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Technological innovation and productivity in dryland agriculture in Australia

A joint paper prepared by the Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE–BRS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO)

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Foreword

Technological innovation and productivity in dryland agriculture in Australia is a collaborative effort between the Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE–BRS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and was developed from Australia’s contribution to the United Kingdom Government’s Foresight project on Global Food and Farming Futures.

There are a number of major challenges facing the future of food and farming. A growing world population, changing demands in consumption and climate change are examples of the critical issues that will place pressure on agriculture and food production in the coming years. Globally, governments must seek to identify and analyse critical issues facing agriculture, and identify and analyse possible policies and interventions for addressing these problems.

Dryland farming in semi-arid environments faces special problems in contributing to the world’s food supply. In this respect, Australia’s contribution to global efforts to meet the challenges facing agriculture provides a potent case study. Despite our variable climate and fragile environment, Australian dryland farming systems have performed favourably compared to agricultural sectors in most other countries over the past 30 years. Australian research, development and extension has been a significant contributor to the realised agricultural productivity growth over this period.

Another strength lies in Australia’s capacity to collaborate across government, bringing together scientific, research and policy expertise to solve complex problems. This report, in drawing on such expertise in CSIRO and ABARE–BRS, makes a valuable contribution to the deliberations by decision makers on food security and productivity.



Phillip Glyde
Executive Director
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July 2010

Summary

This report is the result of a collaborative effort between the Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences and the Commonwealth Scientific and Industrial Research Organisation. It is based on Australia’s contribution to the United Kingdom (UK) Government’s Foresight project on Global Food and Farming Futures, whose findings are due to be launched in November 2010.

The Foresight Programme is run by the UK Government Office for Science. Individual Foresight projects look at least 10 years ahead, develop visions of the future and analyse issues at the interface of science and society. Cutting-edge science and other evidence are used to identify future risks and opportunities, and inform strategies to manage those challenges. The Foresight project on Global Food and Farming Futures seeks to answer the following question: ‘how can a future global population of nine billion people all be fed healthily and sustainably?’. The project looks out to 2050 and takes a global view of the food system, considering issues of demand, production and supply as well as broader environmental issues. Because of the project’s global perspective, the work draws heavily on the skills and perspectives of leading experts and stakeholders from around the world, including Australia.

This report briefly reviews the latest developments in the science and technology approaches relating to dryland farming systems in Australia. It sets the context for dryland agriculture in Australia and examines the risks and returns from technological innovations over the past 30 years. It then examines possible sources of productivity gains in the next 30 years.

The review found that despite Australia’s variable climate and fragile environment, Australian dryland farming systems have performed favourably compared to the agricultural sectors in most other countries over the past 30 years. Australian Research, Development & Extension (RD&E) has been a significant contributor to the realised agricultural productivity growth over this period. However, growth in productivity of agriculture appears to have slowed in the last 10 years: this is partly a result of extended dry conditions, declining growth in public investment in RD&E but also linked to ageing of the farm population. It is reflected in slowing rates of technology adoption on broadacre farms and changes in investment confidence of farm owners.

Future productivity gains will require continued strong investment in RD&E to meet current and emerging challenges. Future technologies and policies will help improve productivity by removing inefficiencies, increasing the efficiency of resource use and developing breakthrough innovations.

As evidenced by Australia’s success in productivity growth—despite farming in one of the most variable climates in the world—meeting the global challenge to produce 70 per cent more food by 2050 will depend partly on investments in RD&E, risk management systems, farmer skill and human capital, and policies that encourage efficiency gains.

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Introduction

The challenges for global agriculture in the 21st century are to produce 70 per cent more food by 2050 to feed a projected increased population, while implementing more sustainable methods and responding to climate change (FAO, 2009). In addition, the mix of foods demanded by the population is expected to change from cereals to meat and dairy. Much concern about feeding the world in 2050 relates to the slower increase in yields of the major cereal crops over the past three decades (Alston et al., 2009). For example, annual increases in wheat yield are shrinking and are now just below 1 per cent (Fischer et al., 2009). Yield growth is considered the major route to meeting future global food demand, through increased potential yield (maximum yield with best varieties and agronomy, and removing constraints) and closing the gap between actual farm yields and potential yields (Fischer et al., 2009).

The 'drylands', covering about 41 per cent of the Earth's land surface, will need to contribute their share to this yield increase. Drylands are limited by soil moisture, the result of low rainfall and high evaporation, and show a gradient of increasing primary productivity, ranging from hyper-arid, arid, and semi-arid to dry sub-humid areas, based on a decreasing level of aridity or moisture deficit (Safriel et al., 2005).

Dryland agriculture is practiced in Australia (Figure 1) mostly between the latitudes 21° S to 37° S (with some extending to 42° S) in the semi-arid to dry sub-humid regions, which receive 300–600 mm of annual rainfall (Squires and Tow, 1991). Dryland agriculture has been trialled in the semi-arid tropics of northern and north-western Australia (i.e. latitudes of 15–20° S) but a host of economic, social and technical constraints have limited the establishment of any significant commercial industry other than extensive beef production, which dominates agricultural land use in Australia's semi-arid tropics (Carberry et al., 1996). Dryland agriculture largely fits the warm, seasonally wet/dry agro-climates—category E, extending into D5 (Hutchinson et al., 1992). Other regions of the world with similar agro-climates include southern China, the Mediterranean, southern Africa, mid-South America and southern North America.

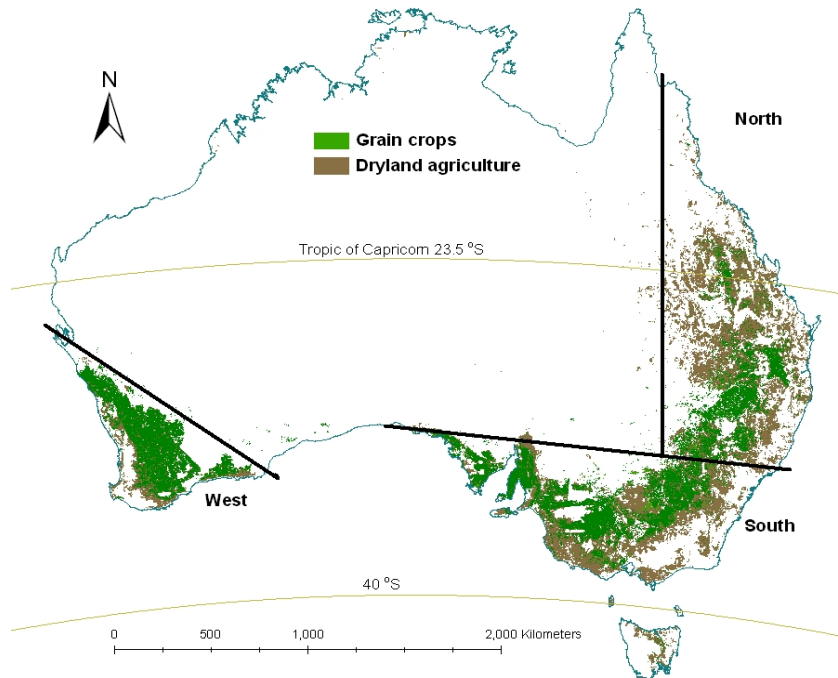
In dryland regions plant production is usually low yielding, variable and difficult to predict. For instance, plant growth indices for the most productive 16-week (four-month) period is between 0.2 and 0.4 (out of a maximum of 1.0; Fitzpatrick and Nix, 1970), and for the most productive 13-week (quarter-year) period is between 0.35 and 0.7 (Hutchinson et al., 1992). Potential grain yields (assuming no biotic or abiotic stresses) in some of these regions tend to be about double achieved farm yields (economically attainable yield) (Fischer et al., 2009). Therefore, viable agricultural production relies on managing risks well, and on optimising the use of local resources to minimise the yield gap between farm and water-limited potential production (maximum production under normal rain-fed conditions with all other constraints removed) (Fischer et al., 2009; Lobell et al., 2009).

This paper illustrates the research investments which have enabled dryland or rain-fed agriculture in Australia to increase in productivity. We consider that a systems approach that incorporates crops, pastures and grazing animals is most likely to optimise the use of resources. The extensive livestock grazing in Australia's arid regions is not included. We begin by setting the context for dryland agriculture in Australia before examining the risks and returns from technological innovations over the past 30 years and possible sources of gains in the next 30 years. Social and economic risks to Australian agriculture are not considered.

Australian context

Dryland agriculture occupies 97 million hectares, or nearly 13 per cent, of the Australian continent (BRS, 2006; Figure 1). The distribution of dryland agriculture is largely a function of low rainfall in the interior and the topography towards the coast.

Figure 1: Distribution in Australia of dryland agriculture



Notes: the map in Figure 1 is overlain with dryland grain cropping areas extracted from land use maps of Australia (BRS, 2001; BRS, 2006; BRS, 2010). The ability of soils to store water enables crops to be grown outside the dryland agricultural boundary in some years. Lines on the map demarcate the three broad dryland agricultural regions in Australia.

In Australia's dryland agriculture, mixed crop–livestock systems predominate and include diverse enterprises where wool production, dual-purpose flocks, prime lamb and beef production are integrated with cereal, pulse and oilseed crops and where forage crops are incorporated into the cropping sequence (Kirkegaard et al., 2010). The intensity of cropping on farms ranges from very low to very high (where it generates more than 80 per cent of farm income) and usually inversely reflects the contribution by livestock (ABARE, 2009a). Dryland agriculture supports 80 per cent of Australia's sheep, 50 per cent of its meat cattle and 93 per cent of its grain production.

There is considerable diversity in the enterprise mix at the regional and local level (Table 1; Figure 1), driven partly by differences in the biophysical resource base and climate (Kirkegaard et al., 2010). Sown pastures or heavily modified pastures are used for livestock grazing, either permanently or as leys in grain cropping rotations (Perry, 1989; Squires and Tow, 1991). In the northern cropping region, ley systems are uncommon and continuous cropping with fallows is more typical. In recent decades there has been a move towards more intensive cropping in the southern and western regions as a result of the collapse in the wool price (Connor, 2004; Kirkegaard et al., 2010) and changes in seasonal conditions. However, ley farming systems remain a key component of dryland agriculture in these areas. Comprehensive and more detailed descriptions of dryland agriculture in Australia can be found in Freebairn et al. (2006), NLWRA (2001), Squires and Tow (1991) and Tow et al. (2010).

Table 1: Percentage breakdown of volume of production, by industry, for the northern, southern and western dryland agricultural regions of Australia, 2005–06. Source Australian Bureau of Statistics 2010.

	Grains	Sheep	Meat cattle
North	20	15	65
South	45	58	30
West	35	27	5
	100	100	100

There was an almost continuous upward trend in crop yield in Australia during the 20th century, following an era of yield decline, predominantly caused by loss of soil fertility, at the end of the 19th century (Angus, 2001). The introduction of pasture legumes, particularly subterranean clover, supplemented with superphosphate, resulted in substantially improved crop productivity, and the ley farming system that developed has remained a key component of Australian dryland agriculture since the 1950s. Later improvements to cropping practices (such as stubble retention, crop rotation, and soil fertility management), combined with disease resistance and improved quality of crop and pasture varieties, has led to increased productivity of mixed farming systems. In particular, wheat yields have almost quadrupled over the past 100 years and now average 2 t/ha (NLWRA, 2001). Despite these increases, yield and efficiency gaps (between potential and farm yield) still remain, because of underlying site characteristics, seasonal conditions and their interactions with management. Improved grain yield under limited water supply remains a target.

With considerable fluctuations, due to many innovations and market factors, sheep numbers increased in the period from 1860 until 1970 (NLWRA, 2001), but have since declined to around 70 million. Likewise, national cattle numbers peaked in the mid-1970s at around 33 million and declined to around 22 million by 1988 but have since risen to 28 million (ABARE, 2009b). Relative price signals, economic booms and recessions, world wars and trade barriers have all influenced livestock and crop production. Improvements in animal genetics and tolerance of pasture legume and grasses to soil acidity, waterlogging and diseases have contributed significantly to the overall improvement in winter forage production of new varieties, which has been a key profit driver in animal enterprises. The extensive use of performance indicators in the grains industry (e.g. water-limited potential yields or yield frontiers) has no obvious parallel in the livestock sector (Kirkegaard et al., 2010), probably because of the more complex needs of grazing animals. However, individual consultant groups that specialise in livestock-dominated industries use stocking rate benchmarks such as Dry Sheep Equivalents/ha/100mm and \$/Dry Sheep Equivalents, and provide overall summaries of options (e.g. Millar et al., 2009). The concept of livestock water productivity is being developed internationally (Descheemaeker et al., 2009).

Considerable research has focused on optimal stocking rates (White, 1987) and livestock carrying capacity (McKeon et al., 2009)—with consequences for production, quality and risks in profitability—as powerful management tools in livestock systems. A research focus has been on addressing ‘feed gaps’ (times of year when the supply of forage is insufficient to meet livestock demand) that limit livestock productivity and result from seasonal and stochastic changes in forage availability (Bell et al., 2008; McKeon et al., 2009; Moore et al., 2009).

Water productivity

Some of the key features of Australia’s dryland agricultural region are low rainfall, high rainfall variability and long wet and dry periods (Freebairn et al., 2006). Farming practices have evolved to cope with the highly variable nature of the rainfall; for example, through the use of fallows in the northern cropping region and in-season adjustment of fertiliser inputs in the southern and western regions.

Reliably achieving growing season (April to October) rainfall of more than 175 mm is required for dryland grain production (Figure 2); 175 mm equates to a potential grain yield of 1.5 t/ha using the water-use-efficiency calculation of French and Schultz (1984). The major factor moderating the effects of rainfall reliability is the ability of soils to store water, enabling crops to be grown where rainfall reliability is low but water holding capacity is high; for example, in the northern cropping region (Figure 1). Rainfall reliability is the likelihood of a specified amount of rain falling during a particular period, thus introducing threshold values to rainfall analyses. This can be meaningful for producers because the distribution of rainfall, which is often notoriously variable across Australia, can deviate from normal and complicate the use of measures such as deciles particularly where rainfall is low. An analogous situation applies to pastures (French, 1991; Pearson et al., 2003). Productivity is closely aligned with water use of up to 600 mm a year (Bolger and Turner, 1999; French, 1991). However, the relationship between water availability and productivity is not as simple in pastures systems because of the impacts of grazing pressure (Asner et al., 2004).

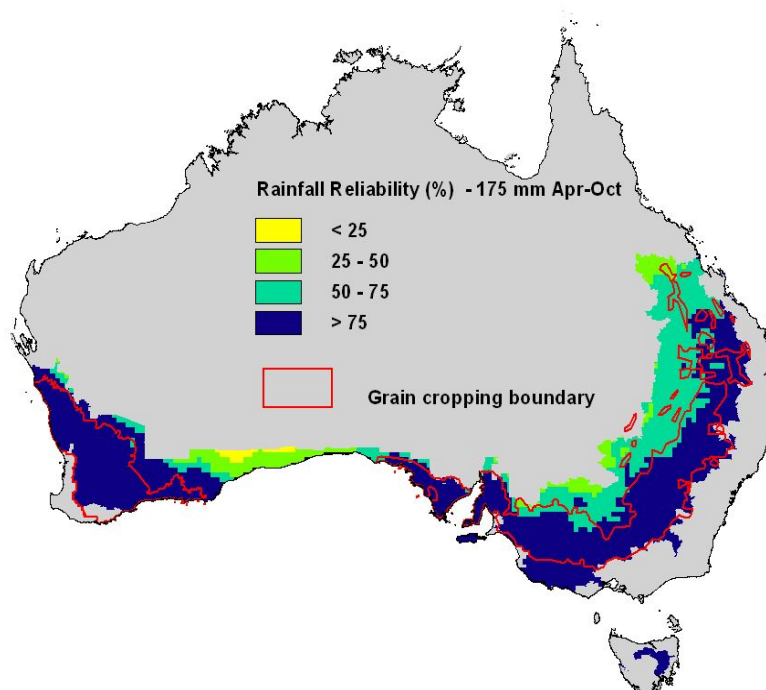


Figure 2: Rainfall limitations to dryland grain production

Notes: Figure 2 provides a comparison of the grain cropping zone (Hamblin and Kyneur, 1993) with reliability of achieving 175 mm of rainfall during the winter growing season of April to October (rainfall reliability wizard, (Laughlin et al., 2003)).

Generally, in dryland agriculture, factors that influence the amount of water stored in soils, such as infiltration and storage capacity, and the ability of roots to extract the water from the soil, have major effects on crop and pasture yields. However, other environmental or management factors (such as losses of water from fallows over the summer months in the northern cropping region) frequently limit crops from reaching the water-limited potential yield (Angus and van Herwarden, 2001; French and Schultz, 1984). Overcoming the relative limitations of these factors in different regions is the core of efforts to improve productivity (Fischer et al., 2009; Passioura, 2006), and could lead to between 2 and 14 million tonnes of additional grain a year (gains of about 4% to 30% respectively) from presently cropped areas in Australia (Walcott et al., 2006).

Review of technologies

Dryland agriculture in Australia has adapted to an extremely variable climate. Keating et al. (2010) proposed an approach to explore returns to technology interventions relative to their riskiness, particularly because of the impact of climate variability. Risk can be defined in multiple ways—variability in economic returns (Anderson et al., 1977), downside risk of failure (Keating et al., 1991) or environmental risks from soil degradation (Carberry et al., 2000) and climate change (Steffen et al., 2006). The return–risk framework suggests that ‘efficiency frontiers’ exist at which the return from existing knowledge and technology is maximised for different risk levels. The curves in Figure 3 are styled examples of such frontiers: the lower, solid line represents the frontier for currently adopted technologies and practices; the higher, dashed line represents the frontier for yet-to-be adopted technologies which create new opportunities and return–risk dimensions. Using this framework, pathways for technology intervention can include:

- Moving from B to D by adopting current best practices to remove system inefficiencies with no increased exposure to risk;
- Moving along the efficiency frontier using existing technologies (D to A) but with an associated increase in inputs and risk;
- Adopting breakthrough practices or technologies to move to a new efficiency frontier (dashed line) that enables
 - Maintaining output through increased efficiency of resource use while reducing exposure to risk (D to C)
 - Increasing output with the same exposure to risk (D to F)

In this framework it is continually important to strategically manage risks from biotic and abiotic threats that lower productivity and lead to a regression from these frontiers.

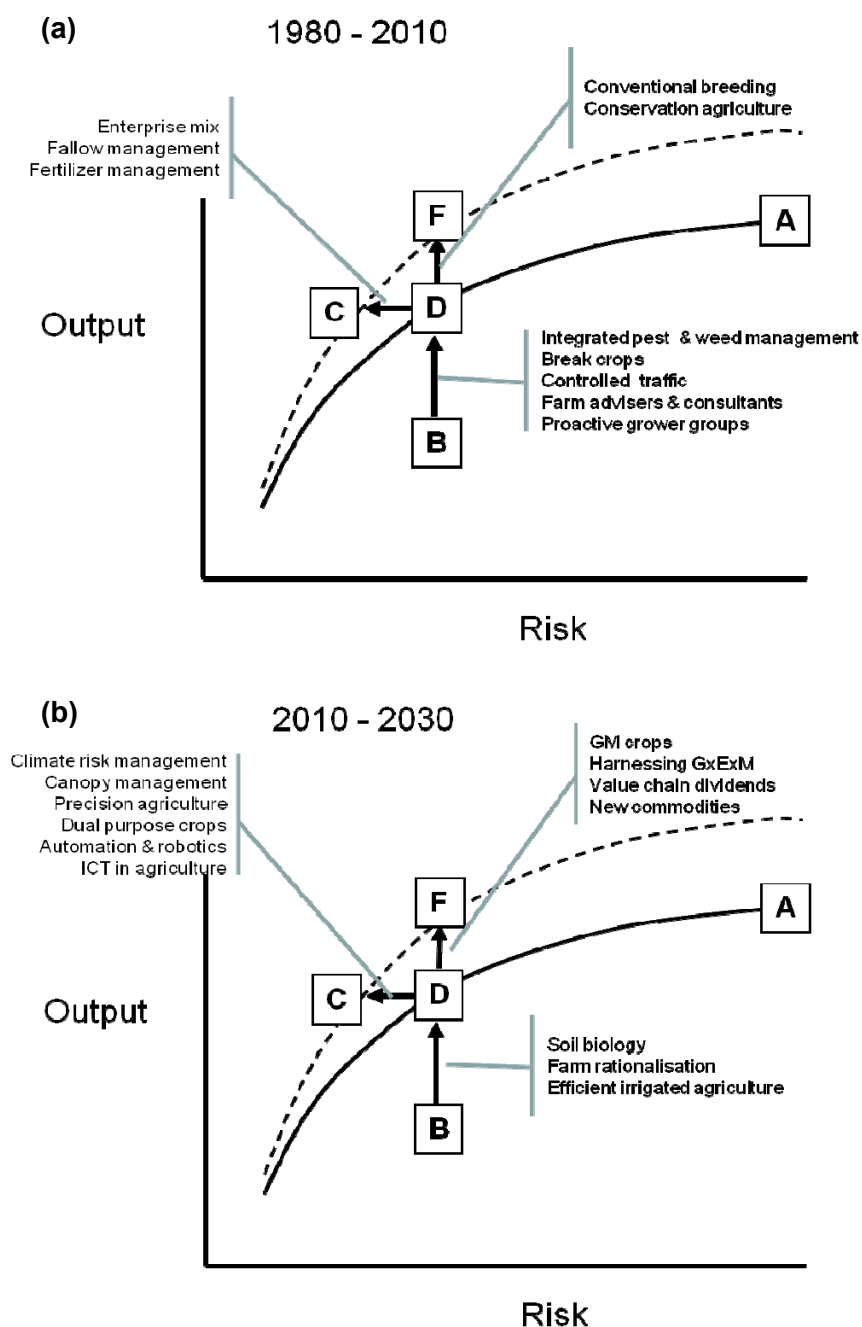
Assessing farm performance against defined benchmarks (e.g. potential yield, water-limited potential yield, or farmer attainable yield) is useful (Fischer and Edmeades, 2010)—the return–risk framework adds value by enabling technological interventions to be assessed in terms of risk. For example, few, if any, farmers would seek to produce water-limited potential yields (point A) (Fischer et al., 2009; Lobell et al., 2009) due to the greater exposure to financial risk associated with the higher levels of investment. In reality, most farmers choose acceptable risk investments which return closer to 60–80 per cent of the potential (point D) (Hochman et al., 2009a). To increase returns with little added risk, the only real option for these producers is to move from the current efficiency frontier (solid line) by adopting breakthrough technologies (D to F).

Figure 3a employs the return–risk framework of Keating et al. (2010) to illustrate how Australian farmers have adopted technology and information systems over the past 30 years to improve their economic performance and deal with the high risk of farming in a variable climate. Figure 3a nominates some of those technologies which, by 2010, have largely been adopted in Australia’s dryland cropping industries—a similar figure could be developed for livestock-dominant industries. Figure 3b suggests technologies which are likely to be developed and adopted over the next 20 years to assist Australian farmers to continue to farm successfully.

Technology adoption 1980–2010

Australian and global agricultural development over the past 30 years has been characterised by productivity growth in food and fibre production. Over this period, agricultural productivity growth in Australia has been high relative to other sectors of the Australian economy (Table 2) and high relative to the average of the agricultural sectors in other Organisation for Economic Cooperation and Development (OECD) countries (Mullen, 2007). This is achieved despite farming, largely unsubsidised (OECD, 2004), on fragile soils and in one of the most variable climates in the world.

Figure 3: Return–risk framework and technologies 1980–2010 and 2010–2030



Notes: Return–risk framework and technologies which either (a) affected Australian dryland agriculture from 1980 to 2010 or (b) are identified as having potential to affect it between 2010 and 2030. In both figures, A and D are representative points on the efficiency frontier for the best technologies at a point in time (—) and C and F are specific points on new efficiency frontiers for hypothesised new technologies (- -). Point B represents a position below the current efficiency frontier (after Keating et al., 2010).

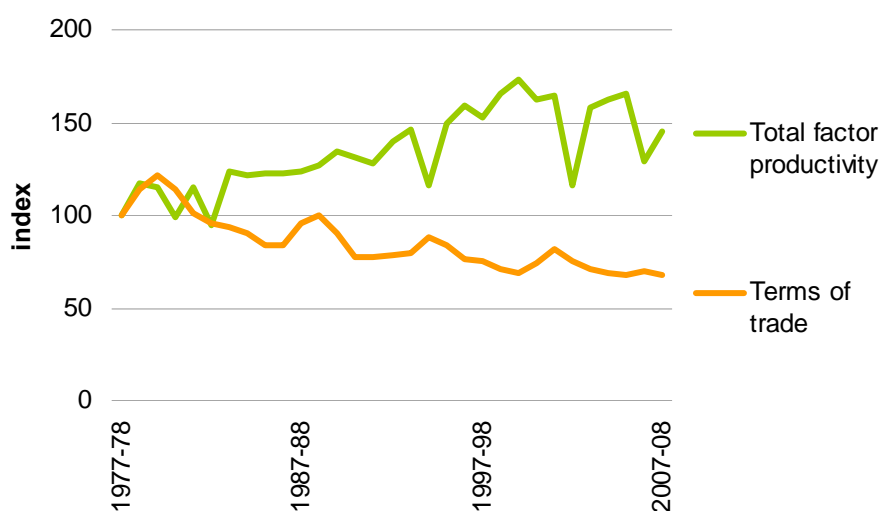
GM: genetically modified; GxExM: genotype by environment by management interactions; ICT: information and communications technologies.

Table 2. Annual productivity growth (%) in sectors of the Australian economy. Selected from Mullen (2007).

Sector	1994-1999	2000-2005
Agriculture	4.3	2.7
Mining	1.2	-2.8
Manufacturing	1.3	1.3
Construction	0.4	2.2
Finance and Insurance	0.8	0.2

The impressive performance of Australian dryland agriculture in countering declining terms of trade (Figure 4) has been achieved through innovation, based on research leading to technology development and adoption. Research has been well supported by strong investments from sectoral funding (Australia’s Research and Development Corporations) and public research agencies (Mullen, 2007). Historically, such productivity growth has come both from improving farming practices and from adopting better varieties and breeds although it varies with time and across agricultural industries (Nossal and Sheng 2010). Recent reviews of Australian agriculture comprehensively examine how Australian farmers have adopted these technologies and practices (Angus, 2001; Fischer, 2009; Freebairn et al., 2006; Kirkegaard et al., 2010; Tow et al., 2010). A number of these key technologies have been mapped onto the return–risk framework in Figure 3a.

Figure 4. Broadacre total factor productivity and agricultural terms of trade. Source Nossal and Sheng (2010)



One assertion is that more progress has been made over the past 30 years in moving most cropping farmers closer to the existing efficiency frontiers (i.e. B to D) than from the science-initiated generation of new efficiency frontiers, which either increase resource-use efficiency or raise potential economic returns (i.e. C and F). Recent analyses (Carberry et al., 2009; Hochman et al., 2009a) suggest that the leading Australian farmers are achieving crop yields that are close to their attainable efficiency frontiers; that is, there is a small gap between the harvested yields of their commercial crops and the corresponding attainable yields simulated by models using actual management and environmental drivers. Adoption of technologies such as disease-tolerant

varieties, integrated pest and weed management, crop rotations which include legumes and disease break crops, conservation agriculture and controlled traffic have resulted in agronomic practices that enable leading growers to approach their production potential, as limited by their environmental and management boundaries.

Even if the varieties and agronomic practices are available so that crop yields can be largely determined by climate and the supply of soil water and nutrients, threats remain from weeds, diseases, pests and soil degradation—a notable example in Australia is the increasing threat of herbicide-resistant weeds (Owen and Powles, 2010). Much past and current research effort has targeted the prevention of any breakdown in the strategies evolved to counter pests and diseases. In addition, practices which threaten the natural resource base for agriculture will result in an unavoidable loss of productivity. Issues such as soil salinity, acidification, erosion and nutrient rundown are current and emerging threats to productivity in Australia (Keating and Carberry, 2010; NLWRA, 2001).

Technologies that generate new efficiency frontiers for the different production systems and agroecological zones around Australia result from a combination of improved genetics and management practices. Australian agriculture invests significant resources into breeding programs, and conventional breeding has contributed strongly to increased crop production (Fischer, 2009). However, the total investment into breeding has to be partitioned between efforts to develop and maintain resistance to biotic threats (e.g. Bariana et al., 2007), deal with abiotic hazards, improve quality and create new water-limited production potential (e.g. Richards et al., 2002). Successful examples of the latter are difficult to quantify.

The widespread adoption of conservation agriculture in most regions of Australia (D'Emden et al., 2008) is a significant management practice which has raised cropping productivity over the past 30 years. Conservation tillage practices improve rainfall infiltration and increase soil water storage (Freebairn et al., 2006), which commonly results in increased water use efficiency of crops in Australian dryland farming. Important management aspects of conservation agriculture are crop nutrition, improving soil biota, residue management and crop rotation, all of which contribute to yielding higher efficiency dividends. Major innovations for mixed crop–grazing systems include aligning animal cycles with pasture production, better breeds, supplementary feeds, forage crops, pasture species and pest and disease prevention (McKeon et al., 2009; Moore et al., 2009).

Dryland agricultural research in Australia has not only sought to achieve higher yields, but also agronomic and business management practices that reduce production risk. Practices that lower risk, such as farm enterprise diversity (especially mixed crop–livestock systems), pre-crop fallowing to store soil moisture and judicious use of fertilisers, have been widely promoted and adopted by Australian farmers (Freebairn et al., 2006; Tow et al., 2010). The agronomic support to farmers from public extension and private advisors has been a key characteristic in Australian agriculture, enabling the adoption of current best practices (Marsh and Pannell, 1998). More recently, the emergence of proactive, self-organised farmer groups has given an added dimension to supporting adoption of good agronomic practices (Carberry, 2001).

There is mounting concern about a recent global slowing of growth in yields of grain crops and their ability to feed a growing population (Fischer et al 2009, Pardey 2010). Despite general increases in broadacre total factor productivity (TFP) over the last 30 years, in more recent years, there are signs that TFP growth may be slowing or declining (Figure 4). Explanations for the changes in TFP may include poor growing conditions such as reduced seasonal rainfall and prolonged drought across Australia (Mallawaarachchi et al 2009); slowing intensity of public investment in research and development (Nossal and Sheng 2010); ageing of the farm population; slowing rates of technology development and adoption on broadacre farms; and changes in investment confidence of farm owners (Nossal and Sheng 2010).

Future technologies 2010–2030

In a recent analysis of opportunities and constraints in Australia's broadacre industries, Keating and Carberry (2010) suggested that, while new products or services from agriculture, such as biofuels or bio-sequestration of carbon, may deliver benefits to both farmers and the wider community, these alone will not transform the nature of Australian agriculture. Rather, the greatest emerging opportunity for agricultural land use in Australia must be sought from productivity breakthroughs that address current and emerging constraints. Figure 3b suggests some of the technologies which may deliver productivity increases in Australian dryland agriculture, along the three intervention pathways.

First, remove system inefficiencies (point B to point D).

- An improved understanding of the biology of agricultural soils to address edaphic constraints would help farmers move towards a new efficiency frontier. Research in this area may lead to characterisation of the function of soil biota (e.g. Torsvik and Øvreås, 2002), quantifying the consequences of poor management and pursuing opportunities to enhance agricultural performance.
- The rationalisation of farms under economic and social pressures, whereby poor-performing farms continue to be bought out by leading farmers (Kingwell and Pannell, 2005), will improve the aggregate industry performance in a particular region.
- As water supplies for irrigation become less secure under climate change (CSIRO, 2008), formerly irrigated agricultural systems may be replaced by dryland agronomic practices with supplementary irrigation to increase the efficiency of water use.
- Opportunities to modify government policies that impede efficiency gains could be addressed; for example, recent assessments of the Australian National Drought Policy (http://www.daff.gov.au/agriculture-food/drought/national_review_of_drought_policy) suggested that it must increase its emphasis on creating an environment of self-reliance and preparedness for drought and climate change.

Second, invest in breakthrough technologies that increase the efficiency of resource use whilst reducing risk (point D to point C).

- Managing climate risk in Australian agriculture remains a challenge (Hochman et al., 2009b). Maintaining returns with reduced risk can be achieved if farmers are able to flexibly adjust their agronomic and marketing management in order to avoid, in any one season, either over-investing in enterprises with poor prospects or under-investing in enterprises with good prospects.
- While precision agriculture has long been researched, and adopted in part, by Australian farmers (Robertson et al., 2009), key aspects such as variable rate input applications of fertiliser are yet to have industry-wide effects (Bramley, 2009). To achieve increased resource-use efficiency in Australian agriculture, there will need to be continued innovation in precision agriculture to improve the management of spatial and temporal variation; widespread adoption of precision agriculture by farmers; and extension of precision agriculture to pasture and livestock management.
- Dual-purpose crops offer grain production and forage supply to livestock and thus potentially provide a profitable and flexible break-crop option for mixed farms (Kirkegaard et al., 2008).
- Managing livestock, pastures and forages, including dual purpose crops, to optimise carrying capacities and minimise climate-induced risks is complex and is likely to require continued investment in models and decision support tools, especially as the climate changes (Moore et al. 2009, McKeon et al. 2009).

- Information and communications technologies, including the internet, telecommunications, video and print technologies (McLaren et al., 2009), and the associated fields of automation and robotics (Wark et al., 2007) potentially offer Australian dryland farmers and graziers improved access to agronomic and marketing advice, better monitoring of resources, automated measuring of livestock and increased efficiency of labour use.

Third, continue to invest in breakthrough technologies that offer greater returns for the same level of risk (point D to point F).

- Gene technologies could be considered the source of ‘breakthrough’ innovations in agriculture, particularly given the significant research investment into genetically modified crops (Brookes and Barfoot, 2005; Hattersley et al., 2009). Harnessing the interactions between the available genetic variability in crops or livestock targeted to specific environments and using adaptive management is seen as a basis for a ‘Genetics x Environment x Management’ revolution that will push water-use efficiency and enterprise performance beyond the current production frontier (Richards et al., 2002).
- Greater participation by farmers in agricultural value chain activities provides the capacity to increase efficiencies, business integration, responsiveness and market competitiveness (Higgins et al., 2007).
- Other emerging opportunities in Australian agriculture will likely include new products or services such as biofuels, forest-based carbon storage in agricultural landscapes, bio-sequestration of carbon in agricultural soils (Bruce et al., 2010) and environmental stewardship schemes that would reward farmers for nature conservation and related non-production services from farming land (Keating and Carberry, 2010). However, it is likely that there may be benefits and trade-offs with food production in delivering these products and services.

In practice, productivity increases will be realised through combinations of these strategies as managers respond to market signals, availability of technologies and immediate drivers such as drought.

Governance and policy issues

Government policies for agriculture in Australia often aim to reduce the regulatory constraints on agricultural innovation while acceding to social demands for environmental quality, food safety and quality assurance (Williams and Walcott, 1998). Some of these policies align with the return-risk framework.

For instance, to help manage climate variability, the Australian, state and territory governments set up a national drought policy in 1992. The policy has a central philosophy of self-reliance and effective risk management, recognising that farmers can best make their own decisions based on their own assessment of risk. The intention is that farmers be able to manage their position on the return-risk frontier (e.g. D to A in Figure 3). Here, the role of government is to assist farmers to enhance their skills in key areas of risk management and business planning through education and training, and to provide a safety-net level of support during exceptional circumstances. Similar efforts are being directed to help agricultural industries manage climate change.

There are now significant programs to address the market failure associated with environmental impacts, biodiversity conservation and sustainable development. These programs that aim to move producers up to the existing return-risk frontier (i.e. from B to D in Figure 3) may have inadvertently slowed rates of productivity gains by diverting investment away from breakthrough technologies for direct productivity research. For instance, Pardey (2009) notes that a diversion in research investment from farm productivity towards environmental effects, food quality and alternative uses during the 1990s is, because of considerable lags in adoption, now likely to contribute to the slowing in productivity gains.

An investment approach to create new return-risk frontiers is to obtain productivity gains (Mallawaarachchi et al., 2009) through innovation (research, development and adoption of new technologies), by matching farmer contributions in the form of levies on production to fund research activities. These funds, which originally supplemented state government, university and private research resources, will increasingly play a more central role as they are now providing the major growth in investments while that from state governments is declining.

A risk management approach has been adopted to protect Australia from incursions by exotic pests and diseases that would reduce in-country productivity (www.daff.gov.au/animal-plant-health) and prevent regression to lower return-risk frontiers. Australia's very low risk approach—enabled by its relative physical isolation from sources of many incursive agents—has so far mostly shielded its agriculture from the effects of significant disease outbreaks or pest incursions. A complementary strategy is to prepare for responses to possible contamination or malicious disruption of Australia's food supplies.

However, some policies do not easily readily fit within a return-risk framework. An international approach is to pursue efforts to increase access to overseas markets and to overcome emerging technical trade barriers and liberalise international trade. Domestic governance policies focus on improving competition, market information and fair trading in food supply chains. While state governments have primary responsibility for agriculture and land use in Australia's federal system, globalising trends and cross-cutting issues such as irrigation water and reducing greenhouse gas emissions are increasingly involving the Australian Government.

Future challenges

Keating and Carberry (2010) identify the future threats to Australian broadacre agriculture as:

- climate change and greenhouse gas emissions
- water availability for irrigated agriculture
- energy and input costs
- degradation of soil and natural resources

- access to human capital.

Much effort is currently being expended in Australia to prepare industries to adapt to projected future climate change. Most assessments suggest that both irrigated and dryland agriculture in Australia will be significantly affected by climate change (Stokes and Howden, 2010). It is also desirable that agricultural industries are able to respond to any emission reduction strategies that are likely to be imposed.

The dryland salinity that results from a mismatch between the timing of rainfall and the water requirements of annual crops and pastures (Passioura and Ridley, 1998) remains the significant unresolved legacy of past practices that will challenge Australia's future agricultural endeavour. The recent decade of extended below average rainfall and reduced irrigation allocations has alleviated many of the symptoms of salinity, but it is likely that efforts to address the underlying causes remain incomplete (Ali 2008 <http://www.csiro.au/files/files/pmyj.pdf>). Whether agricultural research or public policy can adequately address such environmental degradations, and the associated biodiversity loss, is a source of current intense debate (Hamblin, 2009).

Australia's access to the skills and human capital needed to maintain viable agricultural enterprises and their associated rural communities is being seriously questioned (Pratley and Leigh, 2008). A limited skills base will likely increase time to adoption of technological innovations because innovations require extensive trialling to manage the relative riskiness between innovations (Abadi Ghadim et al. 2005).

Lessons learnt from the Australian context

Despite its variable climate and fragile environment, Australian dryland farming systems have outperformed the agricultural sectors in most other countries over the past 30 years (Mullen, 2007). Australian research, development and extension (RD&E) has contributed significantly to the realised agricultural productivity growth. Continued investment in RD&E will be needed in the face of current and emerging challenges. The close relationship between productivity growth in agriculture and RD&E investment has been well documented, both for Australia (Mullen, 2007) and globally (Alston et al., 2009). Innovations have elements from locally developed and imported technologies, sometimes as a result of complex interactions. Therefore the recent global trends of slowing productivity growth and reduced RD&E funding for agriculture are clearly of concern (Alston et al., 2009).

Australian farmers have adopted and adapted technologies, whether locally derived or imported, that have improved their productivity and profitability. Two key drivers of such technology adoption have been the dominant need for continued on-farm productivity gains in order to maintain economic viability within the prevailing cost-price squeeze, and the essential consideration of risk in managing farms in a highly variable climate. Australian dryland agriculture has been a price-taker on the world export markets and, as such, its gross value of production has been maintained over the past 30 years mainly through productivity growth rates of at least 2 per cent a year (Mullen, 2007, Nossal and Sheng 2010). Such rates of productivity growth need to be maintained, not only for Australian farmers to survive but also to help meet the global challenge of achieving food security (Keating et al., 2010).

Being largely unsubsidised and farming in one of the most variable climates in the world necessitates that Australian farmers, and their technology providers, fully consider risk when making decisions either tactically (e.g. fertiliser inputs) or strategically (e.g. converting the farm and its equipment to conservation agriculture or introducing new crops better suited to a changed climate). Much promotion of new technologies and criticism of the gaps between farmer performance and potential yields largely ignore the influence of risk in decision-making. The framework proposed by Keating et al. (2010) and utilised in Figure 3 explicitly incorporates both production (output in yields or dollars or productivity measures such as water use efficiency) and risk dimensions.

A systems approach to agriculture has been a defining aspect of both the evolution of farmer practice and the RD&E effort in Australia (Kirkegaard et al., 2010). In fact, the active participation of farmers in the RD&E effort is a defining characteristic of Australian agriculture (Carberry, 2001).

As evidenced by Australia's success in productivity growth despite farming in the one of the most variable climates in the world, the global challenge to produce 70 per cent more food by 2050 will depend partly on investments in RD&E, risk management systems, farmer skill and human capital, and policies that encourage efficiency gains. A strong and competitive agricultural sector is better able to adapt to new situations and opportunities as they arise.

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