of other problems—in that case reduced weed control. Minimum-till provides a strong example of the complex consequences, both positive and negative, often encountered when existing management systems are perturbed. It underlines the need for greater development and use of state-of-the-art modelling systems for extensive scenario testing and assessment.

[51] Manyika et al. 2013. McKinsey Global Institute report.

Optimising water use in agricultural production is one of the most important integrated farming systems activities that can lead to significant productivity gains. As dryland farming dominates Australian field cropping, efficient use of the limited water available is paramount to productivity. Much has already been done on this front but there are still promising avenues, the efficacy of which will continue to rely heavily on integrated whole-of-system approaches[52]. For example, the simultaneous deployment of multiple changes in management practices can result in synergistic improvements in water use efficiency[53]. Improving seasonal forecasts, soil additives or better genetics that respectively lead to better matching of crop growth with rainfall, reduced in-crop evaporation or better tolerance of extremes—heat, water deficit and frost—all have the potential to lift productivity significantly. Changing climatic conditions that lead to new combinations of temperature, precipitation, evaporation and humidity will interact with crops and livestock, and with pests, weeds and diseases, in ways for which we will often have no past analogy upon which to draw. Even within simple statistics such as increasing temperatures, it is more subtle measures such as the length and intensity of temperature extremes or the extent of higher night-time temperatures that will have the greatest impact on heat stress on animals and plants, or on plant growth respectively.

These examples support the need for (and potential of) highly integrated approaches with strong involvement of information and digital technologies to improve the productivity and sustainability of farming systems. Integration and optimisation of remote sensing, crop modelling and real-time monitoring systems with more traditional knowledge of the physiology of crops and livestock are already realising productivity and sustainability advances in areas as diverse as multi-scale soil nutrient mapping; precision livestock management from the paddock to large catchment scale; and prediction of current and future frost-prone areas. This is the way of the future.

The long-term success of integrated farming systems that generate major improvements is highly dependent on successful integration of a diverse array of monitoring technologies, big data analytics and in-depth knowledge of plant and animal physiology and ecological interactions brought together in sophisticated

[52] Barlow S, Fischer T, and Mareels I. 2015. Optimising water use in agricultural production. Focus April 2015.

[53] Kirkegaard JA, and Hunt JR. 2010. Increasing productivity by matching farming system management and genotype in water-limited environments. Journal of Experimental Botany 61:4129-4143.

modelling approaches that generate meaningful, easily comprehensible and executable advice for practical on-ground use.

*Future opportunities*

Realisation of the maximum potential of the major changes sweeping through the basic biological sciences, robotics and automation, climate science, and information technologies can only occur through the integrating hub of farming systems science. ***Ensuring that this key area of research and delivery is well resourced is essential to achieving continued growth in agricultural productivity and profitability.***

### 2.2.2 Biosecurity

***Areas of application:*** disease and pest control strategies; animal vaccines; local, regional and national quarantine.

***Contributing disciplines:*** evolutionary biology; biomedical science; pathology; molecular biology; ecology.

Australia's agricultural producers have long benefited from the country's relative geographic isolation and a strong ongoing quarantine process that has successfully managed to exclude multiple weed, pest and disease species that, if introduced, could substantially impact both plant and animal production. However, with ever-increasing personal mobility and international trade, our agricultural industries are under constant threat. The potential impact is not always easy to determine, but the cost of existing introduced weeds to the grains industry exceeds ~$3.3 billion per annum[54]. Major horticultural industries such as almonds and pome fruit would be put at serious risk (up to 40-90% decline in fruit set and size) if the varroa mite that attacks honey bees became established. An outbreak of foot-and-mouth disease would result in the indefinite closure of all international markets to beef, sheep and other cloven-hooved animal exports. Outbreaks of highly contagious avian diseases routinely result in the destruction of large numbers of birds and highly restrictive quarantine impositions on farms and whole districts.

Australian science needs to continue to devise new approaches to:

1. prevent invasive weeds, pests and diseases entering the country
2. respond more effectively to novel incursions with the aim of elimination

[54] Llewellyn RS, Ronning D, Ouzman J, Walker S, Mayfield A and Clarke M. 2016. Impact of Weeds on Australian Grain Production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. GRDC Report ISBN: 978-1-921779-91-6

3. devise efficient, durable methods for countering those that are already present and cannot be eliminated.

*a) Over-the-horizon intelligence*

Maintaining the integrity of Australia's borders is a vital yet challenging and ongoing reality. The level of knowledge concerning different potential invasives is highly variable—a great deal is known about major animal diseases, while that for many potential weeds and plant diseases is quite limited. As with many other research focus areas, traditional approaches involving relatively unsophisticated assessments of potential future distributions need to move to more holistic approaches that assess potential patterns of spread in light of detailed knowledge of existing land use, soil types and climatic patterns (and how they are changing through time). In the case of pests and diseases, additional consideration needs to be given to dynamic changes in host (crop or livestock) genetics and distribution patterns; the extent to which invasive organisms may move in and out of non-agricultural lands; and the potential that interaction with other secondary host species may lead to changes in the pathogenicity of the invasive organism.

Furthermore, as agricultural development ramps up in northern Australia, a significant part of the spatial quarantine protection afforded to many agricultural industries by virtue of the relative lack of cropping in the region will decrease significantly. In addition, given the likely size and isolation of agricultural operations in the north, the level of surveillance of growing crops and livestock may be lower. As a consequence, new pests and diseases may only become apparent after they have already established a significant bridgehead into the country. In the case of livestock diseases this may also include the possibility of spread into feral populations with concomitantly even greater difficulties associated with eradication. To maintain a degree of spatial quarantine protection, spatial modeling approaches could assist with the design of agricultural land use patterns.

*b) Control strategies for established pests*

Control methods for weedy species have traditionally been based on cultivation, grazing and the use of herbicides; for pests and diseases of livestock on genetics, therapeutics, chemicals, isolation and slaughter; and for pests and diseases of crops on genetics, pesticides and cultivation. The use of genetics is a very powerful means of achieving control over many pests and diseases but selective forces generated by the unsophisticated use of genetically based resistance can also be very powerful in inducing changes in the infectivity and aggressiveness of disease-causing organisms. Similarly, repeated and monotonous use of herbicides and pesticides can also induce selection for resistance in weeds, pests and pathogens. A consequence of

ignoring the evolutionary potential of weeds, pests and diseases through an over-reliance on simple genetic and chemical approaches is that management of these organisms often lurches through repeated cycles of control and loss of control.

In future, control strategies that involve greater consideration of the evolutionary potential of target organisms need to be devised and implemented. New advances in gene technologies and especially gene editing in plants have opened the way for novel resistance gene deployment strategies (for example, multi-gene cassettes; varietal mixtures) which, when set in a whole-of-farm or region systems context, may impose much more complex sets of selective forces on pathogen populations. In a similar way, opportunities for the more sophisticated use of chemical control of weeds and of therapeutic agents in livestock husbandry should focus on addressing evolutionary weak points in the target organism. Much of this has been recognised for some time, but more effective delivery via interactive decision support tools is essential to provide longevity to increasingly expensive chemically based solutions.

*c) Threat profiles and changing climate*

Weeds, pests and diseases are all biological agents that have the potential to adapt to their environment. A major future need is to address the threat that these organisms may pose as changes in climate—such as the amount and seasonal timing of precipitation, temperature and humidity—drive changes in their ecology and spatial distribution. Such changes have already been documented with respect to several insect-vectored zoonotic diseases including Ross River and Dengue fevers, both of which now are occur further south than previously. Modelling approaches that integrate environmental changes with the ecology of the species and the current and future likely nature of farming operations is essential to provide guidance for future control strategies.

### Future opportunities

Pests, diseases and weeds have a major impact on all forms of agriculture, substantially reducing productivity and profitability. ***Increasing trans-global movement of people and products combined with changing environmental conditions that drive changing distribution envelopes, underline the need for continuing investment to maximise productivity, minimise control costs, and retain open international markets for Australian plant and animal produce.***

### 2.2.3 Sustainable resource base

***Areas of application:*** long-term sustainability and resilience; on-farm biodiversity management; ecosystem service benefits; alternative land-use.

***Contributing disciplines:*** molecular biology; chemistry; evolutionary biology; systems modelling; pathology; entomology; climatology; soil sciences; remote sensing; ecology.

The resource base for agricultural production is complex, covering both the immediate arable and grazing lands as well as surrounding semi- or natural vegetation. Maintaining these is vital to ensuring a sustainable resource base as well as earning a social licence to operate.

#### *I - Soil–plant interface*

Understanding, controlling and manipulating below-ground interactions involving plants and the soil environment has great potential to generate significant productivity and sustainability gains for Australian agriculture. Soils and their biotic and abiotic characteristics are a fundamental resource underpinning virtually all plant and animal agricultural production. However, given that soils are the most complicated biomaterial on the planet[55], it is not surprising that, in contrast to the huge amounts of information available with regard to above-ground plant performance, knowledge concerning the physical and biological soil–plant interface is still very patchy.

There are many ways in which a deeper knowledge of soil–plant interactions could benefit all agriculture. For example, the development of new crop varieties with greater nutrient and water foraging abilities would be significantly advanced by a better understanding of root architecture and how plants explore and exploit different soil environments. However, the complexities of soils—their geological origins, chemistry, diverse biological content and the ways in which conditions can alter dramatically over extremely small spatial scales—makes effective research and application the domain of diverse multi-disciplinary teams involving biologists, biogeochemists, ecologists, agronomists and spatial modelers among others.

The genomics revolution has provided a very powerful set of tools with which to uncover the diversity of organisms that make up soil communities. Such studies have been immensely valuable in sketching a picture of the diversity present, but

[55] Young IM and Crawford JW. 2004. Interactions and self-organization in the soil-microbe complex. Science 304, 1634-1637.

major questions remain around many issues including: levels of redundancy among soil organisms; functional links between below-ground processes and plant performance; second-order interactions with animals; the ways in which micro-organisms affect the availability of nutrients; the role soils play in sequestering carbon; and the contribution of soil biology to agro-ecosystem sustainability. Pressing questions that lie at the centre of an understanding of the complexity of soils and how they should be managed for productivity and sustainability include:

1. how to effectively 'bridge' the soil microbial community structure–function gap
2. the relationship between soil microbial assemblages and plant growth performance
3. whether such information can be used in a practical manner to promote sustainable production and system stability.

### *a) Towards functional genomics*

The era of simply identifying and cataloguing the biological component of soils is coming to an end. Knowing that soils contain a multitude of species, many of which are currently unculturable, and that the structure of these communities varies in line with associated plant and animal production systems, needs to be replaced by a 'functional genomics' approach directly linking processes and microbiome results (e.g. transcriptomics) to plant responses. Major issues will include understanding the significance of functional redundancies in soil microbes and the interplay of this in a temporal and spatial setting.

### *b) The microbiome as part of the extended phenotype*

Instead of asking questions about individual traits, especially in such a complex environment as the soil, questions need to be cast at a systems scale—essentially at a multi-trait loci/holistic community or extended phenotype level. This becomes particularly apparent when one bears in mind the long-demonstrated importance of the rhizosphere where mycorrhizal fungi provide more than 80% of plant species with a broader sphere of influence than that generated simply by direct contact between individual roots and root-hairs and the soil.

The challenging questions include: how to measure the extended phenotype; what is its relevance; and in knowing this, how can we derive benefit? To do this will require a shift in focus from looking at the 'phenotype of an organism' at the scale of the individual variety towards considering the phenotype of the production system. For very many species in the system—bacteria, fungi—the concept of an

extended genome or phenome is a reality with horizontal gene transfer being an important evolutionary process.

*c) Manipulating soil communities*

Manipulation of soil microbial communities has long been practised; for example, the use of specific rhizobial strains, incorporation of microbial biocontrol agents aimed at specific pathogens or use of the allelopathic effects generated by some plant exudates. While such approaches may be more or less successful in the immediate term, they are essentially inundative approaches that rarely have an ongoing impact on the community. At the same time, planting a crop into fallow land, or the growth of a nitrogen-fixing legume, typically sees a response by the soil community such that the community present at the end of a season is often very different from that at the beginning[56]. Whether the derived community provides benefit or is detrimental to the associated plant community is rarely clear and, more importantly from a management perspective, currently is an ephemeral change. Being able to consciously select the soil microbiome has the potential to significantly influence productivity and sustainability. Lack of understanding of resilience, redundancy and processes in the rhizosphere where biology, chemistry and physics interact[57] currently precludes predictable management-driven manipulations.

### Future opportunities

The interface between plant roots and the soil microbiome is still largely a 'black box' with regard to a true understanding of the functional diversity of the soil microbiome, the role of redundancy and the reciprocal ways in which plants and the microbiome influence each other. ***A sustained emphasis on funding is required to move this understanding to the point where practical manipulation to improve the productivity and sustainability of agriculture is possible.***

### *II - Ecosystem resilience*

The conservation and maintenance of natural communities is an increasingly important component of the long-term sustainable use of Australian landscapes. Agriculture and the maintenance of the diversity of Australia's flora and fauna are inextricably linked. Over 60% of Australia's land mass is controlled by agricultural enterprises; within this headline figure some natural ecosystems are far more heavily affected (e.g. white box woodlands of eastern Australia) while the

[56] Osborne CA, Peoples MB, and Janssen PH. 2010. Detection of a reproducible, single-member shift in soil bactieral communities exposed to low levels of hydrogen. Applied and Environmental Microbiology 76:1471-1479.

[57] Hinsinger P, Bengough AG, Vetterlein D and Young IM. 2009. Rhizosphere: biophysics, biogeochemistry and ecological relevance. Plant and Soil 321, 117-152.

consequence of some agricultural practices such as water extraction, nutrient run-off and excess use or dispersal of herbicides and pesticides has the potential to affect rural and urban communities and other major industries such as tourism.

Increasing community concerns regarding environmental integrity, health and changing climate will see greater expectations placed on agriculture to adopt new approaches to minimise detrimental effects. This will include not only effectively addressing existing issues such as water extraction, nutrient run-off, and excess use or dispersal of herbicides and pesticides, but also increasing expectations that agriculture will make significant contributions towards greenhouse gas emission targets. Failure to address these issues is likely to see an increase in legislative requirements and controls. However, the opportunity exists to use these looming pressures to institute changes in farming practices that will lead to more effective nutrient application and use, reduced effluent discharge and improved quality and 'health' of our soils. Indeed, agriculture stands to gain through a range of beneficial interactions (or 'ecosystem services'), particularly those associated with water storage and efficient utilisation, pollination, and pest control, as well as opportunities to meet consumer demand for 'clean and green' quality produce.

To ensure these benefits accrue emphasis needs to be given to:

*a) Transfers across the agri-ecological interface*

Although agriculture has evolved a very long way from its initial development at the close of the hunter–gather phase of human history, understanding the operation of the natural world still has considerable relevance to some aspects of farming systems. This is particularly the case in biotic interactions involving pests, diseases or beneficials where past lack of attention to the dynamic nature of interactions between these organisms and crops or livestock has often resulted in ephemeral success in pest and disease control.

The interface between agriculture and wild and or weedy vegetation—whether occurring as narrow strips between adjacent fields (e.g. European hedgerows) or more substantial blocks of natural or semi-natural vegetation, provides opportunities for pest and disease reservoirs, or environments in which new infectivity may arise through selection and recombination. These possibilities have the potential to cause major economic loss in both plant and animal production industries (see also 2.2.2 Biosecurity) with collateral zoonotic spread to the human population (e.g. the association between Hendra virus, flying foxes, horses,

vegetation and humans[58]). Similarly, this interface may be important in providing reservoirs for beneficial insects—for example, pollinators or invertebrate predators of crop pests. Understanding the extent and magnitude of such interactions and how to value them is an important part of holistic IPM programs.

### *b) Landscape-level management*

There are always likely to be tensions among different sectors of society as to the way in which finite resources are utilised. With increasing demand for such resources and the real possibility of reductions in their availability (e.g. water), decisions regarding their utilisation will inevitably need to take a broad spatial view to ensure that actions taken at one place in a catchment are done in full knowledge of their consequences for other users elsewhere. Major efforts need to be made to develop modular integrated management systems capable of scaling across the continuum from the sub-paddock, to the paddock, farm, and ultimately watershed and landscape scale. Research teams and institutions need to bring expertise in paddock-scale production together with expertise in cross-landscape transfers and in functioning of rivers and wetlands. Indeed, the delivery of water to finely tuned intensive agriculture needs to be managed on a basin scale. At the larger spatial scales such systems would need to accommodate the needs of multiple users with different requirements and expectations.

### *c) Land use under warming scenarios*

Given changing climatic conditions in Australia, it is increasingly likely that over the next few decades land use patterns in currently more marginal cropping and rangeland grazing areas will change. Such changes may involve shifts in crop mix, changing balance between cropping and grazing or even abandonment of marginal lands as has occurred in the USA in recent decades[59].

What sort of vegetation communities do we want these lands to regenerate into? Questions about the appropriate mixture of cropping with grazing on natural vegetation in different zones will need to be thought through afresh. Abandonment without some intervention runs the risk of major weed infestations and increased cover for feral animals that may act as reservoirs for important exotic livestock diseases (e.g. foot-and-mouth) should they circumvent quarantine controls.

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[58] Field, HE, Breed, AC, Shield, J, Hedlefs, RM, Pittard, K, Pott, B and Summers, PM. (2007). Epidemiological perspectives on Hendra virus infection in horses and flying foxes, Australian Veterinary Journal 85, 268-270.

[59] Zumkehr, A. and Campbell JE. 2013. Historical U.S. cropland areas and the potential for bioenergy production on abandoned croplands. *Environmental Science & Technology* **47**, 3840-3847.

Finally, some topics of significant importance—for example, understanding the evolution of invasive weeds, or of pathogens and pests of crops—while highly relevant under this heading are also considered under other topics such as biosecurity (Section 2.2.2.). Similarly, the ways in which agriculture may reduce the extent of nutrient and sediment export are, in the context of this plan, more appropriately considered in Section 2.2.1.

### Future opportunities

Most Australian agricultural enterprises are embedded in a landscape of nature vegetation and ecosystems. The interaction between these different elements has the potential for major impacts and will continue to evolve as climate change effects become increasingly apparent. ***To maintain agriculture's licence to operate with minimal regulation and restriction and maintain a market clean–green image, there needs to be a continuing focus on research investigating ways to minimise disbenefits (particularly those associated with nutrient and farm chemical pollution) while maximising positive ecosystem services. Research institutions need to build teams that unify expertise in on-farm production with expertise in functioning of other landscape components and in transfers of water, sediment, chemicals and organisms between landscape components.***

## 2.2.4 Increasing value through quality and market advantage

***Areas of application:*** food quality; personalised nutrition; market chain integrity.

***Contributing disciplines:*** molecular biology; chemistry; food science; logistics.

*Quality*

Consumer preference is an increasingly important driver in agricultural production. Initially more focused on horticultural industries where consumers typically have more direct contact with the raw product, market signals are increasingly directing changes in quality and nutritional value across all plant and animal production systems. A particular driving force is recognition in all levels of society that improving the nutritional quality of agricultural produce is critical for global food security and human health. All governments face financial pressures associated with rapidly increasing health care costs reflecting the rising incidence of various 'lifestyle' diseases such as diabetes, obesity and colo-rectal cancer, all of which have a strong diet-related component. Manipulation of the genetics and management regimes under which plants and animals are produced for market can significantly change the nutritive value of products with resultant consumer health benefits.

Performance of cereals in traditional food processing is determined not only by their protein content and characteristics, but also by other major constituents (starch, fibre, lipids) and their complex interactions. Many of these traits can be manipulated genetically, leading to beneficial impacts on human health and nutrition. Manipulation of biosynthesis genes encoding starch synthases and branching enzymes, to increase resistant starch levels and lower the digestibility of cereal grains, brings benefits for gut health and lowers the risk of cardiovascular and other diet related diseases. Similarly, the fatty acid, micronutrient and vitamin composition of seeds can be manipulated to engineer new profiles with improved nutritional and functional properties. For example, by using *Agrobacterium* transformation approaches the provitamin A (B-carotene) biosynthetic pathway has been inserted into rice endosperm resulting in grain with the potential to counter vitamin A deficiency—a serious public health problem in many parts of the world[60]. In animals, breeding programs have changed protein profiles in cow's milk and in combination with management and feed regimes have significantly changed aspects of beef, chicken and other meats (e.g. texture; percent fat). Cow's milk can be altered to reduce digestive difficulties or even mimic human milk.

In some cases the genetic manipulation of plant or animal product quality has been achieved through conventional means; in other cases more complex GM technologies have had to be deployed. Clearly the future of more fundamental changes in the quality and nutritional value of animal and plant products will be the subject of on-going debate but regardless of this the increased focus on health care and preventative medicine means that there will be a continuing drive to improve the quality and nutritional value of farm products.

### *Market advantage*

Grower decisions around what to grow and when are influenced by an increasingly broad range of factors ranging from prices on futures markets to issues that are much more directly linked to the consumer. The various consumer-based campaigns seen in recent years—for example 'food miles', 'fair-trade', organic production, free range egg production—are all evidence of an increasing interest by consumers in the processes whereby agricultural products are grown, harvested, prepared and delivered to the consumer. Consumer attitudes drive buying decisions by marketing chains leading to significant issues around post-harvest losses and the development

[60] Beyer, P, Al-Babili, S, Ye, X, Lucca, P, Schaub, P, Welsch, R. and Potrykus, I. 2002. Golden Rice: Introducing the β-carotene biosynthesis pathway into rice endosperm by genetic engineering to defeat Vitamin A. The Journal of Nutrition 132:506S-510S.

of just-in-time supply chains. Similarly, the need for security in uncertain times is driving the need for product traceability back to the individual farm or even paddock level. Such traceability becomes vital in public health moves to rapidly isolate parts of the supply chain that fail to meet appropriate safety standards. Indeed, safety through the traceability and the rigour of our food safety systems is an important market driver as seen in the market in China for Australian milk and milk products. Increasingly, products that can be given a 'human face' through linkage to individual farms are likely to see favour with consumers. Whether this leads to a new premium for growers or simply avoids a discounting process is yet to be seen but there is no doubt that consumers and marketing chains will demand increasingly tough quality assurance and supply-chain protocols.

### Future opportunities

Lifestyle diseases related to diet impose a significant cost on the Australian economy in terms of health care costs, increased morbidity and reduced workforce effectiveness. ***Improving population health through proactive dietary means is a practical and achievable outcome provided sustained support is given to research aimed at generating fundamental changes in the nutritional quality of the basic ingredients entering the food manufacturing chain.*** Social research is needed to help introduce these health benefits to a community that is skeptical about what they see as fads in nutrition, while increased emphasis must be placed on systems that enhance product safety and traceability of origin.

## 2.3 Other transformational technologies

Agriculture, like any other human activity, is not exempt from the impact of new transformational technologies. Indeed, the advent of mobile internet is already having a profound effect on aspects of agricultural production. Ready 'anywhere' access to the internet[61] is driving rapid change in the way and speed at which agronomic and market information is delivered—partly offsetting declines in extension services previously provided by state government agencies. Demand for wireless technologies will continue to grow rapidly as big data analyses and innovative farming systems management approaches provide more detailed content and the opportunity for interactive learning and decision-making processes.

Some transformational technologies impacting agriculture today have been considered in sections 2.1.1: Next-generation genomics; 2.1.2: Smart IT and 2.1.3:

[61] It is recognised that high-speed internet connection is yet to be achieved in some rural areas of Australia.

Big data. Here we address additional transformational technologies that have yet to be applied to agriculture but appear to have great potential.

Renewable energy and energy storage are both regarded as disruptive or transformational technologies[62]. Over the last few years there has been a major surge in domestic and SME use of solar panels but, as yet, relatively little application of renewable energy to agricultural operations. However, for agriculture the increasing availability of reliable, scalable, low-cost energy storage systems is particularly exciting as, beyond initial capital costs, this opens the door to a range of extended hour operations with near zero-cost energy inputs. Thus while lithium-ion battery systems have particularly caught public attention, different technologies such as flow batteries offer other major advantages. For example, vanadium redox flow batteries are now commercial and are currently the cheapest storage technology for applications requiring storage of up to 8 hours[63].

It must be anticipated that battery technology will continue to improve and within the foreseeable future next-generation storage systems perhaps used in hybrid systems with back-up diesel generation will be able to provide very low-cost 24 hour power supply. The impact of this is yet to be felt in agriculture but could include greater intensification and greater use of controlled environments particularly in horticultural production. It may even move to more localised (farmer co-operative style) manufacture of inputs that have a high energy demand during manufacture (e.g. nitrogenous fertilisers). As the full implications of on-site energy generation and storage become apparent, novel uses that need radical redesign of current systems and operations will be an inevitable consequence.

Similarly, 3D printing has the potential to provide great benefit to agriculture. The ability to manufacture items in real-time, locally, provides efficiency savings to producers, particularly those in remote locations with limited access to suppliers.

## 2.4 Agriculture's role in the National Science and Research Priorities

A wide diversity of researchers across Australia identified six specific research areas that are seen to be the most likely to contribute to advancement of the productivity, profitability and sustainability of Australian agriculture in the near future. These research areas—development and exploitation of genomics, agri-intelligent technologies, big data analysis, sustainable chemistry, coping with climate variability

[62] Manyika et al. 2013. McKinsey Global Institute report.

[63] Energy Storage Association. Vanadium redox (VRB) flow batteries. http://energystorage.org/energy-storage/technologies/vanadium-redox-vrb-flow-batteries. Accessed 15 February 2016.

and molecular engineering—while important in their own right, rely on integration of their individual findings to ensure increased productivity, enhanced biosecurity, maintenance of a sustainable resource base and increased product value through quality and market advantage.

The Australian Government's National Science and Research Priorities[64] outlines 'a set of Science and Research Priorities, and corresponding Practical Research Challenges, designed to increase investment in areas of immediate and critical importance to Australia and its place in the world.' It also assesses corresponding areas of existing research strength and new opportunities in Australia.

Agriculture is intimately connected with many of the nine priorities identified (food, soil and water, transport, cybersecurity, energy, resources, advanced manufacturing, environmental change, health). Taking the three most directly applicable priorities of food, soil and water and environmental change, it is possible to show substantial agreement between the specific priorities and outcome implementation areas identified in this plan and the capability assessments made by the Australian Government against its declared priorities.

For example, the capability statement for the priority 'food' notes that Australia's relevant research strengths are in biology, agricultural biotechnology, plant science and biosecurity: all areas that fit within this plan's specific research areas or, in the case of biosecurity, an important and desired outcome. The national priorities assessment did not confine itself to scientific and research-related issues as this plan does, but to the extent that it identified scientific practical challenges (including technologies such as robotics and real-time data systems; food quality and safety, biosecurity, and genetic technologies to adapt to changing growing conditions) they are similarly identified herein. Regarding the opportunities assessment in the national science and research priorities, this plan shares observations such as a need to facilitate technology transfer and encourage cross-disciplinary research, and also presents a strong case that the human capacity and funding arrangements in Australia need reform to allow us to capitalise on these opportunities.

While the scope, process and stakeholders that were engaged during the development of the national priorities were independent and quite different from this plan, the level of agreement between the research priorities in both reports—in the areas where the scopes overlap—provides a measure of confidence and a strong indication that the priorities are indeed worth pursuing.

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[64] Commonwealth of Australia, 2015. Science and Research Priorities and Practical Research Challenges. http://www.science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx Retrieved 29 July 2016.

Pivotal to success of these science solutions for the future is the human capital required to implement them and the funding arrangements required to support both the people and the research. Chapter 3 examines current trends in Australia's agricultural science capacity, and Chapter 4 examines a funding model that would provide a suitable framework to support Australian scientists to rise to the ever-increasing challenges facing agriculture into the future.

# 3 Addressing capacity

Agricultural sciences is an all-embracing term with contributions commonly from other sciences—such as chemistry, physics and biology—as well as from engineering and technology. As a consequence, it is a major challenge to accurately assess the agricultural component of capacity training from all relevant areas. For the purposes of this analysis, focus was directed to 'mainstream agriculture' representing agronomy, livestock and horticultural sciences. Capacity to deliver the agricultural science agenda involves a whole-of-education supply chain approach. It starts with capturing the minds of school children and ends with qualified practitioners to create and implement innovation. At that point the funding opportunities determine both the direction and output of new ideas and processes that deliver innovation in the agricultural economy.

## 3.1 The education supply chain

Understanding the process whereby students are trained and successfully contribute to science-based improvements in agriculture is greatly complicated by the diversity of contributing disciplines. The primary focus of many disciplines (for example, mathematics, engineering and chemistry, but even many parts of animal and plant sciences) often makes no mention of agricultural applications. Consequently capturing even relatively basic data about their contribution to agriculture is extremely difficult. In contrast, information about university training in agricultural science programs is far more readily available. In this chapter we focus initially on this aspect of agricultural science capacity before expanding to a broader consideration of the availability of relevant research.

Our capacity to undertake research and deliver outcomes to agriculture in terms of productivity and sustainability starts in the school system where students are either inspired by agriculture and science or are 'turned off'. In response to negative perceptions, the invigoration of science teaching in the classroom has become a focus to ensure primary school students remain engaged with science and enter secondary schools with an open mind.

Changing perceptions about agriculture has been a particular challenge in secondary schools, with career advice commonly directing students away from agriculture. Such advice has been based on misconceptions that career options in agriculture are poor. A severe shortage of graduates and other skilled people in agriculture highlighted to agricultural industries that it was their responsibility to provide a positive sector image, to address social licence issues and to promote their industries as having rewarding career options.

Figure 3.1 describes the education and research training supply chain as it now operates in Australia. University intakes are determined by secondary school student interest which is triggered by knowledge and understanding of rewarding career options. Successive intakes determine the annual enrolments in agriculture courses in universities. Enrolments determine the funds received by universities and thus their capability to deliver quality courses. This pipeline of students determines the number of graduates in any year to meet the employment needs of agricultural industries. As part of the process, industry should ensure that schools are continually made aware of employment prospects through positive promotion of careers. Graduates have options of a research career or an immediate move into a range of agribusiness activities. Those seeking a research career are complemented by an additional cadre of graduates from other science areas (particularly plant and animal sciences) whose research interests, while often more focused on basic investigations, are highly relevant to the future. However, in all cases, ensuring that sufficient students take the research option requires attractive conditions for higher degree study, sustainable levels of research funding and a clear career path for the doctoral graduate.

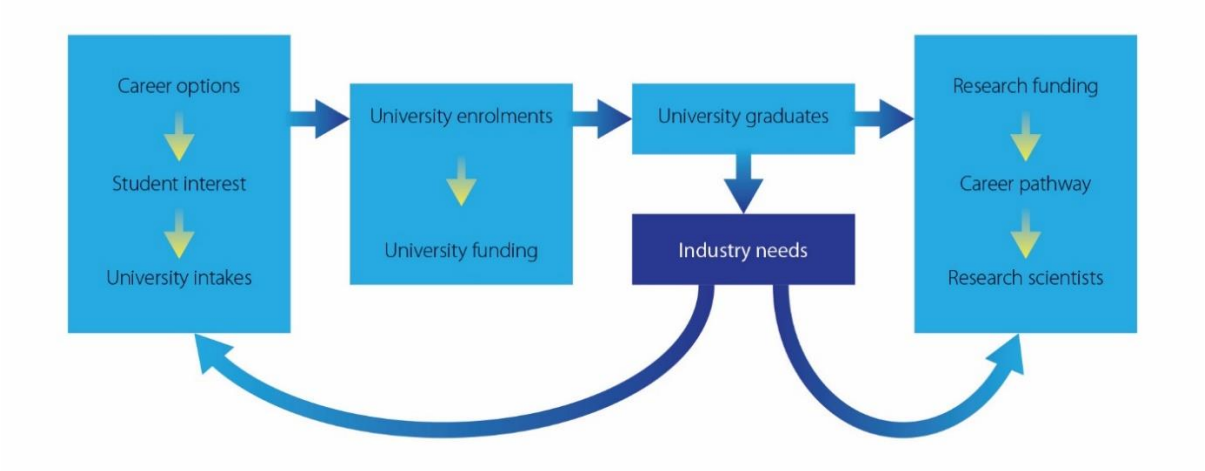


Figure 3.1: The supply chain in education and research training in agriculture in Australia. Each box represents separate components in the chain; the yellow arrows are determining directions[65].

Much has been written of the poor image of agriculture in the first decade or so of this century. An active campaign to change that perception, together with a buoyant job market and the concerns about global food security, have resulted in a substantial turnaround and the portents for improving the supply of agricultur graduates are encouraging. Action in the school system in promoting agriculture and

[65] Pratley J. 2016, Australian Council of Deans of Agriculture, Australian Farm Institute's quarterly newsletter vol.13 No 2, School of Agricultural and Wine Sciences, Charles Sturt University.

food, together with associated positive media coverage, has helped to improve community attitudes as well.

### 3.1.1 University intakes into agriculture courses

There has been a long-term decline in higher education intakes into agriculture in Australian universities, dating back to at least the early 1990s. The decline was particularly severe from 2001, as shown in Figure 3.2, with 2012 being the low point—a 45% decline in that time. Since then there has been a stabilisation and slight recovery in numbers with the upward trend in 2013 and 2014 continuing through to 2016 according to unofficial advice from the universities. Similar but worse trends have also been experienced in horticulture/viticulture and agribusiness programs over the same period (Figure 3.3). The decline is reflective of the perceptions of students towards agriculture. The recovery since 2012 most likely represents the response by students to the modernised image of the sector and revelations regarding job opportunities.

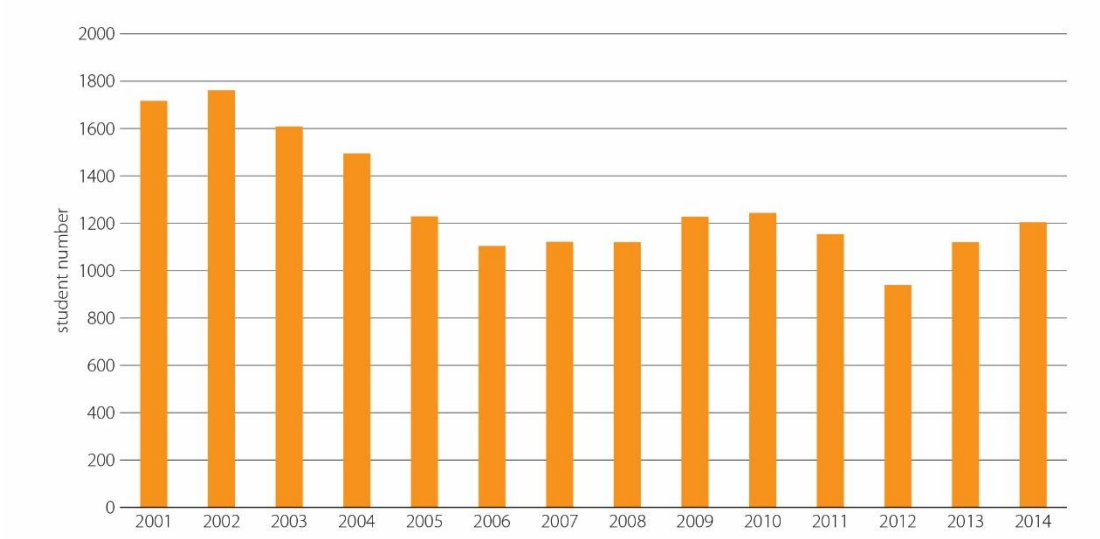


Figure 3.2: Intakes into undergraduate agriculture courses in Australian universities 2001-2014.

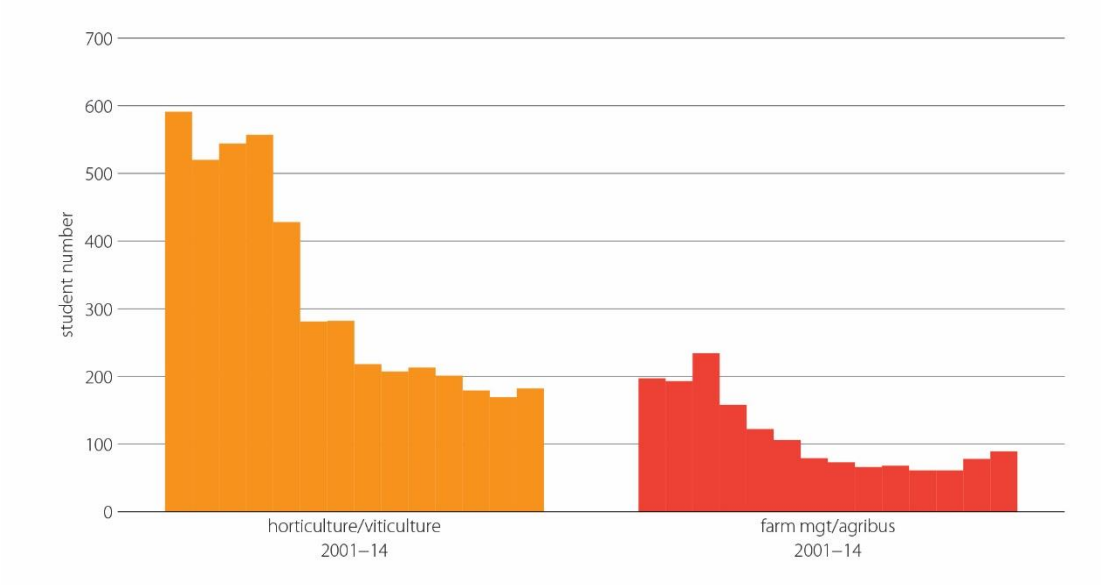


Figure 3.3: Intakes into undergraduate horticulture and farm management courses in Australian universities for the period 2001-2014.

A decline in intakes triggers a potent negative feedback cycle as lower total enrolments in such academic programs threatens their sustainability, given that universities are funded according to enrolments. This trend is shown in Figure 3.4 with enrolments falling from 4300 to 2500 over the period 2001 to 2014. The decline equates to the loss of around 100 academic staff from the system, resulting in compromised courses and diminished academic capability. Although there has been a recent partial recovery in intakes, there is a lag phase to improvement in total enrolments and a further lag to the recruitment, if any, of replacement academic staff. Turnover of staff, however, does allow for the introduction of new technologies and sciences and adjustments in course curricula to reflect modern agriculture. Of interest is the gender ratio across university enrolments. Often considered a male domain, data show that women are now at least half the student cohort and have been since 2002.

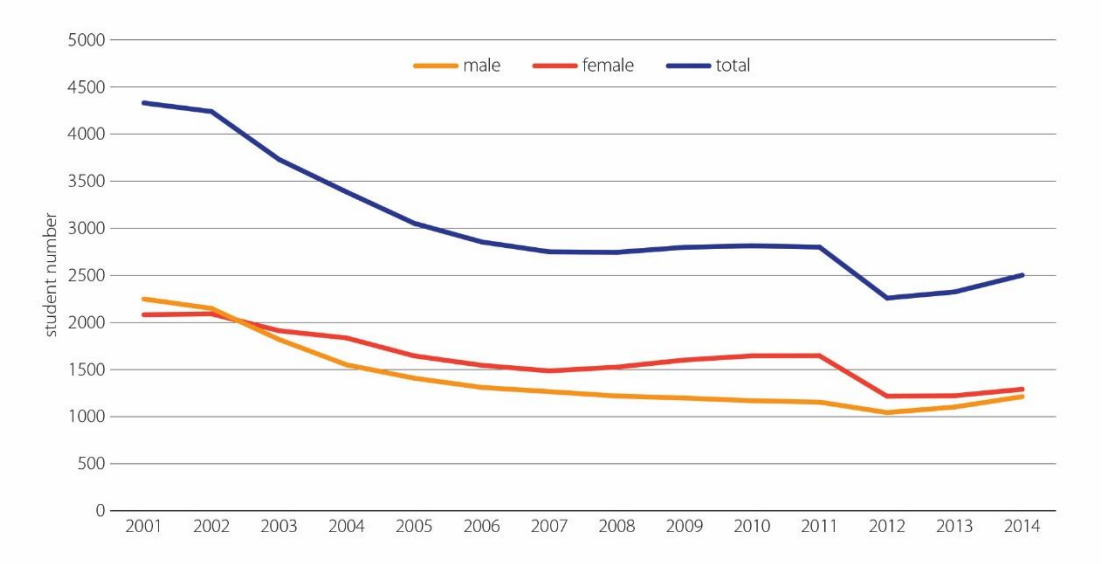


Figure 3.4: Enrolments in agriculture programs by gender in Australian universities 2001-2014.

One outcome to arise from this decline has been the realisation by industries that universities do not retain programs that are not financially viable. Whereas in times gone by, universities may have preserved an area of study for its own sake, modern universities are now medium-sized businesses in which financial considerations are highly influential. Thus, over the past 25 years there has been significant rationalisation of campuses and of courses delivering agricultural instruction. Further rationalisation in recent times has been averted with the turnaround in intakes. New programs have been introduced. The world food crisis, the aspirations of the emerging Asian middle class and various free trade agreements have rekindled interest in food production in Australia. This is likely to remain at a high level for at least the coming decade, providing a degree of certainty to educational providers that demand for graduates will continue.

### 3.1.2 Graduate supply and demand

In the last decade or so, industry has complained of the scarcity of university graduates in agriculture. That message has been recognised widely. The problem has been in quantifying such demand. The surrogate measure has been the collation of employment advertisements in newspapers and on the internet and while this is not a perfect measure it at least provides a 'ballpark' figure against which to judge performance (Figure 3.5). The estimates are discounted for duplicate advertising and do not take account of direct targeting of individuals by employers, which is considerable. While the numbers have softened towards the end of the period of monitoring, there is a strong indication that at least 4000 jobs were advertised each

year of the study. These advertisements were spread over the range of occupations and across Australia.

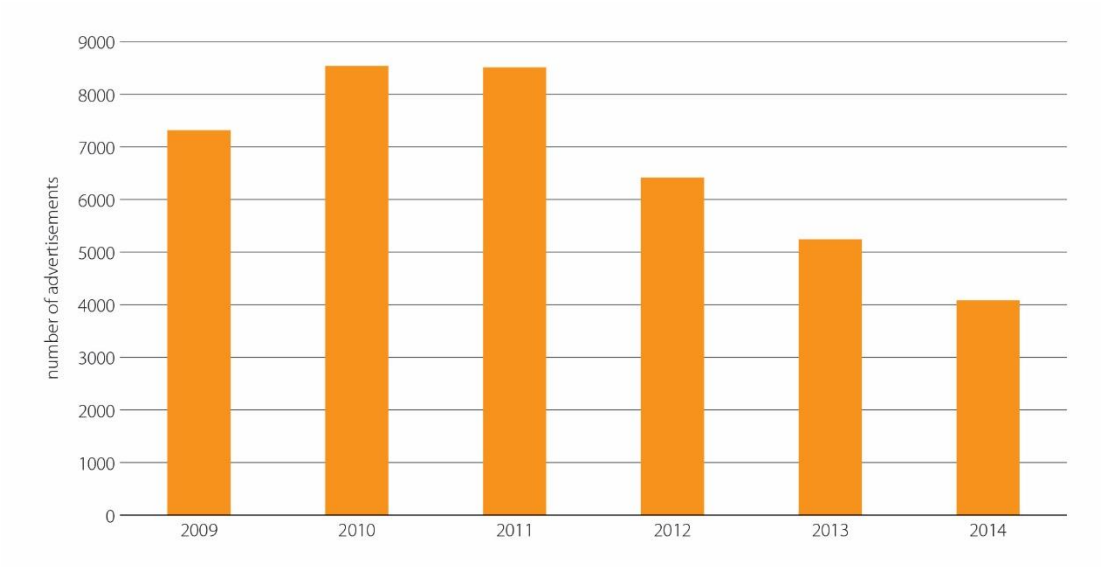


Figure 3.5: Job opportunities for agricultural graduates from Australian universities based on paper and internet advertisements for the period 2009-2014.

The question raised is whether there are sufficient graduates to meet such a demand. Figure 3.6 shows the trend in graduate numbers in agriculture and related areas since 2001 with a shortfall being apparent between supply and demand. If just the agriculture programs are considered, the supply of graduates is around 300 per year. If related courses are added then the number approaches 600 per year. Whichever number is used it is clear that supply is nowhere near satisfying the job market with numbers suggesting at least 6 jobs for each graduate.

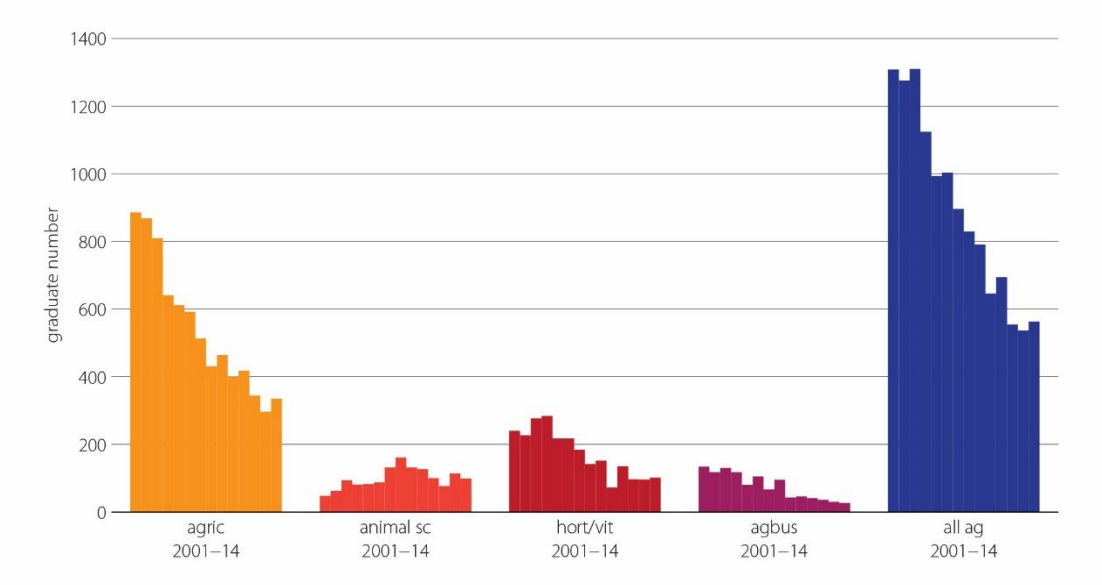


Figure 3.6: Graduates from the agriculture and related undergraduate courses from Australian universities for the period 2001-2014[66].

Another measure is the annual replacement requirement for existing graduates in the agricultural workforce; this is estimated to be around 2300 per year. By any measure, supply falls significantly short of demand, a situation which is not sustainable and threatens the capability of agriculture to meet the technological demands of a sophisticated sector into the future. Economic theory indicates that this imbalance will result in a market response through higher remuneration to those with qualifications. This has certainly happened as agricultural graduates now attract starting salaries in the pre- and post-farm gate service industries well in excess of those offered to most university graduates. The competitiveness of such salaries in business has implications for the attraction of graduates to further study in research training, as discussed later.

## 3.2 Education and innovation

Most graduates gain employment in industry or on farm. In each case they play an important part in the innovation system either through advice to producers or as producers implementing new ideas and practices. They are particularly important in agriculture since the level of higher education training is relatively low in this field compared with other sectors[67]. Innovation has been shown to be related to

[66] Pratley J. 2016, Australian Council of Deans of Agriculture, Australian Farm Institute's quarterly newsletter vol.13 No 2, School of Agricultural and Wine Sciences, Charles Sturt University.
[67] Pratley, J 2013. Review into Agricultural Education and Training in New South Wales. NSW Government. ISBN 978-0-646-59653-2.

education attainment[68]. Studies show that the education level of producers is directly related to productivity growth and broadly influences their disposition towards adoption of new technologies and practices. Adoption is facilitated by knowledge, decision-making skills, attitude to risk and capacity and willingness to innovate. This is shown schematically in Figure 3.7 in respect to on-farm activities and confirmed in studies with the dairy[69] and grains industries in Australia. The study of grain growers, for example, showed that university educated farmers were 29% more likely to be high innovators and 34% less likely to be low innovators than their less well educated counterparts[70]. This translated into higher productivity levels, with university-trained growers 36% more productive than farmers without formal education. Those with TAFE qualifications fell between the two groups.

A confounding factor is the age of the farm owner/manager. Education levels are more likely to be higher in the younger generation whereas decision-making on farm is more likely to be by the older generation—the owners. This conundrum is likely to be holding back innovation and extending by one or two decades the lag time between R&D outcomes and their adoption on farm. This is likely to be accentuated by the relatively recent demise of public extension services. These services are being replaced by the private sector and by electronic means, with the younger generations more likely to access electronic sources.

### 3.2.1 The R&D agenda

As shown in Figure 3.7, the innovation process on farm starts with R&D and there can be no doubt that agriculture has benefited from the long-time contributions from research (Figure 3.8). Some of the benefits come from international spillovers but a significant proportion has been generated in Australia by Australian researchers, or by the involvement of Australian scientists in large-scale, international projects.

The questions are:

- whether this effort and impact will continue to be sustained. This question considers what impact R&D has had on Australian agriculture and whether the R&D effort nationally has consistently met international benchmarks that indicate quality and acceptance.

[68] OECD 2010. The high cost of low educational performance – the long run economic impact of improving PISA outcomes.

[69] Liao, B and Martin, P 2009. Farm innovation in the broadacre and dairy industries 2006-07 to 2007-08. ABARE research report 09.16, Canberra.

[70] Nossal, K and Lim, K 2011. Innovation and productivity in the Australian grains industry. ABARES research report 11.6, Canberra.

- whether the research training system is in good order and positioned well to continue to deliver, and improve, the outcomes of R&D to Australian agriculture. This question assumes a regular supply of trained researchers entering the system, which in turn implies that there is an attractive training path and a clear career structure to ensure that the best minds are encouraged into a science career.

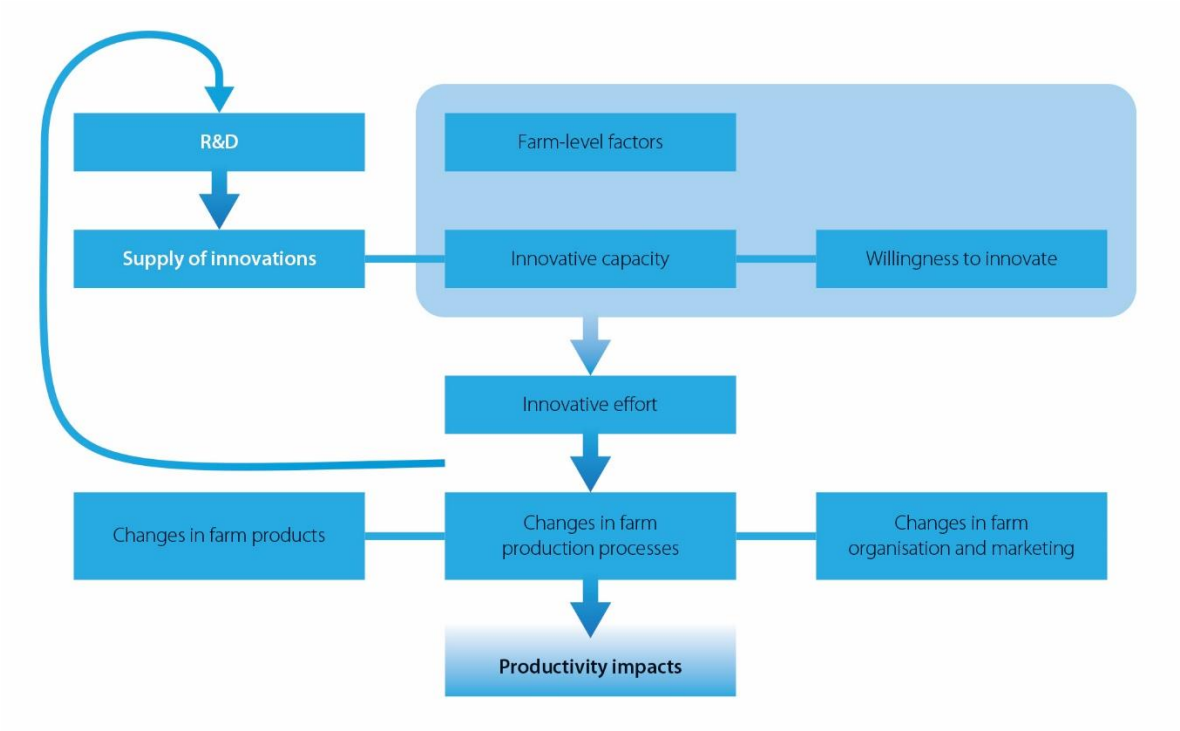


Figure 3.7: A simplified innovation system framework as applied on farm[71] with feedback loops from the farm to the researcher.

*Australian agricultural R&D –* the productivity of Australian agriculture owes much to the R&D effort of Australian scientists. Mullins and Keogh[72] show that there has been real growth in gross value of production (GVP) in national agriculture due to innovations resulting from research (Figure 3.8) with annual trends being more than 2% per year for much of the second half of the 20th century. Since the mid-1990s, however, there has been a levelling off of this trend and this has continued to the present.

[71] Nossal, K and Lim, K 2011. *Ibid*.

[72] Mullen, J and Keogh, M 2013. The future productivity and competitiveness challenge for Australian agriculture. Proceedings of 57th AARES Annual Conference, Sydney.

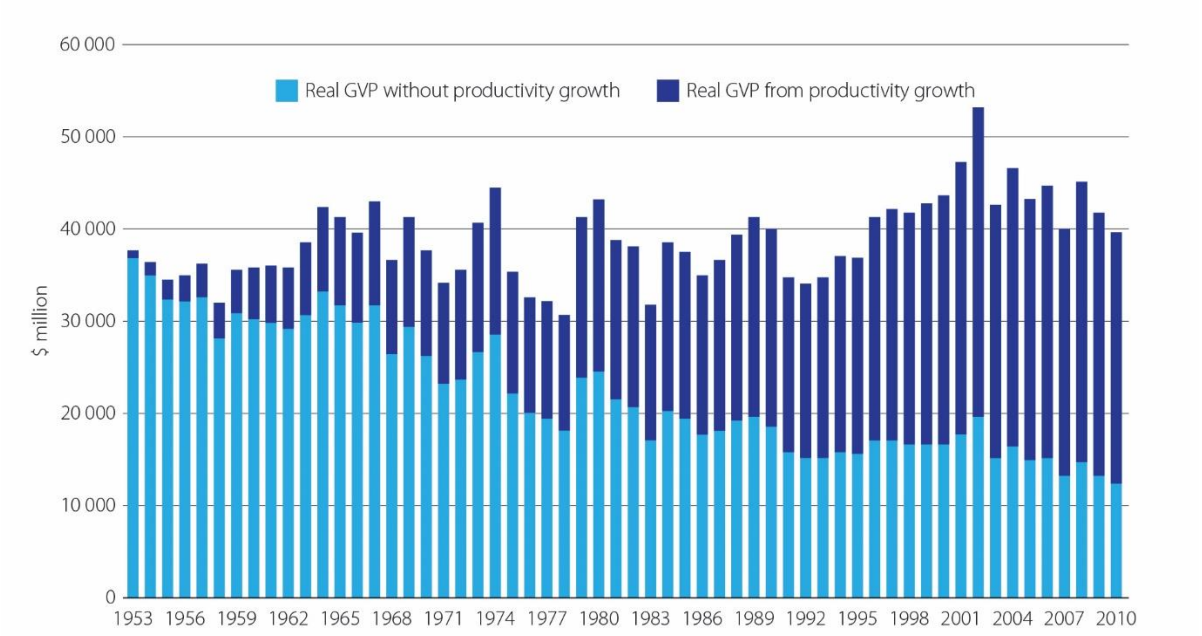


Figure 3.8: Impact of R&D on productivity in Australian agriculture[73].

Global benchmarks of Australian R&D in agriculture are difficult to find in this context. About the most useful indicator is the publication of papers which represents the endeavours of scientist to seek peer review as a measure of research quality and acceptance, as well as a criterion for promotion. The publication process provides a public record of the work as well as a quality assurance mechanism through the scrutiny of others.

Using agronomy, livestock and horticultural research as representative of directly agriculturally focused research, Australian output has been relatively consistent over the period 1996–2013 (Figure 3.9). However, when the performance of Australian agricultural scientists is shown in relation to publications in other countries, there is a substantial decline in proportion of research publications attributed to Australian authors (Figure 3.10). Indeed, their contribution declined from 6% of global publications in 1996 to 3% in 2011. There has been a drop in proportion of over 30% since 2006. This pattern differs from that of all other sciences except for mathematics.

[73] Mullen, J and Keogh, M 2013. *Ibid*.

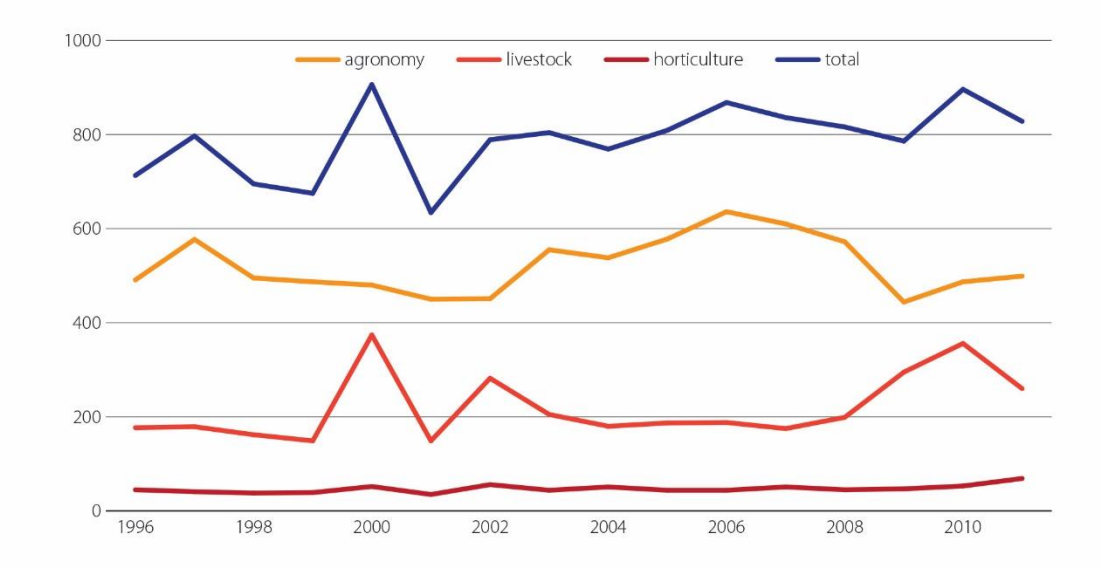


Figure 3.9: Number of papers published in agriculture by Australian authors for the period 1996–2011.
Note: Data are based on Scopus database. Agriculture is represented by agronomy, livestock and horticultural research[74].

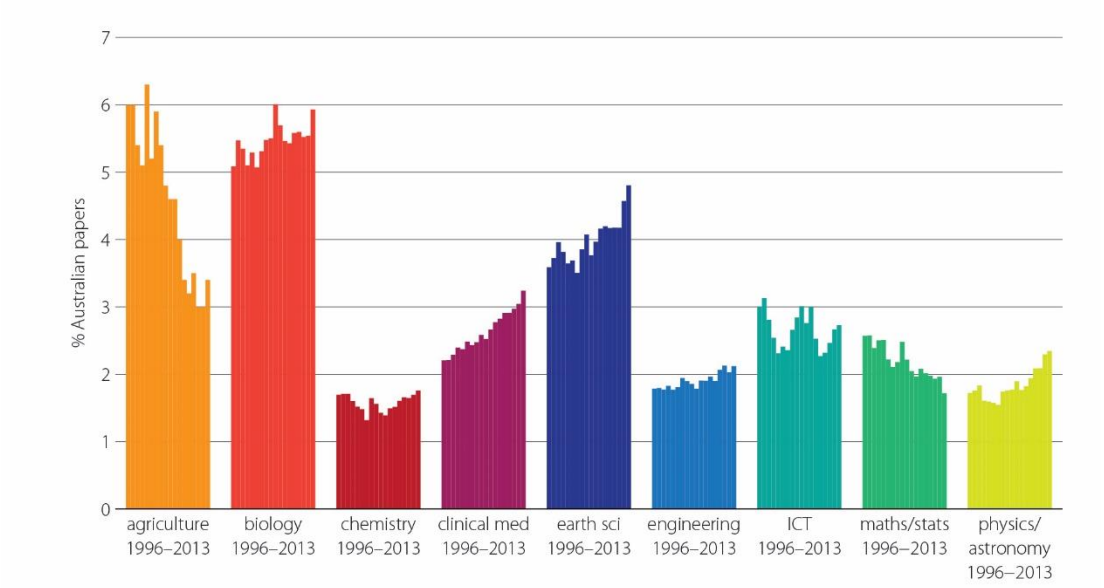


Figure 3.10: Proportion of the number of global papers published by Australian authors in science disciplines for the period 1996–2013.
Note: Each column represents a year in chronological order and data are based on the Scopus database. Agriculture is defined here as agronomy, livestock and horticultural research[75].

[74] Australian College of Deans of Agriculture (ACDA), unpublished analysis.
[75] ACDA. *Ibid*.

While it is recognised that there has been considerable investment in agricultural research in countries such as China and Brazil, the extent of the decline should be of concern to Australian agriculture. The maintenance of numbers is due to a significant increase in output from Australian universities to counterbalance the declines in output from government and CSIRO (Figure 3.11). There has been little movement in output over the period of study from the private sector and this remains at a low level, reflecting perhaps the lack of incentive to publish in that sector, its low activity in research in Australia, or both.

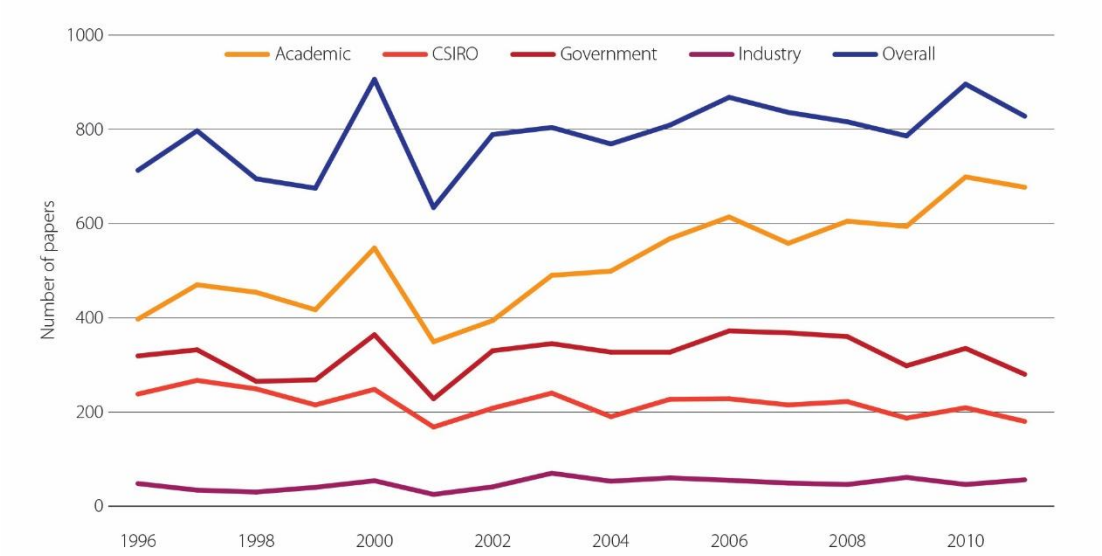


Figure 3.11: Output of papers from research organisations in agriculture for the period 1996–2011[76].

The number of papers per se is an inadequate measure, however, as there is no indication of relative quality or impact. Citations provide some indication of paper quality and perhaps impact among the research community. These data are provided in Figure 3.12 and show that the proportion of citations of Australian-authored papers is well above the proportions of published papers and that the influence over the period of study is increasing as the gap widens.

[76] ACDA. *Ibid*.


Figure 3.12: The proportion of citations for Australian authored papers relative to the number of Australian authored papers[77].

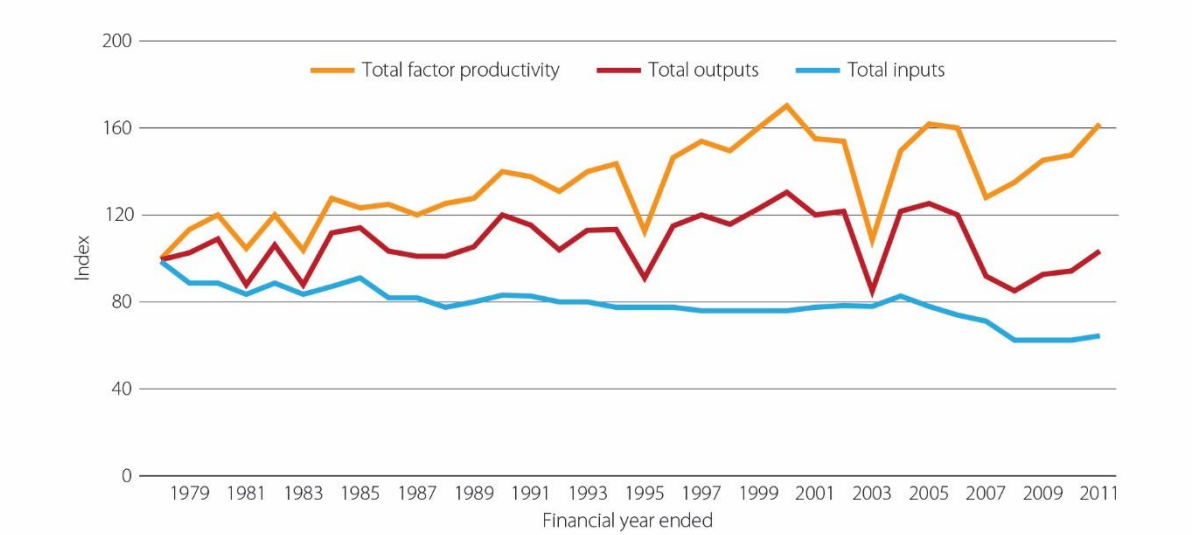


Figure 3.13: Total inputs, total outputs and total factor productivity (TFP) for Australian agriculture for the period 1979 to 2011.
Note: Blue line shows the indicative TFP from 1995[78].

Impact on productivity is a further measure providing some indication of the value of R&D although detailed attribution remains a challenge. Productivity in Australian agriculture (Figure 3.13) has stalled since the mid-1990s despite the R&D activity

[77] ACDA. *Ibid*.
[78] Dahl, A, Leith, R, and Gray, E (2013) Productivity in the broadacre and dairy industries. Agricultural Commodities 3(1) 200-220.

discussed previously. Productivity gains have slowed internationally as R&D investment declined through the 1980s and 1990s[79] and in Australia this was potentially further compounded by a concentration of research effort on environmental issues around the turn of the century. Applying the lag phase principle[80], the productivity stagnation today is a response to the R&D activity of 10 to 15 years ago and this might continue in response to the contraction of R&D in recent times.

Traditionally, transformational change to generate productivity increases have been generated through the state agencies, CSIRO and the universities. Whereas in the past state agencies and CSIRO invested in public good and transformational research, their activities are increasingly determined by leverage from outside bodies such as the research and development corporations (RDCs) which is driving a major shift in research emphasis. The RDCs attract their funding through producer levies matched for the most part by Commonwealth Government co-investment based on gross value of production (Figure 3.14). The research investment from these funds is directed largely where levy providers determine, being largely tactical rather than strategic investigation. These RDCs provide the main R&D investment.

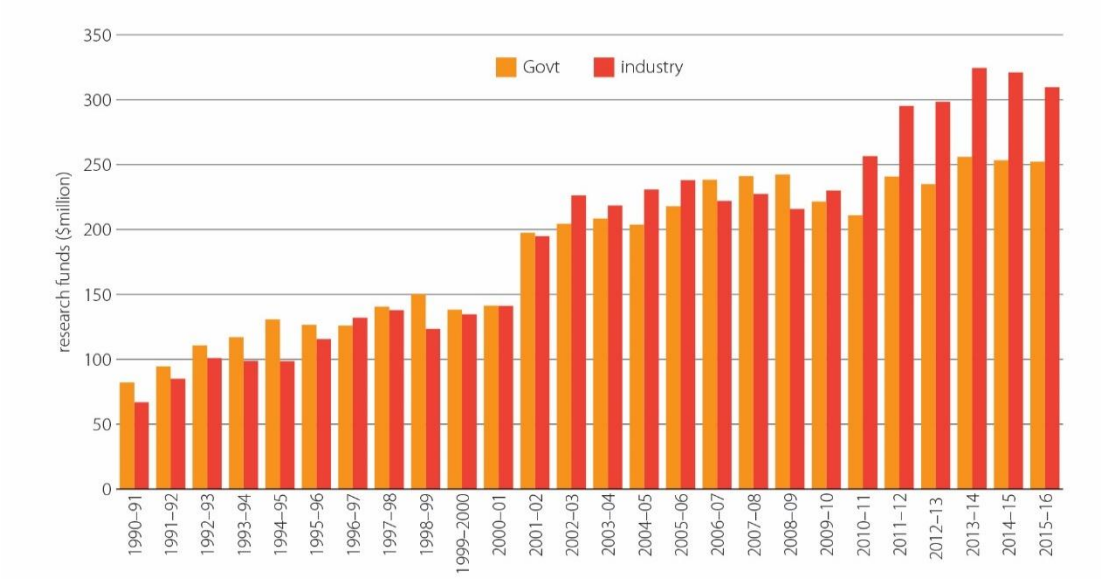


Figure 3.14: Producer levies and government co-investment for research for the period 1990 to 2016[81].

[79] Alston, JM, Beddow, JM and Pardey, PG 2009. Agricultural research, productivity and food prices in the long run. Science 325:1209-1210.

[80] Alston, JM, Pardey, PG and Ruttan, VW 2008. Research lags revisited: concepts and evidence from US agriculture. Staff Paper Series PO8-14, College of Food, Agricultural and Natural Resource Sciences, University of Minnesota.

[81] Australian Government budget papers. [Annual].

Increasingly, state agencies are reducing their investment and involvement in agricultural R&D. The arrangements vary from contraction to complete transfer of activity to universities to retaining capability. This has resulted in a real dollar term decline in state government R&D investment across Australia from around $230 million in 1995 to around $120 million in 2012 (Figure 3.15). This inevitably has considerable impact on public good and other strategic research investigations. Research intensity (the ratio of public investment in R&D to gross agricultural domestic product) declined from around 0.9% to around 0.4% over that period, confirming the reduced commitment by governments.

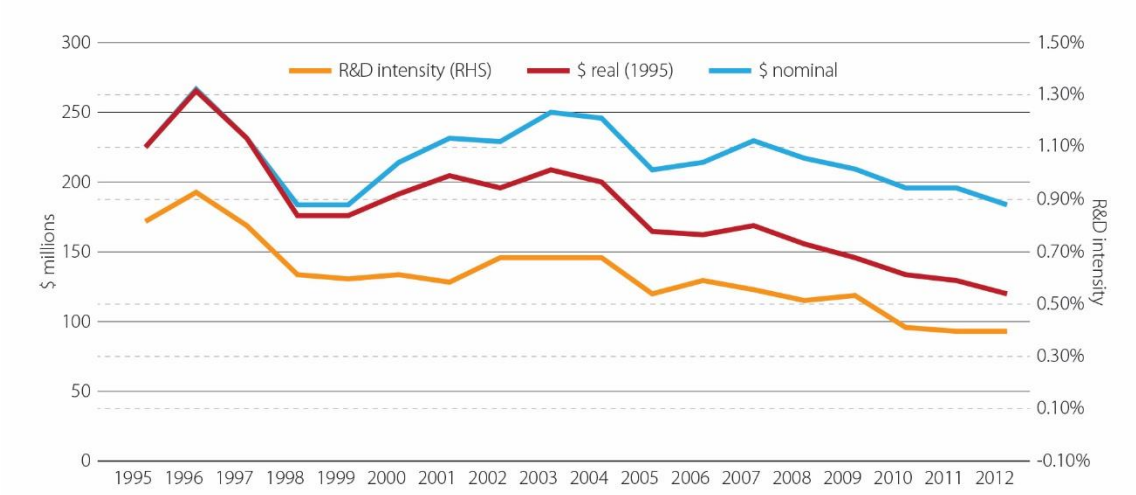


Figure 3.15: Investment in R&D by state agencies over the period 1995 to 2012 in actual and real dollars, together with the research intensity being the ratio of public investment in R&D to agricultural GDP[82].

Universities have their own challenges. They too are increasingly reliant on RDC funding. Traditionally these institutions have depended to some extent on funding from the Australian Research Council for basic strategic research that might lead to some transformation. The ARC itself though is challenged by increasingly tight budgets. Within those budgets, agriculture has to compete with most other disciplines. Trends in recent times show agriculture as being increasingly unsuccessful in grant attainment (Figure 3.16). Over the period 2003 to 2014, the number of grants to agriculture declined from around 2.6% to about 0.6% and the value of grant applications declined by a similar proportion.

[82] *Keogh M (2013) Australian agricultural R,D&E systems under scrutiny. Farm Institute Insights 10 (4):1-5*

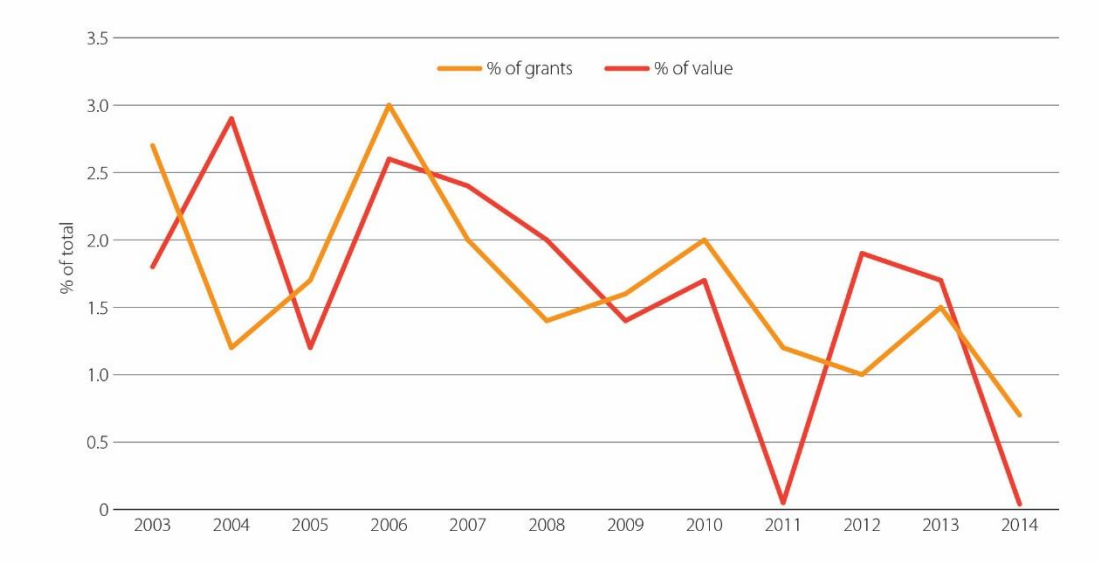


Figure 3.16: Proportion of the number of ARC grants and grant value for agriculture in the period 2003 to 2014[83].

*The scientist pipeline*[84] – The other major component of agricultural research in universities is through the efforts of the higher degree research scholars. An analysis of this component is warranted as these scholars are the next generation of scientists and represent much of the transformative research undertaken by higher education institutions.

Universities depend heavily on a strong cohort of postgraduate students, and agriculture competes with all other discipline areas in an institution for scholarships and other internal funding sources. As postgraduate scholars are an important contributor to the research effort in universities it might be expected that the research training pathway would be attractive in order to entice the smartest into research careers. Such pathways need to be attractive since the job market for agricultural graduates in particular is buoyant at this time; salaries are strong, and likely to remain so for the mid-term at least; and conditions in general are much more enticing than conditions for research higher degree scholars. As a consequence, some reflection on postgraduate scholar conditions is warranted.

Eligibility for entry to postgraduate research study requires a 4-year degree at honours level (first class or upper second class) and during that period an agricultural science student will have accumulated a higher education contribution scheme debt of around $30,000. That debt becomes progressively payable through

[83] ARC, unpublished.

[84] It is important to reiterate that transformational outcomes arise from chemistry, biotechnology, engineering and other research areas but limitations on data do not necessarily identify those as agriculture.

the taxation system at a salary around $54,000 and accumulates interest based on CPI adjustment for the duration of the debt, including time as a postgraduate scholar. The standard scholarship for a research student is currently around $24,000 tax-free which approximates to the poverty line in Australia. The tax-free status is of little use now as the minimum tax threshold is in excess of $18,000. Relativities over time with minimum wage rates continue to deteriorate. There are no increments and no superannuation entitlements. Scope exists under taxation laws for funders to provide a 75% stipend top-up but even that improvement falls far short of comparability with industry salaries and conditions. All universities in most disciplines now find difficulty in attracting high quality domestic applicants for postgraduate study; this is particularly acute in agricultural sciences.

Figure 3.17 shows the data for PhD scholars in agriculture from domestic and international sources. Domestic scholar intakes increased until 2011 but subsequently there has been a significant decline. Over the course of this evaluation period, international students have assumed greater importance, increasing from 30% of the cohort in 2001 to 60% in 2014. There have been consistently around 80 domestic scholars graduate per year whereas international graduates have increased from under 40 to around 140 in the same period. Data are not available to indicate what proportion of international graduates remain in Australia but anecdotal evidence would suggest it is reasonably significant.

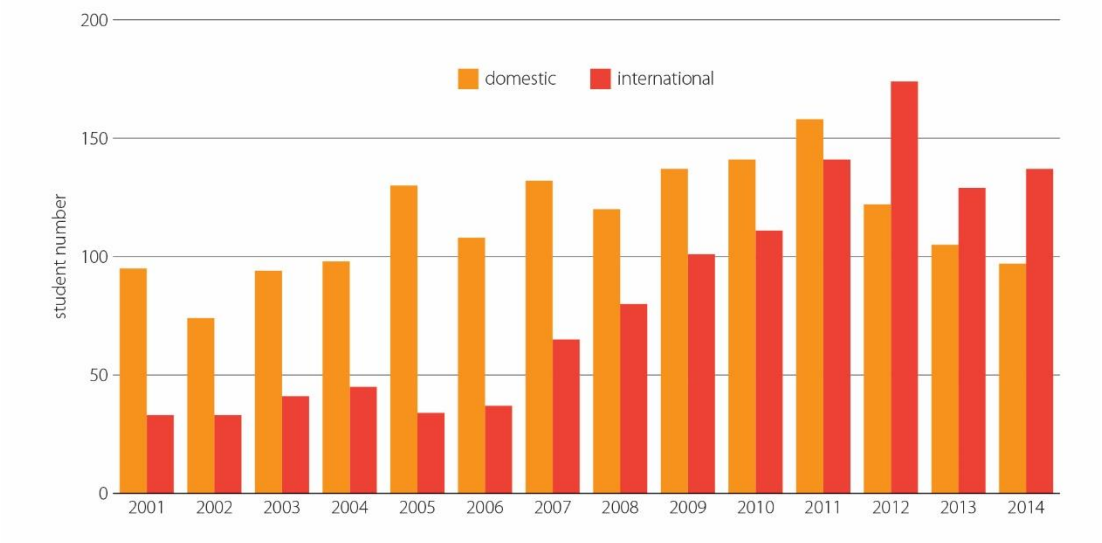


Figure 3.17: PhD intakes in agriculture from Australian universities from 2001 to 2014[85].

[85] ACDA. *Ibid*.

When completions are compared with their respective intakes to estimate attrition (Figure 3.18), differences exist between international student and domestic student cohorts in completion rates. A close correlation exists between intakes and completion rates in international student cohorts whereas Australian completion rates are roughly two-thirds of intakes in most years. This likely reflects the attractiveness of the job market in agriculture for Australian residents and the uncompetitive nature of postgraduate conditions and prospects.

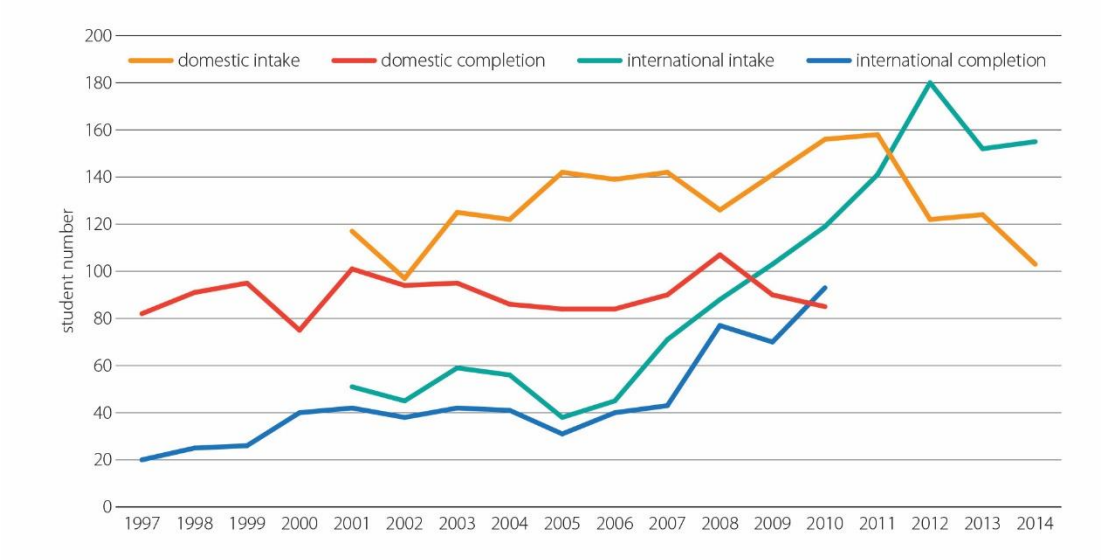


Figure 3.18: Comparison of intakes and completions of related cohorts of PhD scholars[86]where completions have been offset by 4 years to link completions directly with intakes.

At the end of their research training, graduates expect reasonable prospects of a research scientist appointment. This is not the case currently as state agencies in particular contract their R&D effort. Both CSIRO and state agencies are heavily dependent on external funding for research, most of which comes in three-year funding cycles. As a consequence, where research jobs exist, new graduates are very often on short-term funding arrangements. This three-year cycle is highly inefficient due to start up and wind down components, is demoralising for the postdoctoral scholars and eventually is wasteful of expertise as significant numbers leave the industry. Together, the conditions for training and then for post-doctoral employment provide a highly unattractive option for those keen minds that we would want to entice into research careers.

[86] ACDA. *Ibid*.

## 3.3 Looking ahead

It seems clear from the data that the professionalisation of agriculture is happening. Prospective students are now considering careers in agriculture as a serious option. It can be expected that graduate completions at the first degree level will start to increase and help to satisfy industry demands for qualified staff. As more young people take up the production option the level of qualifications will build up on-farm. This should increase the rate of uptake of new technologies and practices, reducing the innovation adoption lag times that have been characteristic of times past.

What is of concern, however, is the sustainability of the pipeline of agricultural research scientists. The current conditions for their training are nowhere near competitive with the employment conditions offered to first-time graduates. Nor are employment prospects after doctoral attainment enticing as opportunities have contracted substantially due to state agencies vacating this space. The major option is a short-term contract that offers few prospects of being sustainable, and eventually drives people out of research, although it is recognised that private sector agrichemical and life science organisations provide some employment opportunities for PhD agricultural science graduates.

Attention needs to be given to the mix of basic and applied research. In recent decades the pendulum has swung strongly towards applied research and it remains a quandary as to where transformational strategic research will be undertaken. Increasingly Australia will become dependent on international spill-overs rather than generating its own strategic research unless components of available funds are dedicated to new science. It is also recognised that such outcomes are likely to come from research outside agriculture although agriculture will likely need to invest in these areas.

This plan hopefully provides an opportunity to consider the strategies needed to support innovation in agriculture. This process is much easier when market opportunities are opening up rather than during times when agriculture is entering a cyclical downturn.

### Future opportunities

A regular stream of new entrants choosing agriculture as a career could be achieved by maintaining the momentum that has recently been generated through promoting the sector and the career paths therein. There needs to be continual pressure on schools to properly and fully represent agriculture through the food and fibre portal, with ongoing support of agricultural industries.

The high quality scientific community in agriculture that is crucial to Australia's future could be safeguarded through improved stipend conditions that make research training a competitive career option. Research funding agencies and research providers need to ensure that there are sustainable career paths for new researchers. Such positions need to be five years in duration with a review at three years to indicate ongoing or terminating outcome at the end of the five years.

Long-term viability of research provision and scope for transformative research could be achieved through reducing uncertainty that is largely counterproductive and compromises planning processes for RD&E. Additionally, state agencies need to decide whether or not they are players in research. Clearly designated funds need to be identified to ensure that there is an avenue for strategic and transformative research.

Finally, an innovation culture in the agriculture sector could be encouraged if universities frequently renewed their agricultural training programs to ensure students are well educated in contemporary agriculture while at the same time ensuring that the principles of science and business are well-founded. Opportunities should be created for students to gain experience with industry to ensure they enter the workforce well prepared. The professionalisation of the sector needs to become embedded, paving the way for a stronger, more responsive and forward-thinking sector to take advantages of free trade agreements and market opportunities in Asia.

# 4 Funding the future of Australian agriculture

A fundamental premise behind the creation of this Decadal Plan for Agricultural Sciences is recognition of the critical role that research and development plays in ensuring that agricultural practices, productivity, profitability and sustainability remain at the cutting edge of scientific advances occurring both within Australia and overseas.

As the challenges facing agriculture become more complex and inter-related, so too must the programs of work that tackle them. It is no longer sufficient to be comfortable just with the knowledge that many researchers are working on many different parts of a puzzle. There has to be collaboration, integration of approaches and reduction of unproductive rivalry. Increasingly, the most successful large projects are ones in which clear scientific management works to ensure complementarity between different research elements within a holistic plan of investigation. Collaboration is at the heart of research excellence and so the challenge is how to change existing rules that impede collaboration across borders of all kinds. As the distinguished scientist and administrator Dr Richard Flavell put it, *'Essentially 'business as usual' is not what we are looking for; the purpose of research in agriculture is not just to make the break-through—it must be translated. This is a bigger goal than the primary discoveries'*[87].

## 4.1 Current research funding environment

Australia's Decadal Plan for Agricultural Sciences takes a multi-disciplinary, systems approach. It recognises the increasing need to see agriculture in a systems context in which no element is isolated from any other. In the past, narrow, disciplinary-based agricultural science has been very successful in delivering transformational change. However, major breakthroughs based entirely on this approach have become increasingly rare as the impact of individual changes are greatly diluted by the complex and diverse farming systems in which they need to be implemented. Indeed, opportunities for transformational change are increasingly associated with fundamental changes in systems understanding and management. Such systems research is, by definition, trans-disciplinary and addresses limitations imposed by the many interactions of various systems components.

However, the public institutions that aim to support these complex systems do not experience the same pressures as agricultural enterprises or the researchers who work with them, and the constraints that are applied to public institutions do not

[87] Dr Richard Flavell CBE. Address to GRDC on the occasion of the announcement of GRDC's involvement in the International Wheat Yield Consortium; November 2015.

operate on the same timeframes or with the same considerations. The result of these misaligned pressures and constraints is that public funding agencies are often not sensitive to the needs of researchers or enterprises, even though they may be aware of them. Australia's institutional landscape, while supporting many discrete parts of the system, has not yet been able to promote innovation across the whole system. These issues need to be acknowledged and addressed; it is unlikely that the much-needed step changes in productivity and production will be achieved in any single element of the system, and it is likely that marginal gains from issue-specific incremental changes will decline into the future. In this chapter we explore some of these issues and suggest ways in which processes can be streamlined and made more relevant to the needs of agricultural science and the essential sector that it supports.

### 4.1.1 Current funding arrangements for agricultural sciences

Australia currently has a complex funding environment for the agricultural sciences, as depicted in Figure 4.1. Funding sources span multiple levels of government, RDCs, direct private investment and international funding streams. While each of these groups or agencies have processes in place to ensure support for high-quality research, there is no effective mechanism to define priorities and align objectives between them. The benefits of clear national priority setting, accompanied by funding arrangements that recognise those priorities, are outlined in Section 4.2.

A significant component of the agricultural research budget in Australia flows directly from governments to agricultural research agencies in states or at the federal level. Notwithstanding, the ARC and the RDCs have considerable influence on the nature and direction of agricultural research. The ARC dominates the fundamental end of the research spectrum, supporting inquiry into fundamental processes in plant and animal sciences but not requiring an applications vision. The RDCs provide a strong but not exclusive nearer-to-market focus in each of their sectors with emphasis on potential and real applications.

Both the ARC and the RDCs have proved very successful. While improvements to the funding mechanisms for agricultural science in Australia are proposed here, the RDC model in particular has been a tremendous boost to Australian agricultural production and should be maintained. Current criticisms of RDCs are that they need to be generally more receptive to identifying new or enhanced agricultural systems that could create industries in regions where they don't yet exist (e.g. the potential for greater agricultural development of the north), and that cross-industry integrative studies could be better supported (most growers produce more than a single product). To some extent the latter is being tackled independently by the

Australian government through its Rural Research and Development for Profit fund[88]. Similarly, agricultural research would also benefit from the ARC providing more equal opportunity to research involving interdisciplinary science and complex systems approaches.

Without coordination of research funding, there is also a lack of coordination of research effort. Recipients of research funding are equally uncoordinated and typically derive funding from more than one source (see figure 4.1). In the best case, such arrangements can generate widely applicable, multi-purpose research that is suitable for all investors. In a more typical case, such arrangements can divide research capacity to service competing interests and research directions.

Further, the globalisation of science and its vastly increased dimensions mean that Australian researchers have an absolute need to engage with research activities internationally—with universities, government agencies and the private sector—to access novel technologies, avoid unnecessary repetition and keep their science at the cutting edge. The small size of our scientific community and its spatially fragmented nature inevitably means that we cannot engage at a world-leading level in all areas, and this too must be coordinated.

[88] http://www.agriculture.gov.au/ag-farm-food/innovation/rural-research-development-for-profit

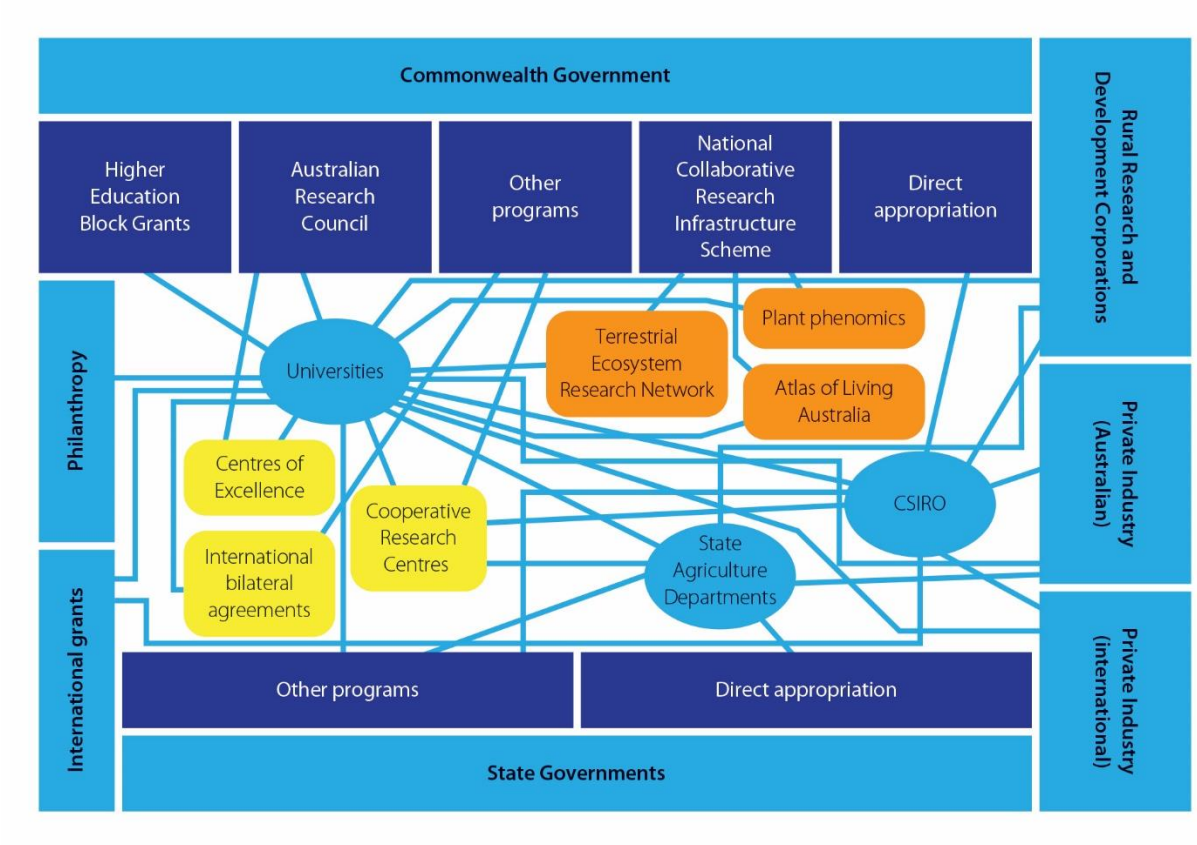


Figure 4.1: Current funding arrangements for the agricultural sciences in Australia.

Notes: This diagram is simplified and indicative only, not all funding flows are shown and no indication is given regarding the size, frequency, impact or tends over time of funding flows.

Source: Information collected during the development of this plan by the National Committee for Agriculture, Fisheries and Forestry.

Figure 4.1 is necessarily simplified and does not show all the funding flows that occur each year, nor does it show the relative scale of each body, the frequency of funding rounds, the impact of the research undertaken or the stability of funding over time. However, it clearly reflects the many circular funding flows that result from funding agencies requiring co-investment in most, if not all, of their research projects. The benefits of inter-agency cooperation that co-investment can offer need to be considered in light of the potential for 'recycling' co-invested funds and counting contributions twice or more against projects relevant to different funding agencies. Cooperation based on agreed national priorities and aligned objectives, rather than on administratively intensive (and therefore costly) co-investment requirements, would be a more efficient and ultimately more effective use of limited research funding.

Funding arrangements are exceptionally complex relative to the size of the agricultural research sector in Australia. Small improvements towards a coherent national research agenda that, by identifying and funding priorities, reducing duplication, eliminating double accounting of co-investments and simplifying administration, would offer proportionally significant improvements in how agricultural science uses its slice of the research funding pie. The following sections examine the benefits and practicalities of such improvements.

## 4.2 Coordinating agricultural research funding

Recognising and acting on the need for a systems-based approach to agricultural research and practice requires leadership to encourage cross-institutional collaboration, reduce duplication, and to commit to tackling critical problems through the formation of major teams. Indeed, new paradigms need to be created that meld 'traditional' sources of research capability—the plant and animal sciences, for example (see Figure 1.1)—with those such as economics and the social sciences. Increasingly, it is the seamless integration of all these different areas that determines the success or otherwise of programs aimed at solving complex problems. The biological sciences may produce one or more potential solutions but such solutions need to fit into pathways to application that include consideration of social factors (e.g. the availability of a skilled workforce, issues of isolation, and availability of internet services in rural areas that are taken for granted in cities), economic aspects of farming systems, and downstream transport and marketing.

National coordination across agricultural research funding will be required for such integrated, whole-of-system research to be successful, and to make efficient use of public and private investments. In the same way, coordinating Australia's scientific engagement with leading international research programs will also be required. Clarification and streamlining of funding arrangements will help marshal Australia's expertise to the challenges that best serve our national interest (including the cases where our interests are supported by joining international research teams), provide efficiencies for governments and other research investors, support research investment over timeframes that are commensurate with the research questions, and provide researchers with the certainty and continuity of employment that is needed to attract and retain the best and brightest minds. These topics are further explored in the following sections.

### 4.2.1 Achieving national priorities

As previously noted, large-scale, coordinated research is required to answer the many complex challenges that will continue to confront the agricultural sector over the coming decade and beyond. As an endeavour that integrates a huge range of

sciences, technologies and general human know-how, agriculture will always be capable of posing more questions than researchers are able to investigate. As such, prioritising scientific research has been, and will continue to be, a difficult exercise[89].

While this plan identifies important areas of research for which it is easy to imagine potential future applications (Chapter 2), the underlying purpose of agricultural science must never be far from view with respect to research funding: to inform agricultural practice and to maintain or improve productivity, competitiveness and sustainability.

This plan presents a long-term vision that proposes independent and rolling assessments of the broad challenges that are directly relevant to Australia's national interest as the basis for establishing priorities, rather than specifying topical research questions that happen to be current at the time of writing. The importance of each challenge, or even what constitutes 'national interest', can change over the course of a decade, but the capabilities and institutions that are required to meet any such challenge are predictable. They include a central coordination function that provides clear, efficient oversight of effort, an ability to identify and adapt to changes on an ongoing basis, a willingness to see a problem or opportunity through from research to application, and trusted, ongoing review and institutional adaptation processes that recognise the dynamic nature of farm systems and their evolving needs.

The benefits of implementing such a coordination function—outlined in the next section—and tackling the most important challenges in a coordinated way will propagate throughout the scientific and farming communities. Taking the maintenance and improvement of Australia's agricultural competitiveness and the associated social and economic benefits as a starting point, Australia's future ability (or inability if the status quo is maintained) to marshal efficient research teams to prepare for and respond to the myriad shocks that could affect the agricultural sector (e.g. an outbreak of foot and mouth disease, a sudden herbicide ban or an aggressively invasive species such as *Varroa destructor*) will determine our success and market share into the future.

The ability of agriculture to engage with consumers and meet changing societal expectations regarding production practices that may impact on the sustainability of the agricultural and broader environment, the safety of products and their dietary

[89] For example, Professor Aidan Byrne quipped as outgoing chief executive of the Australian Research Council "We disappoint the majority of people because they don't get the grant they applied for. And for the ones who are successful, we disappoint them because they don't get as much as they wanted." (*The Australian*, 7 September 2016).

benefits is a further important consideration that forms part of national expectations and priorities. Using a coordinated approach makes it easier to develop and implement a socially cohesive strategy that both informs and is informed by broader community and societal concerns and will foster greater recognition by researchers and producers of the boundaries associated with maintaining a 'social licence to operate'. Early acknowledgement of such concerns provides the necessary base upon which smoother transitions from existing to more socially acceptable practices can be planned.

### 4.2.2 Clear and efficient funding arrangements

Australia's small population, coupled with our large geographic size and the nature of our federation, make it essential to carefully consider the ways in which we can use our financial and human resources most efficiently. As noted in Section 4.1.1, funding arrangements are currently disproportionately complex relative to the size of the Australian agricultural research sector, so the proportional efficiency gains that may be possible from coordinating research are worth pursuing.

Together with an ability to coordinate the work of Australia's various agricultural research institutions, clear funding arrangements for national research priorities would also serve as a powerful means to encourage collaboration among both researchers and institutions (both domestic and international) and to reduce some of the less helpful aspects of competition.

The benefits of clear and efficient funding arrangements go beyond making the most of the limited research funding that is available. Collaborative science can often be applied much more quickly than discrete research efforts, and collaborative research tends to generate greater consistency of understanding among the participants. With government involvement in those collaborations, more consistent rules would be expected to apply to the application of science (compare differences in GM acceptability between different states). Finally, small improvements in the consistency and transparency of research funding arrangements would go some way towards encouraging a wider range of investors back to agriculture, and to promote increased trust and understanding among the current suite of public and private investors.

### 4.2.3 Managing agricultural research for impact: scales and timeframes

Having a pool of world-class agricultural researchers willing to commit to research with a fundamental endpoint of on-farm or associated industrial application is essential. However, researchers can only operate within the support they receive,

and research excellence requires support and flexibility to enable researchers to work on both applied problems as well as fundamental science that often has uncertain applications over a long timeframe. To achieve this balance, agricultural research must continue to take place in a framework of sound scientific principles that embrace an unpredictable but structured, long process of discovery. Making those discoveries often needs sequential testing of ideas that inherently carry a high risk of individual failure, yet build towards greater understanding and medium to long term application.

The general community, and even research managers, often hold expectations that public accountability means allocating research funding to projects with predictable and defined outcomes within short timeframes. However this interpretation of accountability can prevent the integrated, long-term, trans-disciplinary collaborations required to address the big challenges that stand between Australia and our successful agricultural future. Indeed, the benefits of applying realistic expectations and associated accountability and management arrangements to agricultural research lie at the heart of achieving the raison d'être of the agricultural sciences: productivity and competitiveness. Failure to do so presents one of the most serious risks to Australia's competitive advantage by inadvertently discouraging the activities that will increasingly be required to promote it.

### 4.2.4 Safeguarding Australia's agricultural capacity

Australia's agricultural sector is supported by a distributed but significant network of research, development, extension, communication and translation professionals. While coordination of activities has been identified in this plan as an obvious area for efficiency gains, the people and infrastructure that provide Australia's ongoing agricultural research capacity should also be managed more efficiently and more in accord with the long-term nature of the research impacts they provide.

Chapter 3 outlined a number of reasons why the best minds may not be attracted to a career in the agricultural sector, or may not be retained after graduation. Many of these issues could be addressed through establishing clear career paths, alleviating the counterproductive aspects of competition through better coordination and providing the security of employment that is required for a person to solve a long-term research challenge. The efficiency gains that would be available from reducing funding cycle-related gains and losses of capacity through better coordination and longer-term planning would be substantial, and would simultaneously address the issues of greatest importance to the individual scientists, engineers and other researchers that underpin our future agricultural sector.

To achieve such a change, a far deeper understanding is needed among funders and research agencies of the challenges that agricultural science aims to address; how the various research activities across the sector fit together; and who or what is responsible for the different elements that make up the costs of a project, ranging from staff to depreciation on buildings and equipment. With respect to understanding the nature of agricultural research, the loss of deep expertise from state and federal governments needs to be addressed as a matter of urgency. Coordinating research activities across the sector was discussed in Section 4.1 and a solution is proposed in Section 4.3. With respect to establishing clear responsibilities, an absolute commitment is needed to maintain a core capability within and between organisations currently responsible for the future of the agricultural sector. While care has to be taken to avoid the development of an entitlement mentality, such a commitment would create greater stability and also provide flexibility for new research directions that address the challenges of the future.

Infrastructure is also a key component of Australia's research capacity and is the subject of the Australian Government's current National Research Infrastructure Roadmap development process[90] as well as long-term planning processes in federal and state government departments and private companies that develop their own infrastructure. As the roadmap and other established processes will apply over a similar timeframe to this plan, it is essential for the agricultural research community to engage strongly in their development and implementation processes to enable agricultural research to benefit from, and contribute to, shared national capabilities (including data infrastructure and recognising the value of skilled technicians as part of our national infrastructure capability). It is also important to clarify funding arrangements; for example, cross-subsidising management and research infrastructure can dilute the research dollar and reduce clarity and accountability from the funder's perspective.

## 4.3 A future funding and governance model

A comprehensive, coordinated governance and funding framework is required to ensure that Australian agricultural R&D retains its strategic capacity into the future. This should consist of national oversight, coordinated research planning, research

[90] The National Research Infrastructure Roadmap is led by Australia's Chief Scientist, and was 'established to provide advice to the Australian Government through the Ministers for Education and Training and Industry, Innovation and Science on future priorities for strategic investment in those key national research infrastructure capabilities that would support and develop Australia's research capacity and underpin research and innovation outcomes over the next five to ten years.' Available at http://www.chiefscientist.gov.au/2016/03/national-research-infrastructure-roadmap-terms-of-reference/ (accessed 21 September 2016).

training and career support, and priority-driven funding from both public and private sources that recognises the nature of agricultural research challenges and the complexities of implementation.

Funding and governance arrangements for agricultural research have different drivers and different impacts over the short, medium and long terms. However, to sustain and improve agricultural productivity and competitiveness over the long term, Australia must develop and protect its capacity over the medium term, and in the short term we must ensure that research undertaken is consistent with Australia's current and forecast needs.

Explicitly recognising and addressing each of these drivers and the timeframes over which they operate is the basis for a proposed future funding and governance model, consisting of:

- a **National Agricultural Research and Innovation Council**, to provide the coordination of agricultural research that is required, and in doing so, clarify the funding environment for researchers and investors.
- an **agricultural research, translation and commercialisation fund**, to supplement current investments in agricultural research and fill any gaps to help new ideas move from fundamental science to industry practice.
- a **doctoral training and early career support centre** for the agricultural sciences, to ensure Australia develops and retains the skills and expertise it will need to take advantage of future opportunities.

The elements of this proposed framework are intended to supplement and coordinate the already well established and effective institutions whose work Australia currently benefits from, such as CSIRO, the RDCs, the university sector, state agriculture departments and the many enterprises that support agricultural research. The three elements of this plan are discussed further in the following sections.

### 4.3.1 A National Agricultural Research and Innovation Council

A National Agricultural Research and Innovation Council stands at the core of the proposed framework and would provide a central point of coordination for agricultural research and its applications. It would achieve this through a variety of means.

The information required to effectively coordinate the whole sector would be gathered through a rolling identification of national agricultural research priorities

(reporting triennially) and through assessing and forecasting Australia's research capacity requirements (offset reporting at a similar frequency), including both human and infrastructural capabilities. Consideration of international-scale programs should also be considered in assessments of both research priorities and capacity requirements, to position Australia to derive maximum benefit from our comparatively small international contributions. In the current absence of such information, Chapters 2 and 3 may be used as a starting point for promising research directions and skills requirements.

The Council would assume responsibility for ***coordinating*** the priority setting exercises of all publicly funded research organisations and funding agencies, to strongly urge public research organisations towards simplified and transparent funding interactions between them.

To support an increased sense of coordination and collaboration between funding agencies, research organisations and scientists, the Council would also directly manage a modest but influential collaboration incentives program with the intention of filling strategic research gaps and forming teams around nationally important challenges or unexpected shocks that unite the most suitable experts regardless of their location, and over timeframes that are commensurate with the research challenges.

The council would also bear responsibility, as part of its assessment and advice functions, of identifying international initiatives of benefit to Australia and facilitating Australian researchers' involvement. It is essential Australian agricultural science continues to develop a strong global perspective backed up with practical measures that enhance exchange, the development of international consortia and individual skills and expertise. International collaboration should be embedded in the national science vision with strong engagement with our near neighbourhood, the Indo–Asia–Pacific rim, made an explicit target. To achieve this we envisage the establishment of an explicit International Collaboration Platform that coordinates the various bilateral programs that currently exist, to align programs where appropriate, and to address any fragmentation of international engagement effort that may be found. In line with a focus on the Indo–Asia–Pacific rim, it is also proposed that the Council explore, with other nations in the region, the establishment of a multi-national science funding mechanism (an agricultural research fund for the Indo–Asia–Pacific rim) where all countries would contribute to a central pool that would support research groups from multiple countries focusing together on common problems relevant to agriculture.

With respect to implementation, this proposed National Agricultural Research Council is based on the roles and functions that are required of a coordinating

council rather than on a particular institutional setting. Appointments to the council should be both skills-based and representative, and be fixed-term, Ministerial appointments with rolling rather than wholesale renewals to ensure stability yet provide for change over appropriate timeframes. The council could be hosted in an independent statutory agency, as an independent office in the Australian Government Department of Agriculture and Water Resources (possibly analogous to the governance arrangements of the Commonwealth Environmental Water Office, the head of which cannot be directed by the Minister) or in a respected independent organisation.

The essential functions of the council would require $50 million per year, including a modest collaboration incentives fund and the secretariat.

### 4.3.2 An Agricultural Research, Translation and Commercialisation Fund

Recognising that agricultural research occurs within, and contributes to, complex farming systems and necessarily takes a non-linear path from frontier science to agricultural practice, there are many points in the innovation system at which good ideas might fail. More correctly, in many instances it could be said that ideas fail not because they are not sound but because of factors that impede the success of otherwise worthy innovations.

It is well known and frequently asserted that there are weak links in the Australian innovation system—not just within the agricultural sector—yet the problem remains challenging for governments at all levels, researchers of all disciplines, and industry[91]. The coordinating role of a National Agricultural Research and Innovation Council (Section 4.3.1) spanning the whole agricultural sector from research to practice, would place it in a unique position to address this long-standing problem in an informed way.

As previously noted, specific research priorities can change over the planning horizon of this document (see Section 2.4), and the same can be expected of the innovation system—the relative strengths and weaknesses of various parts of the system will change over time. However, the principles that apply to successful responses to change are stable and predictable. Overarching principles for an Agricultural Research Translation and Commercialisation Fund include:

- The fund must be governed by a priority-setting cycle that keeps pace with the rate of change in the sector, but that provides the stability necessary to

[91] In 2015 the Australian Government announced its National Innovation & Science Agenda. The ARC will have an important role in delivering on some of the NISA measures.

undertake large-scale endeavours. Triennial reporting from the National Agricultural Research and Innovation Council would provide a suitable information base for priority-setting over the medium to long term.

- The fund should address the most pressing gaps in the innovation system that present barriers to uptake at the time. It would not diminish the essential existing roles of current research agencies or reduce the need for them, but rather strengthen them all by strengthening the system in which they operate.
- Stable funding arrangements must be aligned with the long-term, complex nature of research translation, commercialisation and uptake.

With respect to implementation, the Agricultural Research, Translation and Commercialisation Fund should come under the broad direction of the National Agricultural Research and Innovation Council, but could be administered in a number of ways. The administering organisation(s) must however be capable of embodying the national, stable and long-term nature of the investment, and may differ by sector. For example, the RDCs dominate their sectors, and could be encouraged and supported through the fund to address the current gap between field trials and commercial trials for some products[92].

It will be essential, if the vision of the National Innovation and Science Agenda[93] is to be fulfilled, to make a serious commitment to adequately resource the whole innovation system in the agricultural sector. Unlike many sectors, the agricultural sector faces a two-fold challenge because of the constant innovation that is required just to maintain production in the face of natural pressures, as well as the need to improve productivity and competitiveness at the same time. $100 million per year with a 10-year planning horizon would realistically be expected to make substantial progress towards Australia's successful future as a major agricultural nation.

Co-investment should be encouraged but, like the successful NCRIS model, should not be used as a target or dictate funding success[94].

In future, assuming successful alignment of international research activities and a greater understanding of regional needs can be achieved by the National Agricultural Research and Innovation Council, Australia may also wish to investigate the formation of a multi-nation R&D fund for the Asia–Pacific region. International

[92] Example high-o safflower. Proven at field scale but not taken on commercially. GRDC Research and Development.

[93] Reference to NISA again here.

[94] Reference here to the NCRIS principles that successfully applied this co-investment model.

collaboration is a vital part of modern science that is hampered by the lack of early-stage resources to establish and grow collaborations over the first few years of their life, and a multi-nation fund with harmonised objectives could provide an effective means of support.

### 4.3.3 A doctoral training and early career support centre for the agricultural sciences

Linked strongly with the national coordination and oversight role of the National Agricultural Research and Innovation Council, a doctoral training and early career support centre for the agricultural sciences would proactively identify and address research capacity constraints before they affect the Australian agricultural sector. It would achieve this in a number of direct and indirect ways.

To address ongoing concerns about the sustainability of the pipeline of agricultural research scientists, the centre would offer substantial and targeted PhD top-up scholarships that can compete with other options available to professional agricultural scientists. This would partially reduce the current financial barrier that prevents professionals from returning to study or bringing on-farm experience back to the research sector.

To address concerns about the industry relevance of research and unclear uptake pathways, the centre would run an agricultural enterprise engagement program to provide graduate students with ongoing exposure to the working farm systems that are relevant to their research, and to encourage research towards the challenges that the National Agricultural Research and Innovation Council identify as being on the horizon. In doing so, the program would also help equip graduates with the skills that industry needs (refer Section 3.1.2).

The centre would address the retention of highly trained researchers—along with related and prerequisite changes to funding timeframes and security of employment—through an early- and mid-career support network to maintain connections between PhD cohorts and provide opportunities for early- and mid-career researchers to connect with mentors, each other, and a wider range of agricultural systems than would otherwise be possible. Considering the small size of Australia's agricultural research community, the centre would be hosted at no more than two nodes to maintain a critical mass of researchers at each node and encourage a culture of research excellence underpinned by excellent research support. Recognised excellence is an indirect but deliberate additional way of encouraging both the retention of top-class researchers in the agricultural sciences and building the confidence of agricultural research investors.

A doctoral training and early career support centre for the agricultural sciences would require approximately $4 million per year if the programs are well targeted, noting that a small investment would have medium- to long-term benefits that accrue over time, but that would also depend on the other parts of the framework being implemented in parallel.

# 5 Recommendations

Chapters 1 and 2 outlined how fundamental science and agricultural research will contribute to Australia's successful agricultural future. Chapter 3 showed that to realise the future that Australia is capable of, we need to enable our researchers to achieve those solutions through education, career development, and retention of top-class researchers. Chapter 4 showed how it will be essential to coordinate Australian research to prioritise and stabilise its funding so that it is commensurate with the nature of the challenges that face agriculture into the future.

All parts of the sector share the responsibility for ensuring that Australia's agricultural future is as bright as it can be: to achieve national priorities, to clarify and implement efficient funding arrangements, to manage research over the scales and timeframes that are commensurate with the challenges, and to nurture and safeguard our agricultural research capacity.

Accordingly, the National Committee for Agriculture, Fisheries and Food recommends that:

1. The Australian Government creates a National Agricultural Research and Innovation Council, or an equivalent body with similar functions, to provide a central point of coordination for agricultural research and its applications. Its functions should be to:

    a. coordinate the priority-setting exercises of all publicly funded research organisations and funding agencies and to strongly urge public research organisations towards simplified and transparent funding interactions between them.
    b. directly manage a modest but influential collaboration incentives program with the intention of filling strategic research gaps and forming teams around nationally important challenges or unexpected shocks that unite the most suitable experts regardless of their location, and over timeframes that are commensurate with the research challenges.
    c. conduct rolling identification of national agricultural research priorities (reporting triennially) and assessment and forecasting of Australia's research capacity requirements (offset reporting at a similar frequency), including both human and infrastructural capabilities.
    d. coordinate Australia's involvement in international research programs, to align programs where appropriate, and to address any fragmentation of international engagement effort that may be found.

2. That the Australian Government establish a National Agricultural Research Translation and Commercialisation Fund, to address gaps in the national research priorities and to strengthen the parts of the innovation system at which agricultural innovations fail to translate into commercial products. The fund should be managed according to the following principles:

    a. The fund must be governed by a priority-setting cycle that keeps pace with the rate of change in the sector, but that provides the stability necessary to undertake large-scale endeavours. Triennial reporting from the National Agricultural Research and Innovation Council would provide a suitable information base for such priority-setting over the medium to long term.
    b. The fund should address the most pressing gaps in the innovation system that present barriers to uptake at the time. It will not diminish the essential existing roles of current research agencies or reduce the need for them, but rather reinforce them all by strengthening the system in which they all operate.
    c. Stable funding arrangements must be aligned with the long-term, complex nature of research translation, commercialisation and uptake.

3. The academic, industry and government sectors partner to create a doctoral training and early career support centre for the agricultural sciences. Its functions should be to:

    a. administer a substantial and targeted PhD top-up scholarships program that can compete with other options available to professional agricultural scientists. This would partially reduce the current financial barrier that prevents professionals from returning to study or bringing on-farm experience back to the research sector.
    b. run an agricultural enterprise engagement program to provide graduate students with ongoing exposure to the working farm systems that are relevant to their research, and to encourage research towards the challenges that the National Agricultural Research and Innovation Council identifies as being on the horizon.

c. manage an early- and mid-career support network to maintain connections between PhD cohorts and provide opportunities for early- and mid-career researchers to connect with mentors, each other, and a wider range of agricultural systems than would otherwise be possible.

4. The agricultural research community engages strongly with infrastructure planning processes at all levels to enable agricultural research to benefit from, and contribute to, shared national capabilities, including emerging data-infrastructure and maintaining the pool of skilled technicians that unlock value from national infrastructure capability.

5. All organisations in the agricultural sector need to do more to understand and engage more effectively with the public on social acceptance of agricultural science and the enterprises it supports. This also applies to understanding that agriculture reaches far beyond the farm gate.