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Adapting agriculture to climate change: a review

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Abstract The agricultural sector is highly vulnerable to future climate changes and climate variability, including increases in the incidence of extreme climate events. Changes in temperature and precipitation will result in changes in land and water regimes that will subsequently affect agricultural productivity. Given the gradual change of climate in the past, historically, farmers have adapted in an autonomous manner. However, with large and discrete climate change anticipated by the end of this century, planned and transformational changes will be needed. In light of these, the focus of this review is on farm-level and farmers responses to the challenges of climate change both spatially and over time. In this review of adapting agriculture to climate change, the nature, extent, and causes of climate change are analyzed and assessed. These provide the context for adapting agriculture to climate change. The review identifies the binding constraints to adaptation at the farm level. Four major priority areas are identified to relax these constraints, where new initiatives would be required, i.e., information generation and dissemination to enhance farm-level awareness, research and development (R&D) in agricultural technology, policy formulation that facilitates appropriate adaptation at the farm level, and strengthening partnerships among the relevant stakeholders. Forging partnerships among R&D providers, policy makers, extension agencies, and farmers would be at the heart of transformational adaptation to climate change at the farm level. In effecting this transformational change, sustained efforts would be needed for the attendant requirements of climate and weather forecasting and innovation, farmer's training, and further research to improve the quality of information, invention, and application in agriculture. The investment required for these would be highly significant. The review suggests a sequenced approach through grouping research initiatives into short-term, medium-term, and long-term initiatives, with each initiative in one stage contributing to initiatives in a subsequent stage. The learning by doing inherent in such a process-oriented approach is a requirement owing to the many uncertainties associated with climate change.

1 Introduction

Regional climate conditions are a primary determinant of agricultural productivity as plant metabolic processes are regulated by such variables as temperature, solar radiation, carbon dioxide (CO_2), and water availability (Chaves et al. 2003; Pidwirny 2006; Lucier et al. 2006). Agricultural productivity can also be disrupted due to damage to crops caused by climate extremes, such as heat waves, storms, droughts, and flooding (BoM 2006a, b, 2011). Regional mean and extreme climate conditions are affected by natural influences both external to the global climate system, including changes in the Sun's intensity and volcanic eruptions, and internal modes of variability, such as the multiyear El Niño Southern Oscillation (ENSO) (Harries 1996; Power and Colman 2006; Collins et al. 2010). There are also human influences that affect climate conditions

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globally and regionally, such as the emission of greenhouse gases (GHGs) into the atmosphere and human influences that have a more limited geographical influence, such as changes in land surface properties due to agriculture (Zhao et al. 2001; Betts et al. 2011).

Agriculture covers 38 % of the world's land area (FAOSTAT 2012) with 1.2–1.5 billion hectares under crops, 3.5 billion hectares being used for grazing and pasture, and an additional 4 billion hectares being under forest (Easterling et al. 2007). Agriculture utilizes 70 % of the Earth's available fresh water (Somerville and Briscoe 2001). With global populations projected to rise from the current 6.7 billion to 9.3 billion by 2050 (UN 2011) accompanied by rising incomes in developing countries, agriculture faces the challenge of producing sufficient food, feed, and fiber to meet greater demands under conditions of a changing climate and depleting natural resources. Additionally, continuing an observed increase in atmospheric CO_2 concentrations from 280 ppm before the Industrial Revolution to the current level of 380 ppm in 2005, CO_2 concentrations are projected to increase to 540–970 ppm by 2100 (Intergovernmental Panel on Climate Change (IPCC) 2007a). An increase in atmospheric concentrations of CO_2 and other GHGs has contributed to a global mean temperature increase of 0.76 °C between 1850–1899 and 2001–2005 (IPCC 2007a). Increases in GHG concentrations are expected to result in a warming of 1.1–6.4 °C over the twenty-first century (IPCC 2007a; Betts et al. 2011). This warming will induce other changes in the global climate system during the twenty-first century. Climatic changes of such magnitude cannot be readily absorbed and have to be carefully planned and addressed over long periods of time. Further, this warming with accelerated GHGs could lead to climatic extremes, such as increased intensity and frequency of hot and cold days, storms and cyclones, droughts and flooding, altered hydrological cycles with precipitation variance, increase in surface ozone (O_3), and sea-level rise (Houghton et al. 2001; Rosenzweig et al. 2002; Ashmore 2002, 2005; Parry et al. 2005; IPCC 2007a, b; Solomon et al. 2009). In light of all of these, global climate change is one of the primary concerns for humanity in the twenty-first century and there is a clear imperative for action to prepare agriculture to adapt to climate change.

Faced with having to adapt to a range of possible climate changes, this review examines the latest research globally on farm-level agricultural system productivity (FASP), with a focus on the role of adaptation of management practices in meeting the challenges of climate change. Given their inherent link to climate and natural resources (e.g., availability of water resources, soil quality), agricultural farming systems are dynamic (Adams et al. 1998; Cline 2007). In addition, agricultural farming systems are continuously responding to other biophysical changes, such as pests and diseases, and changes such as market fluctuations, changes in domestic and international agricultural policies (subsidies, incentives, tariffs, credit facilities, and insurance), management practices, terms of trade, the type and availability of technology and extension, and land-use regulations (Stokes and Howden 2010). Agricultural farming system dynamism and factors determining farmer and farm-level responses to changing climatic conditions are carefully considered in this review, with the objective of identifying an action plan for adaptation. The central risk management questions addressed are (1) what are the plausible scenarios for climate change?, (2) how will such scenarios of climate change affect FASP?, (3) what are the obstacles preventing the agricultural farming system adapting to climate change?, and (4) how can the agricultural farming system overcome these obstacles and effectively mitigate the risks resulting from climate change?

While increasing atmospheric CO_2 can have positive impacts in crop plants and higher-latitude regions may become productive due to climate change (Easterling et al. 2007), the negative effects overwhelmingly outweigh the positive impacts (Easterling et al. 2007; Stern 2006) and this review will focus on the harmful effects of climate change. The adoption of "best agricultural practices" could potentially increase FASP (Tilman et al. 2002). However, future changes in mean climate, climate variability (CV), and incidence of extreme climatic events are likely to be so fundamental that the emphasis will need to shift from incremental to transformational change in agricultural farming systems and, consequently, from autonomous farm-level planning to a systems planning approach in the future. Consequently, the nature and content of systems analysis are likely to undergo major changes (Stokes and Howden 2010; Keenan and Cleugh 2011). This study does not deal with the ways in which agricultural practices could reduce GHG emissions, but this review examines the factors that cause the gap between potential and actual systems yield under alternative climatic conditions and agricultural farming system's adaptation responses to climate change. A review of experiences in different countries and regions provides crucial insights into the various options for bridging the gap in the context of future climate change. The review focuses predominantly on crops and pasture of an agricultural farming system; other aspects such as mitigation, biodiversity, and socioeconomic issues are beyond the scope of this paper. The discussion that follows is aimed at improving agricultural adaptation and addresses implications for climate change policy and directions for future research.

2 Implications of climate change

Natural resources, especially those of soil, water, plants, and animal diversity, vegetation cover, renewable energy sources, climate, and ecosystem services are fundamental for the structure and function of agricultural farming systems. With the established increase in atmospheric concentrations of GHGs (Adams et al. 1998; Houghton et al. 2001; Cline 2007) together with changes in precipitation patterns and increasing temperature (Figs. 1, 2, and 3), the natural resource components of an agricultural farming systems would be altered positively or negatively (Easterling et al. 2007) and, in turn, affect farm productivity throughout the world (Cline 2007), including in Australia and New South Wales (Stokes and Howden 2010). There is also a broad scientific consensus (Fischer et al. 2002; Stern 2006; IPCC 2007a) that, as the Earth warms, precipitation patterns shift and extreme events, such as droughts, floods, and forest fires, become more frequent. These implications of climate change are now well understood; the IPCC Fourth Assessment Report (2007a, b) (Rosenzweig et al. 2007) states, "increased frequency of heat stress, droughts and floods negatively affects crop yields and livestock beyond the impacts of mean climate change, creating the possibility for surprises, with impacts that are larger, and occur earlier, than predicted using changes in mean variables alone." Thus, under the current climate condition, damage to the major components of agricultural farming systems due to CV and extreme events is of great concern. Easterling et al. (2007) concluded that, for increases in global average temperature of <3 °C, a decrease in agricultural output in the tropics will be more than offset by an increase in the temperate zone. However, further warming without appropriate adaptation will result in losses in global FASP (Easterling et al. 2007; Stokes and Howden 2010). Table 1 summarizes the important components of climate change and their implications for FASP.

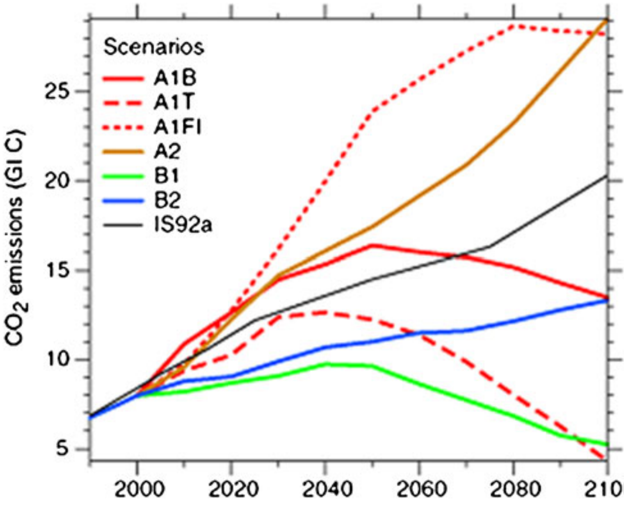


Fig. 1 Emissions of projected CO_2 out to year 2100 under different plausible future scenarios (Nakicenovic and Swart 2000). The higher-emission scenario (A1FI) corresponds to the highest *red dotted line*, while the lower-emission scenario (B1) is indicated by the *solid green line* with other CO_2 emission levels in between. Source: Emissions Scenarios, IPCC, 2000 (http://www.ipcc.ch/ipccreports/sres/emission/)

3 Climate change scenarios

Projections of future climate change are typically based on assumptions about future emissions of GHGs and aerosols into the atmosphere (Nakicenovic and Swart 2000). Future emissions will be influenced by the evolution of the global population, socioeconomic development, and technological advances (Canadell et al. 2007; Le Quere et al. 2009). The interaction of these complex and dynamic factors results in considerable uncertainty about the future trajectory of emissions (Moss et al. 2010; Thomson et al. 2011). This makes it necessary to consider a range of alternative emission scenarios. The emission scenarios described by the Special Report on Emissions Scenarios (SRES) developed by the IPCC are based on scientific data available at the time of the report's publication (in 2000) along with assumptions about future economic growth, technology, energy intensity, and population that seemed reasonable at that time (Nakicenovic and Swart 2000).

Figure 1 (IPCC 2007a) shows the twenty-first century global CO_2 emissions consistent with the six most commonly used SRES scenarios, the A1B, A1T, A1FI, A2, B1, and B2 "marker" scenarios. Global CO_2 emissions have been tracking the upper edge of the IPCC range of emission scenarios (Rahmstorf et al. 2007; Raupach et al. 2007).

The SRES emission scenarios can provide insights into future climate-related risks. However, a single emission scenario does not correspond to a single scenario for future regional climate conditions. Different assumptions can be made about the global carbon cycle and about the sensitivity of the global climate system to atmospheric concentrations of GHGs and aerosols and this means that projected global average temperatures may not be the same emissions scenario (Betts et al. 2011). Furthermore, future climate scenarios illustrating how the climate of each region may evolve in the future do not necessarily give the same regional climate conditions for the same global average temperature.

Scenarios do not attempt to predict the future, but rather help to uncover what is not known, expected, or monitored. Consequently, these scenarios provide advanced warning to assist decision makers in the organization of different agricultural farming systems in order to plan for risk and be alert for uncertainties that may otherwise produce surprises. As an example, Fig. 2 illustrates projected percentage changes in annual precipitation across Australia between 1990 and 2070 under low (SRES B1), medium (SRES A1B), and high (SRES A1FI) emissions scenarios. For each emissions scenario, the values shown are medians calculated from a range of different regional climate scenarios derived from different

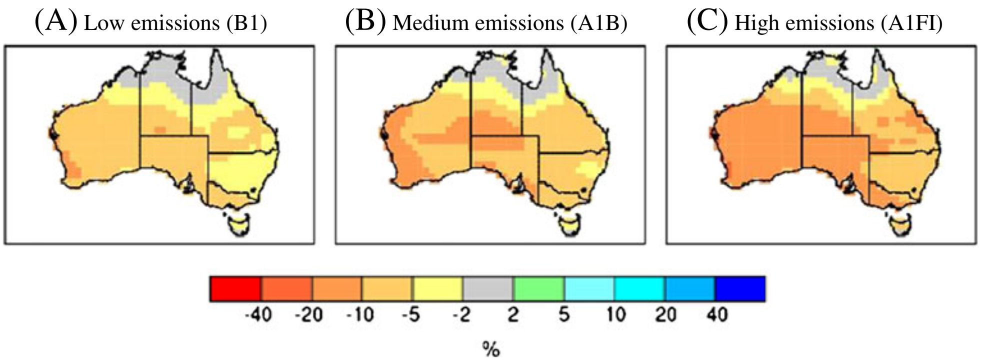


Fig. 2 The median projected annual precipitation change (in percent) of Australia for 2070 relative to 1990 under plausible future scenarios modeled by the IPCC in the SRES (Nakicenovic and Swart 2000). **a** Low emission is the B1 scenario, **b** medium emission is the A1B scenario, and **c** high emission is the A1FI scenario. Source: CSIRO and Bureau of Meteorology (2007) (http://www.climatechangeinaustralia.gov.au)

climate models. Under the low (SRES B1) emissions scenario, the median values show little change in precipitation in the northernmost part of Australia. About 2 to 5 % reduction in precipitation is shown a little further south and in New South Wales. Across most of the rest of the country, precipitation is projected to decrease by 5 to 10 %. However, in localized pockets in central Australia and southwest Western Australia, projected precipitation decreases exceed 10 %. Against this back ground, the medium and high emissions scenarios indicate the progressive expansion of the regions experiencing precipitation decreases >5 and >10 %. The key message that emerges is that even a low emission scenario results in a significant risk of higher levels of aridity by 2070 and this risk is more extreme for higher emissions.

4 Climate variability

CV is defined by IPCC (2001) as “variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events.” Thus, the measure of CV is also a measure of climate change (Alley et al. 2003). As a consequence of CV, changes in agricultural farming system’s productivity are expected because crop growth, development, and yield are products of ecophysiological processes regulated by interacting environmental variables that, together with atmospheric CO_2 concentrations, nutrient availability, and species-related and management-related variables, include climate-related variables such as temperature, water availability, and wind speed (Jablonski et al. 2002; Passioura 2002; Porter and Semenov 2005; Easterling et al. 2007; Olesen et al. 2011). Therefore, improved understanding of the potential implications (Table 1) of CV on FASP is central to climate change adaptation.

The “occurrence of extremes” in the definition of CV by IPCC (2007b) is seen in frequent climatic extremes like droughts and floods, storms, heat waves, as well as large-scale circulation changes, such as the ENSO. All have important effects on FASP (Fischer et al. 2005; Tubiello 2005; Scroxton et al. 2011). Some of the effects of climate extremes on FASP can be region-specific or location-specific. For example, the Australian climate of 2002–2003 reflected a typical El Niño event resulting in severe drought (loss of $7.6 billion agricultural production) with exceptional hot and dry conditions causing devastating bushfires (over 3 million hectares were burnt) in Queensland, New South Wales, Australian Capital Territory, Victoria, and Western Australia (BoM 2006a). The recent flooding in eastern Australia (parts of Queensland, New South Wales, and the Murray–Darling Basin) coincident with a very strong La Niña event in the Pacific Ocean is estimated to have reduced agricultural production valued at least of $500–600 million in 2010–2011 (ABARES 2011; BoM 2011). Furthermore, a globally observed marked decrease in land precipitation, accompanied by increasing temperature since 1970, has enhanced aridity over Africa, southern and eastern Asia, eastern Australia, northern South America, southern Europe, and most of Alaska and western Canada (Dai 2011). This observed drying or drought can be measured by the Palmer Drought Severity Index (PDSI), developed by Palmer (1965), that measures the cumulative departure in surface water balance incorporating precipitation (antecedent and current) and demand (evapotranspiration). The PDSI is a standardized measure, ranging from about −10 (dry) to +10 (wet), with values below −3 implying severe to extreme drought and can be used to depict drought (Dai 2011).

Shifts in the climate affect yield in agricultural crops, for instance, variance in temperature during spring (flowering) and fall (maturity) in cereals (Passioura 2002; Porter and Semenov 2005; Lobell 2007; Tao et al. 2006; Shimono 2011). Variations in observed annual mean temperature and precipitation for the globe, Australia, and Wagga Wagga

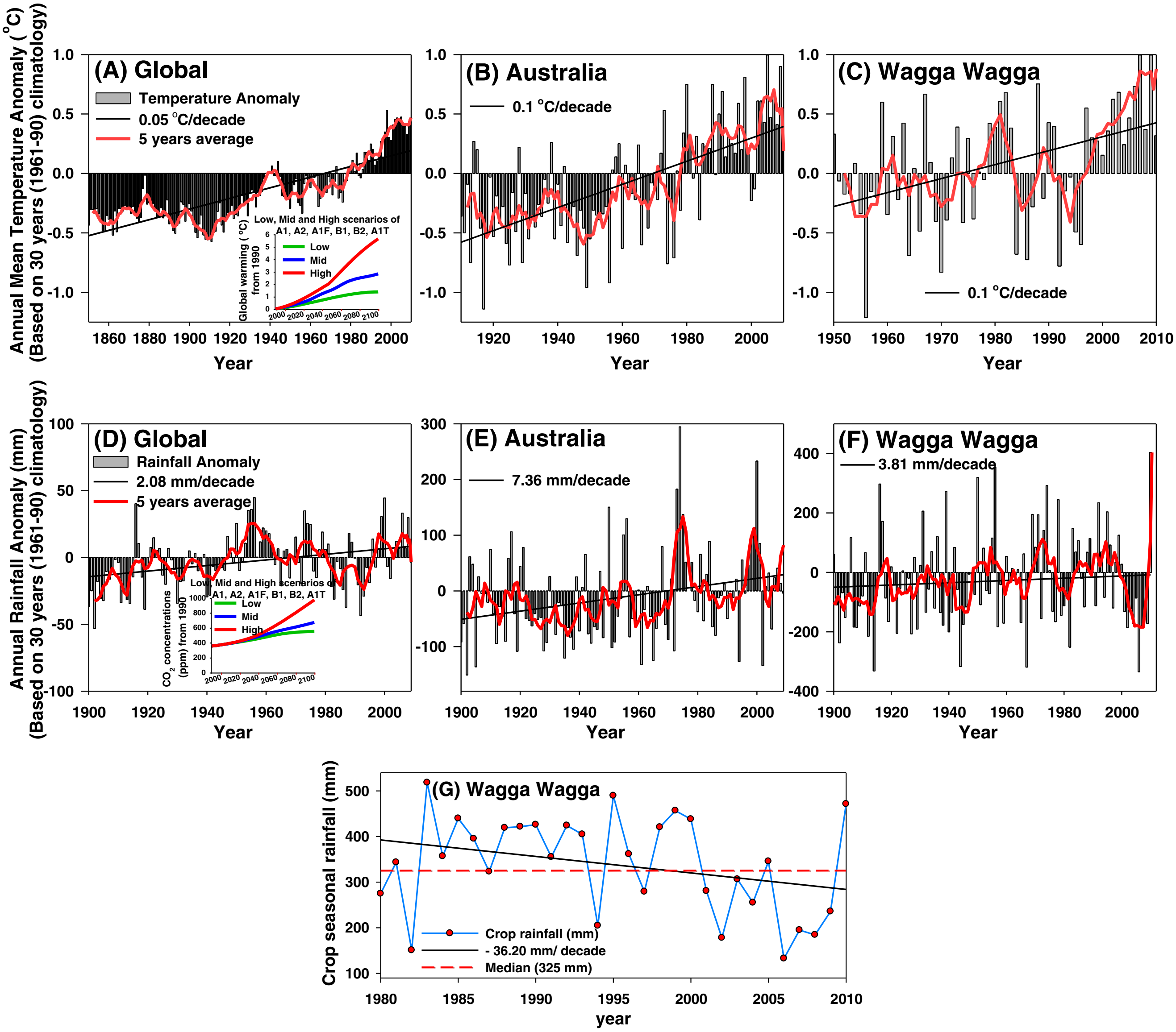


Fig. 3 Observed annual mean surface temperature (in degrees Celsius) and annual precipitation (in millimeters) anomalies (1900–2010) relative to the average 30 years (1931–1990) period for global (**a**, **d**), Australia (**b**, **e**), and Wagga Wagga (35.05° S, 147.35° E) (**c**, **f**). **g** Crop seasonal precipitation (in millimeters) variability at Wagga Wagga. *Solid red lines* indicate the 5-year moving average and *black lines* indicate the trend (fitted by ordinary least squares regression). The *insets* in **a** and **d** are annual global warming values (in degrees Celsius) and CO_2 concentrations (in parts per million) for low, medium, and high scenarios (the SRES; Nakicenovic and Swart 2000) for years between 2000 and 2070 are relative to 1990 which is the IPCC (2001) standard baseline. The observed annual mean surface temperature (in degrees Celsius) of Wagga Wagga (**c**) is from 1950 to 2010. Historical climate data were obtained from the SILO Patched Point Dataset (http://www.longpaddock.qld.gov.au/silo/ppd/index.php) and Australian Bureau of Meteorology (http://www.bom.gov.au/climate/change/global_cvac.shtml)

(35.05° S, 147.35° E) are shown in Fig. 3 as the differences from 1961 to 1990 mean. Figure 3g shows the crop season precipitation variability at Wagga Wagga. Figure 4 shows the annual numbers of hot days (≥35 °C) and frosty nights (≤0 °C) averaged across Australia and for Wagga Wagga. This variation of climate variables imply that the key drivers of farming system's productivity, such as temperature and precipitation, will trigger substantial shifts in crop and livestock productivity (Passioura 2002; Porter and Semenov 2005; Easterling et al. 2007; Olesen et al. 2011). Recent analysis in Australia by Liu et al. (2011) shows that future projected frost days may not change; however, future crop yields may be reduced by temperature increases, accelerating phenological development and increases in the number of hot days coinciding with wheat crop flowering.

There are initiatives for developing decision support tools for on-farm decision making (CSIRO 2009) that use information on CV to provide probabilistic climate forecasts. In

Table 1 Components of climate change: implications for agricultural farming system productivity

Components affecting agricultural farming system	Implications and concern	Observed and projected changes
1. Climate variability due to		
Madden–Julian oscillation	Influence daily precipitation patterns, crop damages, soil degradation, and runoff (Jones et al. 2004; Donald et al. 2006; Cassou 2008)	Observed recent changes (not necessarily due to anthropogenic climate change)
Quasi-biennial oscillation	Drought and cyclone, fluctuation of surface solar radiation and temperatures, precipitation variability, crop yield loss (Oladipo 1989; White et al. 2003; Emanuel 2005; Vines 2008; Malone et al. 2009)	
Southern annular mode	Precipitation variability, crop loss, coastal region production loss (Marshall 2003; Marshall et al. 2004; Cai et al. 2005)	
Indian ocean dipole	Bush fire, drought, crop loss, (Saji et al. 1999; Cai et al. 2009; CSIRO 2009; Kawatani et al. 2011)	
ENSO and interdecadal Pacific oscillation	Precipitation variability, crop yield loss, drought and flood, vegetation loss, and soil erosion (Pittock 1975; Kirono and Tapper 1999; Power et al. 1999; Folland et al. 2002; Nyenzi and Lefale 2006; Cai et al. 2011)	
North Atlantic oscillation	Precipitation variability, drought and flood, land degradation, lower yields/crop damage and failure, livestock deaths (Visbeck et al. 2001; Cullen et al. 2002; Cohen and Barlow 2005; Cassou 2008)	
2. Atmospheric CO_2	Increase biomass in crops and weeds with nonlimiting nutrient supply, weeds competition with crops, increase physiological water use; alteration in soil C/N ratio, in turn, modify hydrological balance, altered N cycle, increase in pathogens and diseases from greater fungal spore production, damage from insect, crop yield decrease (Coakley et al. 1999; Kim et al. 2001; Bassirirad et al. 2003; Hamilton et al. 2005; Easterling et al. 2007)	Increase
3. Temperature	Changes in crop physiological processes and metabolism, in turn, modification in crop suitability, productivity and quality; affects evapotranspiration, in turn, modify WUE; changes in weeds, crop pest and diseases; change in irrigation need (Bowes 1991; Wheeler et al. 1996; Wheeler et al. 2000; Porter and Semenov 2005; Lobell 2007; Easterling et al. 2007; Katerji et al. 2008)	Increase
4. Heat stress	Grain yield reduction associated with pollen sterility, increase pollination failures, increase in pests, reduced productivity including reproductive success of livestock, decease fodder quality (Tashiro and Wardlaw 1990; Wheeler et al. 1996; García-Ispierto et al. 2007; Howden et al. 2007; Liu et al. 2011)	Increase
5. Frost	Influences early and late frost events, in turn, inhibit and damage crops and pasture, changes in frequency (Stone et al. 1996; ScienceDaily 2000; Stokes and Howden 2010).	Increase/decrease
6. Precipitation	Increase year-to-year variability, in turn, productivity fluctuation and agricultural loss, increased precipitation intensity, changes in precipitation distribution, increase dryland salinization, soil erosion and runoff, (Rosenzweig and Hillel 1995; Stephens and Lyons 1998; Rosenzweig et al. 2002; Power et al. 2006; CSIRO 2007; Bates et al. 2008)	Increase/decrease
7. Extreme events	Droughts, in turn, pressure on water supply, bush fires, floods affect water quality and exacerbate many forms of water pollution, soil erosion and runoff, crop and	Increase

Table 1 (continued)

Components affecting agricultural farming system	Implications and concern	Observed and projected changes
	livestock loss (Rosenzweig and Hillel 1995; DAFF 2006a, b; BoM 2006b; Queensland Government 2006; Kron and Berz 2007; Bates et al. 2008)	
8. Atmospheric ozone O_3	Productivity loss in crop and pasture, decrease quality of agricultural produces, lower soil carbon formation rate (Chameides et al. 1994; Loya et al. 2003; Ashmore 2005; Vandermeiren 2005; Volk et al. 2006)	Increase
9. Sea-level rise	Increase intrusion of seawater into estuaries and aquifers, impede drainage and soil quality, increase water salinization, crop damage (Nicholls and Tol 2006; Nicholls et al. 2006; Nicholls et al. 2007; Rosenzweig and Hillel 2008)	Increase

the context of managing CV risk at the farm level, a number of activities have been conducted to evaluate the acceptance and value of ENSO-based climate forecasts for agricultural decision making (Potgieter et al. 2005, 2006; Meinke et al. 2007). The interplay between climate and farm-level decision making is highlighted in Anwar et al. (2008). In this paper, the interaction of short-term climate forecasts and system analysis (crop model) is demonstrated to enable farmers to determine the timing and dosages of nutrient in the farm cycle.

5 Geographic boundary and agricultural practices

The quality of soil in a particular region, the nutrients available in the soil, and the climate significantly influence the suitability of crops that could be grown by farmers. Alternatively, these three major factors establish the boundaries within which certain crops are grown. With climate change, such boundaries could be significantly altered, requiring two major kinds of responses. First, the genetic characteristics of the existing crops could be altered to make the crops suitable for

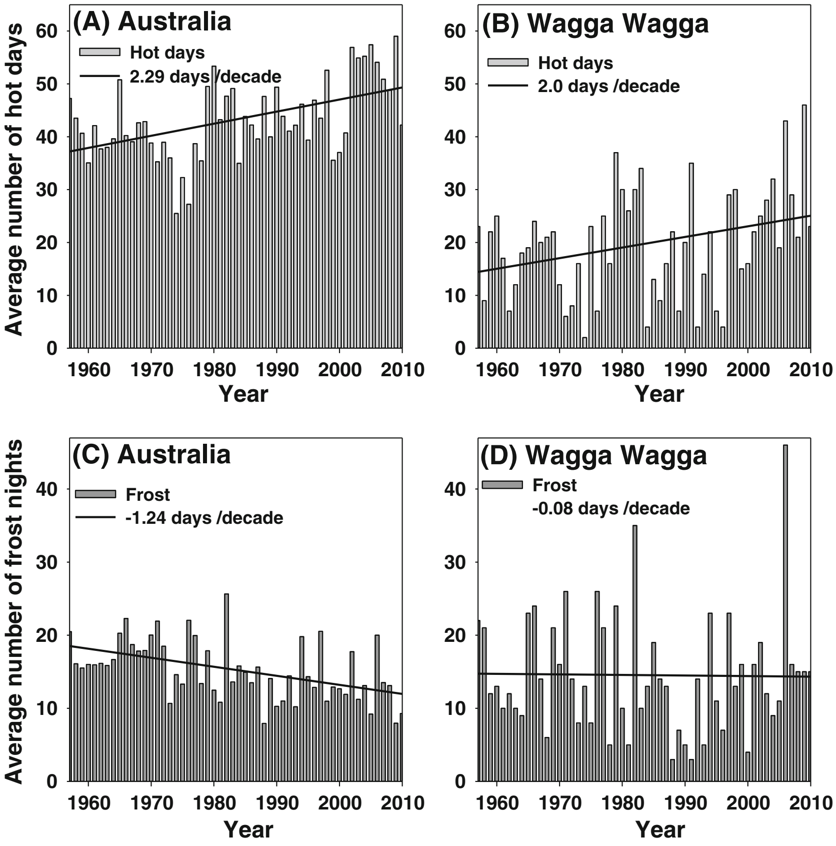


Fig. 4 Observed annual average number of hot days (temperature above 35 °C) and annual average number of frost nights (temperature less than or equal to 0 °C) for the period 1950–2010 in Australia (**a**, **c**) and Wagga Wagga (35.05° S, 147.35° E) (**b**, **d**). *Black line* indicates the trend (fitted by ordinary least squares regression). Historical climate data were obtained from the SILO Patched Point Dataset (http://www.longpaddock.qld.gov.au/silo/ppd/index.php) and Australian Bureau of Meteorology (http://www.bom.gov.au/climate/change/global_cvac.shtml)

the new climate conditions. Second, the existing crops may need to be substituted by a completely different set of crops (Ronald 2011). The challenges associated with these two responses, related to technology, farming techniques, and farmer receptivity, should not be underestimated.

In an agricultural farming system, the geographic boundary and the number of agricultural practices considered are ultimately influenced by the intended application of the investigation. Geographic boundaries can be determined by the range of individual crops or farm operations (Terjung et al. 1984a, b; Bell 2011) or can relate to major food-producing regions (Blasing and Solomon 1984; Rosenzweig 1985). Further, both local climate and agricultural management practices influence geographic patterns of crop yield and the ranges of agricultural practices vary from crop to crop (Parry 1978; Waggoner 1983). A comprehensive assessment of many of the major primary production activities (Williams et al. 1988) would be required. Climate exerts considerable control over the yields obtained from an agricultural farming system. For example, Lobell and Field (2007) found that approximately 30 % of the annual variation in globally averaged yields of wheat, rice, maize, soybean, barley, and sorghum could be attributed to climate variables. At the same time, this result highlights the importance of other factors in explaining crop yields (Goudriaan and Zadoks 1995; Ronald 2011).

6 Mechanism of climatic impacts

Agricultural productivity is affected by (1) quality of land; (2) technology; (3) inputs applied; and (4) climate with the four factors, namely, temperature and precipitation, atmospheric CO_2 concentration, water availability, and extreme events, as described in the Fig. 5 (Rosenzweig and Hillel 1995; Hulme et al. 2001). While items 1 to 4 are all important, our focus is on item 4, which, in turn, can affect the quality of land (1), finding the right technology (2), and identifying the right inputs (3) that are appropriate for the emerging new climatic conditions. Each of the four factors shown in Fig. 5 will be affected by climate change. Consequently, agriculture practices will have to adapt to climate change in order to sustain and, possibly, increase the farm-level productivity in the decades ahead.

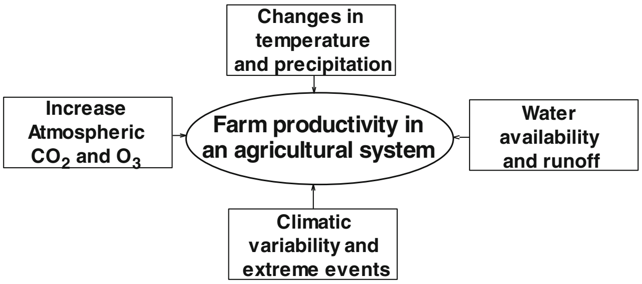


Fig. 5 Physical effect of climate on farm productivity in an agricultural system (concept adopted from Rosenzweig and Hillel 1995; Hulme et al. 2001). *Atmospheric CO_2* carbon dioxide, *O_3* ozone

Divergent effects of temperature and precipitation changes on spatial and temporal distribution will alter the timing and length of growing seasons (Passioura 2002; Anderson 2010). For example, higher temperatures with deficient precipitation will accelerate plant development, reduce grain-filling, decrease nutrient-use efficiency, and increase crop water consumption. As a result, there will be a major shift in agroecological zones. Related to this, soil organic matter, which controls the structure and fertility of agricultural land, will change (Sombroek 1990). Accordingly, the nutrient quantities and farming practices required to grow specific crops in the changed agroecological zones will be modified. Changes in temperature and precipitation, which are likely to increase potential evapotranspiration, may intensify drought stress (Dai 2011), and irrigation availability and demand would be affected. As an example, in Murray–Darling Basin in Australia both irrigation availability and demand for water have been affected by temperature and precipitation changes (Murray–Darling Basin Authority 2011). Decreased precipitation has led to an increase in aquifer exploitation by agriculture that has put additional burdens on the availability of surface and groundwater resources for nonagricultural use (such as industrial and municipal needs). There may be other less obvious but important effects of changes in temperature and precipitation such as weed infestation (Kriticos and Filmer 2007) and increased rate of development of pest and insects (Finlay et al. 2011). Further, for some crops, plant metabolism begins to break down at temperatures above 40 °C, and a reduction in growing periods due to accelerated growth can reduce the quality and yields (Porter and Gawith 1999).

Growth, maintenance processes, and yield of agricultural crops require certain essential inputs like solar radiation, appropriate temperature and water, chemical elements, including nitrogen, phosphorous, potassium, and other micronutrients, and atmospheric CO_2 (Gonzalez-Meler et al. 2004; Lobell and Field 2008). CO_2, the only source of carbon for crops, constitutes an essential input and its effects on agricultural crops are numerous (Kimball et al. 2002; Lobell and Field 2008) and include effects on plant elemental composition (Amthor 2000). Increasing atmospheric CO_2 concentration and changing regional climate conditions are likely to alter the phenological response of certain crops and make crop–weather relationships more complex (Tubiello et al. 2007). For agricultural crops, increasing atmospheric CO_2 can raise the rate of photosynthesis, water use efficiency (WUE; ratio of CO_2 uptake to evapotranspiration), nitrogen use efficiency, and thus crop yield (Kimball 1983; Drake et al. 1997; Tubiello et al. 2007). Elevated atmospheric CO_2 is known to stimulate photosynthesis and growth of plants with the C3 pathway but less of plants with the C4 pathway. However, rising atmospheric CO_2 will have different effects, depending on crop species. The C3 photosynthetic pathway plants (cotton, rice, wheat, barley, soybeans, sunflower, potatoes, certain leguminous and woody plants, some horticultural crops, and many weeds) have better responses to higher CO_2 levels in comparison to C4 plants (maize, millet, and sorghum and many grasses and weeds) and crassulacean acid metabolism (CAM) plants (cassava, pineapple, opuntia, onions, and castor) (Allen 1990; Gifford 1992; Lee 2011). However, C4 and CAM plants show better responses to the CO_2 fertilization effect at higher temperature than C3 plants (Allen 1990; Gifford 1992; Lee 2011).

Anthropogenic CO_2 emissions will result in further temperature increases, changes in precipitation patterns, greater variability in temperature and precipitation within a cropping season, and an increase in the incidence of extreme events (IPCC 2007a). Their combined effects on crop yields are uncertain because they could add or subtract from the beneficial effects of higher CO_2 levels discussed in the previous paragraph (Betts 2012). The WUE will increase under higher CO_2 conditions (Leakey et al. 2009). This increase is caused more by increased photosynthesis than it is by a reduction of water loss through partially closed stomata. Thus, more biomass can be produced per unit of water used, although a crop would still require almost as much water from sowing to final harvest. If temperatures rise, the increased WUE caused by the CO_2 fertilization effect could be reduced and could be altered by changing the planting dates to more favorable seasons (Kimball et al. 2002). In south-eastern Australia, Anwar et al. (2007) concluded that a decrease in precipitation due to global warming would potentially reduce and destabilize wheat yields, although CO_2 fertilization effects would partly compensate for the negative effect of global warming.

The application of nitrogen fertilizer in intensive agricultural farming systems can lead to higher emissions of methane (CH_4), a GHG that complements the effects of CO_2 and which also affects the stratospheric ozone (O_3) layer (Cicerone and Oremland 1988; Hall et al. 1996). A future increase in the intensity of agriculture may contribute to anthropogenic climate change through increased CO_2 and CH_4 emissions and the latter may also result in higher surface ultraviolet (UV-B) radiation (wavelengths from 280 to 320 nm) due to the depletion of stratospheric O_3 (Cicerone 1987). UV-B radiation can indirectly slow down the photosynthetic carbon assimilation (Teramura and Sullivan 1994). These are large-scale effects that could lead to adverse effects on crop growth and productivity on a broad geographic scale (Teramura et al. 1990; Krupa and Kickert 1993; Ashmore 2002, 2005).

7 Farm-level yield gap

The potential yield determined by climate, CO_2, and crop characteristics normally achieved under ideal nonstressed conditions is hardly ever achieved at the farm level by farmers because of yield-limiting factors, such as low soil moisture and nutrient availability, and yield-reducing factors, such as pests and pathogens, weeds, and air pollutants (Fig. 6) (Reynolds et al. 2011). The impacts of climate change on actual yield need to be analyzed, assessed, and understood to determine the responses that would be required to adapt to climate change. As an example, Zhang et al. (2006) reported that, in southern Australia, wheat cultivars currently available for use in rainfed cropping can produce yields of over 7 t/ha, when average farm yield is about 2 t/ha. This is achieved by the introduction of high genetic yield and disease-resistant varieties by farmers and the choice of appropriate farm management techniques (Passioura 2002).

In rainfed cropping in Australia, the major gap between yields achieved in farms and the theoretical potential as estimated by seasonal precipitation or water use is found where seasonal water supply is greater than about 250 mm and where management, not precipitation or cultivar, is limiting productivity. This suggests that tactical (in season) management, including the choice of crop and cultivar, fertilizer amount and timing, and weed, insect, and disease control when combined with management of strategic factors that have an effect for more than one season, such as soil acidity, compaction, low organic matter, nonwetting, and waterlogging, will provide additive benefits that can address the variability imposed by the environment.

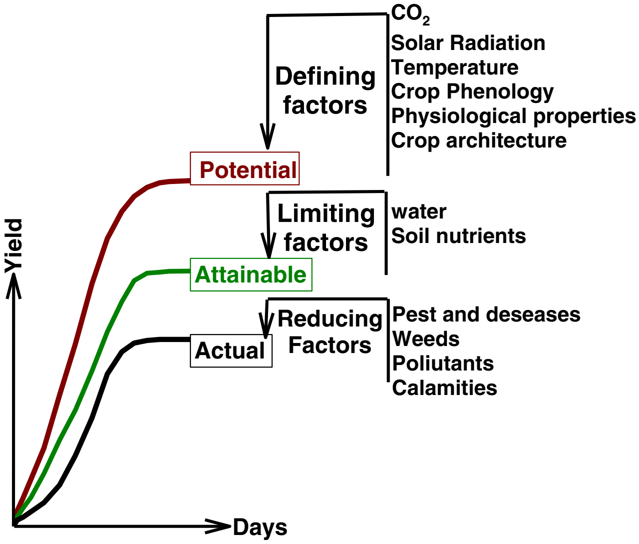


Fig. 6 Factors determining Crop production (adopted from Goudriaan and Zadoks 1995; van der Werf et al. 2007)

8 Agricultural systems simulation

8.1 Crop modeling

Observations of what has actually occurred in the past constitute exposed information. These exposed data, along with estimates of core parameters, can be used to determine response functions. In turn, these functions, with the estimated parameters, can be used to construct models with endogenous and exogenous variables. Forecasting of the endogenous variables, given the values of exogenous variables at a future date in the context of the model, would constitute ex-ante values of the endogenous variables. In this context, process-based agronomic models (PBM) are used to predict changes in yield, given the changes in average climate variables according to biological models of crop growth (Keating et al. 2003; Mathhews and Wassmann 2003; Luo et al. 2009). This sort of PBM forms the basis of both small-scale single-crop studies (e.g., Bindi et al. 1996; Wolf 2002; Anwar et al. 2007) as well as some elaborate global studies covering many crops and which include trade and other economic dynamics (e.g., Parry et al. 2004, 2005). These latter broad agronomic studies, which link to economic models, explicitly include a limited set of farmer adaptations, including changed planting dates and different crop variety selection. There is scope for improving the accuracy of the FASP projections through the collection of additional climate and yield data from the region (s) of interest to aid model calibration. These large-scale agronomic models are unique in providing yield estimates based on relatively detailed climate information, but cannot account for gaps between potential and actual yield, which are already large.

8.2 Global climate model and agronomic model

Agronomic models simulate farming system productivity on a variety of spatial scales, from point to field to district scale. They typically require daily climate data as input and rely on this data being a plausible representation of the real climate on the spatial scale under consideration. Simulations of periods in the past can be forced with climate data derived from meteorological observations. However, there is often the desire to perform simulations for the future climate, for which no observations exist. In these cases, global climate models (GCMs) are a useful tool for providing information on future climate conditions (Liu and Zuo 2012). However, raw output from these models does not represent plausible future, or past, climate conditions on the spatial and temporal scales relevant to agronomic models. Firstly, the models typically output grids of data representing average climate conditions across grid cells hundreds of kilometers across. This scale is much larger than the scale relevant to many agronomic model simulations. Secondly, the models are not perfect representations of the real climate system and bias and systemic errors exist in the output of simulations of the observed climate, which become apparent when model output is compared with observations at the same spatial scale. There are a number of ways in which the limitations of GCMs can be addressed. Firstly, climate observations on the relevant spatial scale can be modified to represent future climate conditions by perturbing them with information on future climate changes taken from GCMs. Secondly, a “statistical downscaling” method can be applied (Liu and Zuo 2012), whereby statistical relationships between climate data at large spatial scales and data at the finer scale of interest can be developed using appropriate climate observations and then applied to future large-scale data from GCM simulations. Such methods can incorporate statistical corrections of model errors developed by comparing GCM output with observations at the same spatial scale. Finally, GCM output can be used to force regional climate model (RCM) simulations (Alves and Marengo 2010). RCMs are capable of simulating regional climate conditions at much higher resolution than GCMs, typically at tens of kilometers or less, though it is necessary to apply statistical corrections to their output and further statistical downscaling may also required for PBM simulations at the finest scales.

Uncertainty in future climate conditions poses another challenge for providing future climate data for agronomic simulations (Roudier et al. 2011). Sources of uncertainty include those associated with future emissions of GHGs, how sensitive global mean temperatures will be to these emissions, and how regional and local conditions will respond to changes in global conditions. To some extent, the issue of uncertainty can be addressed by considering multiple data sets representing future climate conditions. For example, multiple scenarios for future GHG emissions, values for global warming, GCMs, and downscaling methods can be considered.

In addition to climate data, PBM require input data on other environmental conditions—such as soil type and topography—and on management activities and how all these data vary over time and location within the region. In the USA, high-quality spatial data are generally available for soil type and topography and a variety of spatial data sets are available, especially from remote sensing (White et al. 2011). However, accurate data on land-use and management activities are generally less available and are the most limiting data component for model-based estimates. While there is a great deal of aggregate data on agricultural management practices at the county, state, and national levels, this aggregate data have significant limitations for analyzing relationships between GHGs and management practices in specific regions. For example, agricultural cropping systems are comprised of crop rotations; and practices, such as fertilizer application, tillage, and manuring vary for the different crops within the rotation. Thus, for example, county-level data on total fertilizer use fails to provide adequate detail for models attempting to forecast GHG changes due to specific changes in crop rotations.

8.3 Farm-level agricultural system: an overview

Agricultural productivity is a fundamental determinant of the availability and the price of food and hence has a major impact on human welfare. In turn, agricultural productivity depends on the overall farm-level agricultural system, which, in turn, is determined by domestic consumer expectation and preferences, global trade and geopolitics, climate and anthropogenic climate change, and technology and agricultural inputs (Houghton et al. 2001; Carter et al. 2007; IPCC 2007a). This could be broadly grouped under demand and supply factors (Hazell and Wood 2008). Demand would be affected by domestic consumption and export. For example, the major drivers of domestic consumption in Australia would be consumer expectation on income and the kind of diets they would like to consume, consumer taste preferences, and demography (Garnaut 2011a, b). In addition to the same factors for overseas consumers, export demand would be affected by global trade in primary commodities and their prices along with geopolitical forces that influence access to foreign markets (as an example, war and sanctions; Bora et al. 2010).

As is evident from this review, supply would be determined by climate and technology, including agricultural inputs broadly defined. The management of CO_2 emissions and those of other GHGs and government policy in this regard would be determining factors of agricultural supply. Both resource management and industry structure would be included under agricultural inputs. The major components of technology would include breeding, farming techniques, and extension services. Figure 7 captures the essence of the driving forces of the farm-level agricultural system, with its focus on farm and farmer responses to demand and supply stimuli.

Each of the demand and supply factors is affected by many variables that are exogenously determined. In addition, there are interactions among the variables themselves. As a result, there are many uncertainties that affect the entire farm-level agricultural system.

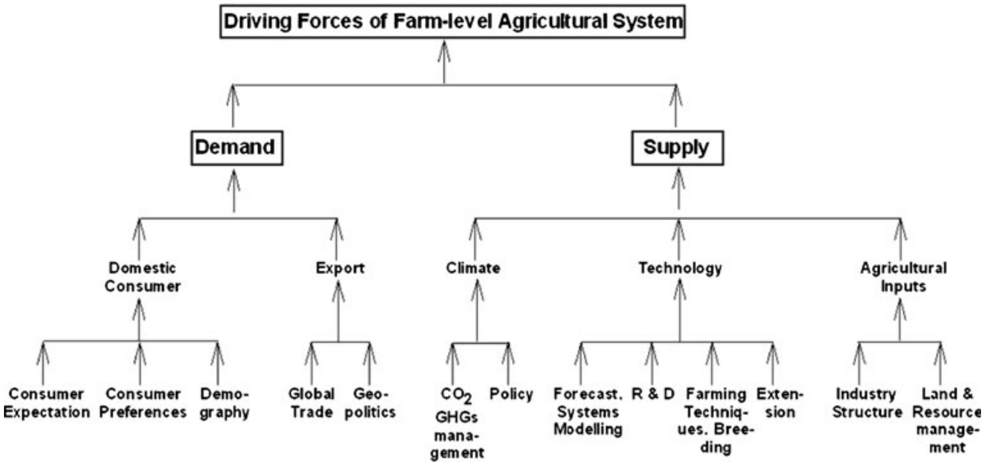
Each of the forces highlighted (Fig. 7) represents an important dimension of change in describing the future. While some of the forces are predictable, others are highly uncertain. The important and uncertain forces constitute the critical uncertainties. The critical uncertainties are vital in developing scenarios as they lead to distinctly different futures. Two critical uncertainties shaping the farm-level agricultural system are climate change impacts and geopolitics. The focus of this review is on climate change. The insights gained by considering alternative climate scenarios would constitute the initial basis for informed decision making in the dynamic and interactive agricultural farming system.

9 Adaptation in agriculture: discussion

9.1 Action plan

The typology for adaptation of agriculture to climate change is twofold: incremental climate change and autonomous responses versus planned and transformational climate change (Stokes and Howden 2010). Historically, it has been observed that adaptation to climate and its variability is natural (Kates et al. 2012). Autonomous responses in the form of incremental changes to agricultural practices in order to alleviate disruptions in farming, land utilization, and productivity resulting from gradual changes in climate and its variability have been observed in many countries including Australia (Stokes and Howden 2010; Kates et al. 2012). In contrast, the nature, extent, variability, and

Fig. 7 Demand and supply forces affecting the farm-level agricultural system. *CO_2* atmospheric carbon dioxide, *GHGs* emission of greenhouse gases, *R&D* research and development



extreme events currently associated with climate change are so large that transformational adaptations would be required. Kates et al. (2012) associate these transformational adaptations to three factors, namely, scale, newness to a region or resource system, and sizeable changes within a particular region. Transformational adaptation to climate change must address the twin challenges of substantial vulnerability in select regions and resource systems and the progressive irrelevance of existing models and farming practices. Given the sheer magnitude and nature of climate change, planned responses would be needed.

The discussion that follows from this review focuses on the broad elements of an action plan that would be needed to affect a calibrated response to climate change in global agriculture, including Australia. This study does not deal with the changes in emissions that might result from the strategies described to adapt to climate change. However, each of the issues highlighted in the discussion is aimed at contributing farm-level adaption to climate change over time. Given the uncertainties associated with climate change, the review of the literature suggests that short-term, medium-term, and long-term responses would need to be determined to facilitate farmers to cost-effectively adapt to emerging climatic conditions. The sequential approach of short-term, medium-term, and long-term responses is tailored to ensure that each sequence feeds into the next, thereby encouraging a synergy between them. These responses will involve modified and new technologies, modified and new farming techniques, information campaigns, and institutional strengthening, including extension agencies, public policy, and public investment programs.

9.2 Short-term adaptation

The short-term initiatives are aimed at mitigating the negative effects of climate change, demonstrating feasible solutions to address these negative affects, and thereby contributing to risk management at the farm level. The main elements are highlighted below.

Adapting the approach proposed by Stokes and Howden (2010) and Cleugh et al. (2011) where time horizon is grouped under intraseasonal and seasonal (tactical), multi-seasonal between 2 and 15 years (mid-term strategic), and decadal (long-term strategic). In this discussion, an alternative grouping is suggested with the short term being viewed to include a span of 5 years. The rationale for 5 years is to include intraseasonal and seasonal CV impacts in order to sensitize farmers on the benefits of responding to proposed short-term adaptation measures. In turn, these would facilitate the adoption over a period of about 5 years' changes that would be proposed as the first steps to adapting to climate change that is a long-term phenomenon. This is an integral part of the sequential approach that is advocated as a part of this review.

9.2.1 Modified and new farming techniques

Adjusting farming management By adjusting the timing of farm operation, such as changing the canopy management and cropping sequence, considerable farming benefit can be achieved. For example, recent New South Wales canopy management initiatives require farmers to change the rate and timing of nitrogen fertilizer application in order to maintain canopy size and duration for optimizing photosynthetic capacity that will result in increased production (Daniel 2009). Alteration in cropping sequence will include changing the timing of sowing, planting, spraying, and harvesting to take advantage of the changing duration of growing seasons. These would require modernization of farm operations. For example, with a climate forecast that allows assessing the likelihood of a cropping season precipitation (Hammer et al. 1996; Potgieter et al. 2006; Anwar et al. 2008), the desirability of planting crops earlier or later or changing the timing of other inputs such as fertilizers is demonstrated. There is evidence of enhanced crop yield when farmers sow earlier in response to lower frost risk (Stephens and Lyons 1998; Chen et al. 2011) and changing the timing of irrigation (de Loë et al. 2001) or the provision of other inputs, such as fertilizers (Anwar et al. 2008).

Diversification Diversification of crop (Bradshaw et al. 2004) and livestock varieties (DAFF 2012), including the replacement of plant types, cultivars, hybrids, and animal breeds with alternatives selected from existing varieties that are intended for higher drought or heat tolerance, has the potential to increase farm productivity in the face of temperature and moisture stresses (Easterling et al. 2007). For example, where there is a likelihood of increases in temperature and reduction in precipitations, it may be advantageous to either keep varieties with similar or earlier-flowering characteristics than are currently used as this will allow grain-fill to occur in the cooler, wetter parts of the year (van Ittersum et al. 2003; Liu et al. 2011).

Land-use practices Changing land-use practices, such as the location of crop and livestock production, rotating or shifting production between crops and livestock, and shifting production away from marginal areas can help reduce soil erosion and improve moisture and nutrient retention. For example, tillage practices (minimum or no tillage), which can include maintaining crop residues from previous harvests on the soil surfaces, are seen as likely to help maintain soil quality, protect against wind erosion, and allow for water to infiltrate (Erda 1996; Ortiz et al. 2008). Where the frequency of droughts increases, farmers could adapt by changing the selection of crops, thereby leading to changes in agricultural land use. In turn, this will impact on soils. Improved soil structure and fertility (Ortiz et al. 2008) could be achieved through sustaining soil organic carbon contents, e.g., extending fallows and reducing or stopping tillage, incorporation of agroforestry to reduce the enhanced risk of soil erosion (Abildtrup and Gylling 2001; Abildtrup et al. 2006).

Livestock management As a response to episodes of poor crop yields, livestock management will need to adapt (Adger et al. 2007; Stokes and Howden 2010; IFAD 2012). For example, livestock stocking rates would need to change (García-Ispierto et al. 2007), feed conservation techniques would become necessary, fodder banks would need to be established, and the mix of grazing animals would need to be altered (Miller et al. 2010; Stokes et al. 2010). All of the above would have to be complemented by changing animal distribution. This would require the utilization of mineral blocks, watering points, and fences. Additionally, in order to sustain feed availability, improved weed management techniques, the restoration of areas that have been degraded, and encouragement of native vegetation would need to be pursued (FAO 2006; Stokes et al. 2010).

Nutrient and pest management In adapting strategies for improved nutrient and pest control management, FAO (2007) reports that farmers diversify output through mixed farming systems of crops and livestock to spread the risk of infrequent, and uncertain, pest and disease infestations. In light of likely pest and disease outbreaks under climate change (Tubiello et al. 2007), changes in the application of pesticides and integrated pest and disease control may be necessary to negate such impacts (Tilman et al. 2002; FAO 2007; Gregory et al. 2009).

9.2.2 Climate forecasting and model development to reduce production risk

Forecasts of seasonal CV based on ENSO have considerable potential to help farmers make informed decisions about agricultural management (Meinke and Stone 2005). The desirability of adaptation measures and tailoring farm decision making in response to information from climate forecasts has been demonstrated (Meinke et al. 2003; Potgieter et al. 2005; Anwar et al. 2008). For example, in 2002 to 2007, wheat farmers in south-eastern Australia responded to the availability of short-term weather forecast by altering their nutrient inputs (GRDC 2008). Additional climate forecasting to reduce production risk could be:

1. Intrayear, seasonal weather forecast contributes to informed decision making at the industry and policy levels. Over time, these forecasts contribute towards managing risks associated with CV that are likely to increase with climate change (Meinke et al. 2003).
2. Utilize the insights gained from weather forecasts to improve water and nutrient management through better on-ground/water measurements (example soil water). In order to have an integrated approach, significant new research would be required to develop and implement new systems of modeling.
3. Develop systems modeling (Keating et al. 2003; Anwar et al. 2008; Liu et al. 2011) that focus on integrating crops, livestock, and grazing and soil–water management. This would have to be linked to meteorological data that would enhance the projection of climate, CO_2 levels, and status of natural resources. Recently, the demand for high-resolution and reliable climate projection such as statistical downscaling of GCMs outputs to support adaptation to climate change is continuously increasing (Roudier et al. 2011; Liu and Zuo 2012). An integrated systems approach to modeling would provide an informed basis for developing quantitative approaches to risk management that would be relevant to farmers, policy makers, and industry.
4. Establish links with meteorological data and use projection of climate and CO_2 level, natural resources status, and management option to provide quantitative approaches to risk management for use in several of these cross-industry adaptation issues. The model can assist proactive decision making on-farm, inform policy, and extend findings from individual sites to large areas (Anwar et al. 2007; Liu et al. 2011).

9.2.3 Financial risk management

Private and public insurance programs have been discussed as effective measures to help reduce income losses as a result of the impacts of climate change-related risks (IPCC 2001). Related to the agricultural sector, the following four production risks associated with climate change have been identified: weather variability, ecological risks, pest and crop diseases, and pollution (Moreddu 2000). As a result, risk-adjusted return to the farmer will decrease. In order to address this, the following measures that are already in place in New South Wales, Australia (Clark et al. 2000) will need to be modified and scaled up in programs such as (1) Crop Insurance Programmes, (2) FarmBis and Transitional Income Support, and (3) Exceptional Circumstances Support.

9.2.4 Information dissemination

Information dissemination initiatives could be an effective climate change intervention intended to help researchers, policy makers, planners, and farmers to establish priorities and act on adaptation (Brown and Crawford 2008). For example, ensuring communication of broader climate change information as well as industry-specific and region-specific information as it becomes available to farmers, policy makers, extension agencies, research and development (R&D) providers, and industry (FAO 2007; IPCC 2010) can provide insights to assessing the needs to plan and implement adaptation and mitigation measures. Targeted approaches tailored to the needs of these stakeholders would need to be designed and implemented and highlight the public and private traits of climate change-related issues to stakeholders at large.

9.2.5 Extension services and monitoring

Extension agencies are the key interface between R&D providers and policy makers with the farmers (FAO 2007; Brown and Crawford 2008). The corresponding functional extension elements can be summarized as follows:

1. Collect, interpret, and dialogue with farmers on the latest farming techniques and emerging technology relevant for farmers.
2. Identify constraints faced by farmers in adapting to short-term challenges and communicate these to policy makers, industry, and R&D providers.
3. Identify critical educational and physical infrastructure investments that would be needed to sustain adaptation by farmers to emerging challenges in the short-term as well as anticipating medium-term requirements.
4. Monitor the cost-effectiveness of extension services through inbuilt monitoring programs to be incorporated at the design stage of new extension services in order to carry out impact assessment at end of each program. This is to ensure learning by doing, which will lead to better design for increased cost-effectiveness in subsequent delivery of extension services.

9.2.6 Land and water management

While land and water management issues require interaction among a number of groups and sectors, the complexity of environmental interaction require a proactive research program to be instituted in the short term in order to make informed decisions about the medium and long terms (ADB 2009). Water quality, land degradation, river sediment loads, salinity in dryland and irrigated areas, river water pollution and shortage, and land suitability are issues to be highlighted (Adger et al. 2007; Stokes and Howden 2010).

9.2.7 Policy and public investment

All of the recommended short-term measures discussed in the preceding sections are geared towards assisting farmers at the ground level to be adequately prepared and respond appropriately to climate change. Major policy and public investment programs would be needed to support extension capacity, research analysis incorporating a systems approach (modeling), and industry and regional networks (Smit and Skinner 2002; Adger et al. 2007). These are integrated to implementing risk management strategies and initiatives at the national, regional, and subregional levels.

9.3 Medium-term to long-term adaptation

The short-term measures proposed influence the design and content of the medium-term to long-term initiatives. The sequential approach proposed in this review can be viewed as a process-oriented approach where learning by doing at each stage fundamentally influences the design and content of subsequent stages. Farmers must overcome and reduce the adverse impacts of short-term CV and climate change. The set of measures that would be necessary to alleviate vulnerability to anticipated medium-term to long-term impacts of climate change include the following:

1. In modeling and forecasting climate change, the emphasis in Australia must shift from intraseasonal and seasonal to short-term, medium-term, and long term (Australian High Commission 2011; Olesen et al. 2011). In the USA, this is being progressively mainstreamed (The National Academies Press 2001). With a longer planning horizon, climate projection will make feasible longer-term strategic decision making at every level of operation anchored on risk. The research efforts and resources required to make this fundamental transition in modeling and forecasting would be significant. A considered action plan developed in partnership among the relevant stake holders in the research and public policy realm is a prerequisite.
2. Agricultural modeling techniques that allow scaling up knowledge from gene to cell to organisms and eventually to the management systems and national policy levels need to be urgently instituted. Long-term perspectives with appropriately financed research programs with clear ly defined time lines must underpin the design and content of this very major agricultural program (e.g., breeding, precision agriculture, geographic information system farming, satellite imaging) that has the support at the political, policy, research, and practitioners levels.
3. Strengthening the partnership between weather forecasters, policy makers, and extension agents to ensure appropriate farm-level responses in the field to climate change and the associated variability in order to sustain

cost-effective agricultural production. The focus would be on institutional strengthening across a broad spectrum in order to mainstream and strengthen partnership for agricultural progress.

4. Physical infrastructure investment would be needed to support new land-use management, such as investment to improve irrigation infrastructure, efficient water use technologies, and appropriate transport and storage infrastructure (Adger et al. 2007).
5. Public policy and public investment initiatives for the development of new technologies for reducing GHGs (Howden et al. 2007).

9.4 Relaxing constraints to adaptation in agriculture

In ensuring that the short-term, medium-term, and long-term measures identified in this discussion lead to changes at the farm and farmer levels will require the identification of binding constraints to adaptation in agriculture and recommendations to relax these constraints. The approach adopted by Marshall et al. (2010) and Smith and Ash (2011) has been modified in this review to provide a framework for the design of a robust action plan that clearly identifies the role of each stakeholders. The broad outline of this action plan is shown in Fig. 8, which is self-explanatory.

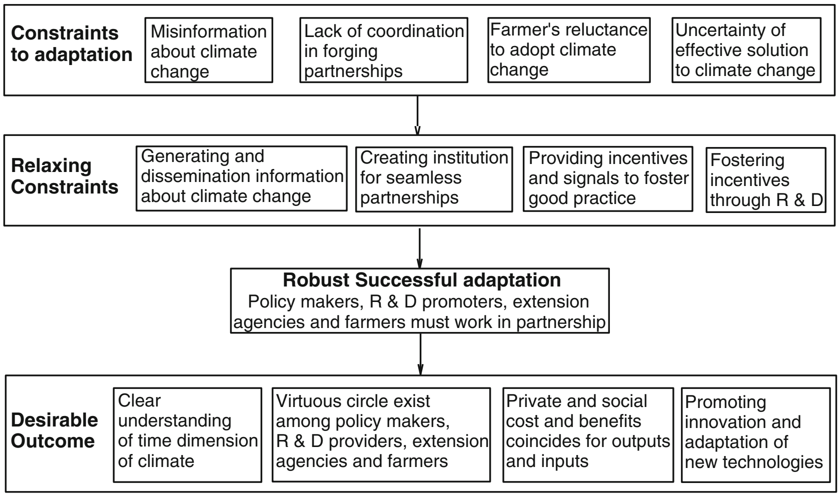
The starting point for determining the broad outlines of the action plan is the identification of the four constraints (misinformation about climate change, lack of coordination in forging partnerships, farmers reluctance to adopt climate change, and uncertainty of effective solution of climate change) to adaptation in agriculture (see Fig. 8). The initiatives needed to relax these constraints automatically follow. Alternatively, the constraints to adaptation provide the basis for identifying the measures needed to relax them. The successful establishment and sustenance of an effective partnership among the four major stakeholders should result in the outcomes shown in the Fig. 8.

10 Conclusions

The key messages of this review are listed under six groups. First, climate change, CV, and the more regular incidence of extreme climatic events triggered by climate change constitute a clear and present danger to not only agricultural farming systems but also to humanity. Second, while, historically, agriculture in Australia has an excellent record of adapting to climate change and variability through autonomous and incremental change, the expected structural change in climate in the twenty-first century will require planned and transformational changes. Third, in terms of modeling, data collection, and calibration, a quantum jump would be required in climate and weather patterns forecasting. Fourth, there is an urgent requirement in building on existing research work within the agricultural farming system in terms of crop genetics, breeding, and yield gaps to get a better understanding of appropriate responses to climate change. Fifth, the research in climate and weather forecasting would need to be better integrated with agricultural research on crop-specific items to better understand and plan for the temporal and spatial dimensions of climate change. Sixth, the constraints to adaptation at the farm and farmer levels must be clearly understood and relaxed in order to get their cost-effective responses to climate change. Risk-adjusted returns to farmers as a result of climate change could only be increased by creating a seamless partnership between policy makers, R&D promoters, extension agencies, and farmers. The institutional arrangements for building and sustaining such partnerships warrant immediate action.

While the review and the emerging key messages suggest that an ambitious research program that is understood and supported by all the major stakeholders is required, planning,

Fig. 8 Relaxing constraints to adaptation in agriculture



managing, and funding such a program involve major challenges and risks. The discussion in this review recommends a calibrated and sequenced approach to research and the accompanying initiatives. These are grouped under short term, medium term, and long term. Inherent is a learning-by-doing process-oriented approach when the lessons of each stage feed into the next stage. The cumulative learning and experimentation would build confidence and garner support for what would ultimately be a major research program accompanied by an action plan. In terms of man power and financial resources required, the commitment would need to be very substantial.

The ultimate target group of the outcome of this review is the farmers. The success and the litmus test of the action plan outlined in the discussion would be the successful adoption of new seeds, farming techniques, water management, and pest and weed technologies by farmers required for the emerging new climatic conditions in the twenty-first century.

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References

ABARES (2011) The impact of recent flood events on commodities. ABARES Special Report, Canberra. Available at http://www.abares.gov.au

Abildtrup J, Gylling M (2001) Climate change and regulation of agricultural land use: a literature survey on adaptation options and policy measures. Danish Institute of Agricultural and Fisheries Economics Farm Management and Production Systems Division. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.194.8068&rep=rep1&type=pdf

Abildtrup J, Audsley E, Fekete-Farkas M, Giupponi C, Gylling M, Rosato P, Rounsevell M (2006) Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environ Sci Pol 9:101–115. doi:10.1016/j.envsci.2005.11.002

Adams RM, Hurd BH, Lenhart S, Leary N (1998) Effects of global climate change on agriculture: an interpretative review. Clim Res 11:19–30

ADB (2009) Building climate resilience in the agriculture sector in Asia and the Pacific. Asian Development Bank, Philippines. Available at http://www.adb.org

Adger WN, Agrawala S, Mirza MMQ, Conde C, O'Brien K, Pulhin J, Pulwarty R, Smit B, Takahashi K (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 717–743

Allen LH Jr (1990) Plant responses to rising carbon dioxide and potential interactions with air pollutants. J Environ Qual 19:15–34

Alley RB, Marotzke J, Nordhaus WD, Overpeck JT, Peteet DM, Pielke RA, Pierrehumbert RT Jr, Rhines PB, Stocker TF, Talley LD, Wallace JM (2003) Abrupt climate change. Science 299:2005–2010. doi:10.1126/science.1081056

Alves LM, Marengo J (2010) Assessment of regional seasonal predictability using the PRECIS regional climate modeling system over South America. Theor Appl Climatol 100:337–350. doi:10.1007/s00704-009-0165-2

Amthor JS (2000) The McCree–de Wit–Penning de Vries–Thornley respiration paradigms: 30 years later. Ann Bot 86:1–20. doi:10.1006/anbo.2000.1175

Anderson WK (2010) Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar. Field Crop Res 116:14–22

Anwar MR, O'Leary G, McNeil D, Hossain H, Nelson R (2007) Climate change impact on rainfed wheat in south-eastern Australia. Field Crop Res 104:139–147

Anwar MR, Rodriguez D, Liu DL, Power S, O'Leary GJ (2008) Quality and potential utility of ENSO-based forecasts of spring rainfall and wheat yield in South Eastern Australia. Aust J Agric Res 59:112–126

Ashmore MR (2002) Effects of oxidants at the whole plant and community level. In: Bell JNB, Treshow M (eds) Air pollution and plant life. John Wiley, Chichester, pp 89–118

Ashmore MR (2005) Assessing the future global impacts of ozone on vegetation. Plant Cell Environ 28:949–964

Australian High Commission (2011) Australia helping farmers adapt to climate change. Public Affairs Section at the Australian High Commission India, New Delhi. Available at http://www.india.embassy.gov.au/ndli/pa0611.html

BassiriRad H, Constable JVH, Lussenhop J, Kimball BA, Norby RJ, Oechel WC, Reich PB, Schlesinger WH, Zitzer S, Sehtiya HL, Silim S (2003) Widespread foliage δ15N depletion under elevated CO_2: inferences for the nitrogen cycle. Glob Chang Biol 9:1582–1590. doi:10.1046/j.1529-8817.2003.00679.x

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. IPCC Secretariat, Geneva, p 210

Bell GDH (2011) Cultivated plants of the farm. Cambridge University Press, Cambridge, ISBN 9781107662797, pp 292

Betts RA (2012) Integrated approaches to climate-crop modelling: needs and challenges. Phil Trans R Soc B 360:2049–2065. doi:10.1098/rstb.2005.1739

Betts RA, Collins M, Hemming DL, Jones CD, Lowe JA, Sanderson MG (2011) When could global warming reach 4 °C? Phil Trans R Soc A 369:67–84. doi:10.1098/rsta.2010.0292

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modelling the impact of future climate scenarios on yield and yield variability of grapevine. Clim Res 7:213–224. doi:10.3354/cr007213

Blasing TJ, Solomon AM (1984) Response of the North American corn belt to climate warming. Prog Biomet 3:311–321

BoM (2006a) Living with drought. Australian Bureau of Meteorology. Available at http://www.bom.gov.au/climate/drought/livedrought.shtml

BoM (2006b) Severe tropical cyclone Larry. Queensland Regional Office, Australian Bureau of Meteorology. Available at http://www.bom.gov.au/weather/qld/cyclone/tc_larry/

BoM (2011) Special climate statement 24. An extremely wet end to 2010 leads to widespread flooding across eastern Australia. Available at http://www.bom.gov.au/climate/current/statements/scs24.pdf

Bora S, Ceccacci I, Delgado C, Townsend R (2010) Food security and conflict. World Developmental Report 2011, Background Paper. Agriculture and Rural Development Department, World Bank. Available at http://www.worldbank.org/

Bowes G (1991) Growth at elevated CO_2: photosynthetic responses mediated through Rubisco. Plant Cell Environ 14:795–806

Bradshaw B, Dolan H, Smit B (2004) Farm-level adaptation to climatic variability and change: crop diversification in the Canadian prairies. Clim Chang 67:119–141. doi:10.1007/s10584-004-0710-z

Brown O, Crawford A (2008) Assessing the security implications of climate change for West Africa: country case studies of Ghana and Burkina Faso. International Institute for Sustainable Development, Canada, 52 pp. Available at http://www.iisd.org/pdf/2008/security_implications_west_africa.pdf

Cai W, Shi G, Cowan T, Bi D, Ribbe J (2005) The response of the southern annular mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. Geo Res Lett 32:L23706. doi:10.1029/2005GL024701

Cai W, Cowan T, Sullivan A (2009) Recent unprecedented skewness towards positive Indian Ocean Dipole occurrences and its impact on Australian rainfall. Geo Res Lett 36:L11705. doi:10.1029/2009GL037604

Cai W, van Rensch P, Cowan T, Hendon HH (2011) Teleconnection pathways of ENSO and the IOD and the mechanisms for impacts on Australian rainfall. J Clim 24:3910–3923

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. PANS 104:18866–18870. doi:10.1073/pnas.0702737104

Carter TR, Jones RN, Lu X, Bhadwal S, Conde C, Mearns LO, O'Neill BC, Rounsevell MDA, Zurek MB (2007) New assessment methods and the characterisation of future conditions. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 133–171

Cassou C (2008) Intraseasonal interaction between the Madden–Julian Oscillation and the North Atlantic Oscillation. Nature 455:523–527

Chameides WL, Kasibhatla PS, Yienger J, Levy HI (1994) Growth of continental-scale metro-agroplexes, regional ozone pollution, and world food production. Science 264:74–77

Chaves MM, Maroco JP, Pereira JS (2003) Understanding plant responses to drought—from genes to the whole plant. Func Plant Bio 30:239–264

Chen C, Qian C, Deng A, Zhang W (2011) Progressive and active adaptations of cropping system to climate change in Northeast China. Eur J Agron 38:94–103

Cicerone RJ (1987) Changes in stratospheric ozone. Science 237:35–42

Cicerone RJ, Oremland RS (1988) Biogeochemical aspects of atmospheric methane. Glob Biogeochem Cycles 2:299–327. doi:10.1029/GB002i004p00299

Clark A, Brinkley T, Lamont B, Laughlin G (2000) Exceptional circumstances: a case study in the application of climate information to decision making. In: Cli-Manage Conference, Albury, NSW, 23–25 October 2000. Available at http://adl.brs.gov.au/brsShop/data/12901_alburyfinal.pdf

Cleugh H, Smith MS, Battaglia M, Graham P (eds) (2011) Climate change: science and solution for Australia. CSIRO, Collingwood, p 155

Cline WR (2007) Global warming and agriculture. Impact estimates by country. Centre for Global Development and Peter G. Peterson Institute for International Economics Washington, DC, 250 pp. Available at http://www.cgdev.org/

Coakley SM, Scherm H, Chakraborty S (1999) Climate change and disease management. Annu Rev Phyto 37:399–426

Cohen J, Barlow M (2005) The NAO, the AO, and global warming: how closely related? J Clim 18:4498–4513. doi:10.1175/JCLI3530.1

Collins M, An, S, Cai W, Ganachaud A, Guilyardi E, Jin F, Jochum M, Lengaigne M, Power S, Timmermann A, Vecchi G, Wittenberg A (2010) The impact of global warming on the tropical Pacific Ocean and El Niño. Nature Geoscience 3. doi:10.1038/NGEO868

CSIRO (2009) Indian Ocean temperature link to bushfires. Available at http://www.csiro.au/news/Indian-Ocean-Temp-And-Bushfire.html

CSIRO, Bureau of Meteorology (2007) Climate change in Australia. Technical Report, pp 140. Available at http://www.climatechangeinaustralia.gov.au

Cullen HM, Kaplan A, Arkin PA, deMenocal PB (2002) Impact of the North Atlantic oscillation on Middle Eastern climate and streamflow. Clim Chang 55:315–338

DAFF (2006a) National water initiative. Department of Agriculture, Forestry and Fisheries, Australia. Available at http://www.pmc.gov.au/water_reform/nwi.cfm

DAFF (2006b) Contours. Department of Agriculture, Fisheries and Forestry, Australia, 24 pp. Available at http://www.daff.gov.au/__data/assets/pdf_file/0020/98201/contours-dec-06.pdf

DAFF (2012) Demonstration of climate change adaptation and mitigation on-farm and food processor projects. Australian Government, Department of Agriculture, Forestry and Fisheries, Australia. Available at http://www.daff.gov.au/. Accessed 28 January 2012

Dai A (2011) Drought under global warming: a review. Wiley Interdisciplinary Reviews: Clim Chang 2:45–65

Daniel R (2009) Canopy management in the northern grains region. Northern Grower Alliance, Northern Focus, Australian Grain, July–August 2009, pp I–V. Available at http://www.ausgrain.com.au/Back%20Issues/192jagrn09/Ni_Canopy.pdf

de Loë R, Kreutzwiser R, Moraru L (2001) Adaptation options for the near term: climate change and the Canadian water sector. Glob Environ Chang 11:231–245

Donald A, Meinke H, Power B, Wheeler MC, Maia A, De HN, Stone RC, Ribbe J, White N (2006) Near-global impact of the Madden–Julian oscillation on rainfall. Geo Res Lett 33:L09704. doi:10.1029/2005GL025155

Drake BG, Gonzàlez-Meler MA, Long SP (1997) More efficient plants: a consequence of rising atmospheric CO_2? Annu Rev Plant Physio Plant Mole Bio 48:609–639

Easterling W, Aggarwal P, Batima P, Brander K, Erda L, Howden M, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello F (2007) Food, fibre and forest products. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 273–313

Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686–688

Erda L (1996) Agricultural vulnerability and adaptation to global warming in China. Water Air Soil Poll 92:63–73. doi:10.1007/BF00175553

FAO (2006) Livestock's long shadow: environmental issues and options. FAO, Rome. Available at http://www.fao.org

FAO (2007) Adaptation to climate change in agriculture, forestry, and fisheries: perspective, framework and priorities. FAO, Rome. Available at http://www.fao.org

FAOSTAT (2012) Food And Agriculture Organization Of The United Nations. Available at http://faostat.fao.org/site/444/default.aspx#ancor. Accessed 16 January 2012

Finlay K, Aurambout J, De Barro P, Trebicki P, Griffiths W, Kriticos D, Parry H, Luck J (2011) Climate change implications for the pest status and vectoring potential of the bird cherry-oat aphid, *Rhopalosiphum padi*. Science Exchange 2011, Preparedness and Prevention, CRC10071: Climate Change. Available at http://www.crcplantbiosecurity.com.au/publications/npb1615

Fischer G, Shah M, Velthuizen H (2002) Climate change and agricultural vulnerability. Special report as contribution to the World Summit on Sustainable Development, Johannesburg 2002. International Institute for Applied Systems Analysis, Laxenburg, p 152

Fischer G, Shah M, Tubiello FN, Velthuizen H (2005) Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philos Trans R Soc Lond B Biol Sci 360:2067–2083. doi:10.1098/rstb.2005.1744

Folland CK, Karl TR, Salinger MJ (2002) Observed climate variability and change. Weather 57:268–278

García-Ispierto I, López-Gatius F, Bech-Sabat G, Santolaria P, Yániz JL, Nogareda C, De Rensis F, López-Béjar M (2007) Climate factors affecting conception rate of high producing dairy cows in northeastern Spain. Theriogenology 67:1379–1385

Garnaut R (2011a) The science of climate change. Garnaut Climate Change Review—Update 2011, Canberra. Available at http://www.ag.gov.au/cca

Garnaut R (2011b) The science of climate change. Garnaut Climate Change Review—Update 2011, Canberra. Available at http://www.ag.gov.au/cca

Gifford RM (1992) Implications of the globally increasing atmospheric CO_2 concentration and temperature for the Australian Terrestrial carbon budget: integration using a simple model. Aust J Bot 40:527–543

Gonzalez-Meler MA, Taneva L, Trueman RJ (2004) Plant respiration and elevated atmospheric CO_2 concentration: cellular responses and global significance. Ann Bot 94:647–656. doi:10.1093/aob/mch189

Goudriaan J, Zadoks JC (1995) Global climate change: modelling the potential responses of agro-ecosystems with special reference to crop protection. Environ Pollut 87:215–224

GRDC (2008) Grain Research & Development Corporation. An economic analysis of GRDC's investment climate research (2002–2007). GRDC Impact Assessment Report Series. Available at http://www.grdc.com.au/uploads/documents/GRDC_ImpAss_ClimateCluster.pdf

Gregory PJ, Johnson SN, Newton AC, Ingram JSI (2009) Integrating pests and pathogens into the climate change/food security debate. J Exp Bot 60:2827–2838. doi:10.1093/jxb/erp080

Hall SJ, Matson PA, Roth P (1996) NO_x emission from soil: implications for air quality modeling in agricultural regions. Ann Rev Ene Envir 21:311–346

Hamilton JG, Dermody O, Aldea M, Zangerl AR, Rogers A, Berenbaum MR, Delucia EH (2005) Anthropogenic changes in tropospheric composition increase susceptibility of soybean to insect herbivory. Envir Ento 34:479–485. doi:10.1603/0046-225X-34.2.479

Hammer GL, Holzworth DP, Stone R (1996) The value of skill in seasonal forecasting to wheat crop management in a region with high climate variability. Aust J Agric Res 47:717–737

Harries JE (1996) The greenhouse Earth: a view from space. Quart J Meteo Soc 122:799–818

Hazell P, Wood S (2008) Drivers of change in global agriculture. Philos Trans R Soc BBiol Sci 363:495–515. doi:10.1098/rstb.2007.2166

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate change 2001: the scientific basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 881 pp

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. PNAS 104:19691–19696. doi:10.1073/pnas.0701890104

Hulme M, Doherty R, Ngara T, New MG, Lister D (2001) African climate change: 1900–2100. Clim Res 17:145–168

IFAD (2012) Livestock and climate change. Livestock thematic papers. Available at http://www.ifad.org. Accessed 28 January 2012

IPCC (2001) Climate change 2001: working group I: the scientific basis. Available at http://www.grida.no/publications/other/ipcc_tar/

IPCC (2007a) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 879

IPCC (2007b) Summary for policymakers. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

IPCC (2010) Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Assessing and Combining Multi Model Climate Projections. In: Stocker TF, Qin D, Plattner GK, Tignor M, Midgley PM (eds) IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland, 117 pp. Available at http://www.ipcc.ch/pdf/supporting-material/expert-meeting-assessing-multi-model-projections-2010-01.pdf

Jablonski LM, Wang X, Curtis PS (2002) Plant reproduction under elevated CO_2 conditions: a meta-analysis of reports on 79 crop and wild species. New Phytol 156:9–26

Jones C, Waliser DE, Lau KM, Stern W (2004) Global occurrences of extreme precipitation and the Madden–Julian oscillation: observations and predictability. J Clim 17:4575–4589. doi:10.1175/3238.1

Katerji N, Mastrorilli M, Rana G (2008) Water use efficiency of crops cultivated in the Mediterranean region: review and analysis. Eur J Agron 28:493–507

Kates RW, Travis WR, Wilbanks TJ (2012) Transformational adaptation when incremental adaptations to climate change are insufficient. PANS 109:7156–7161. doi:10.1073/pnas.1115521109

Kawatani Y, Hamilton K, Watanabe S (2011) The quasi-biennial oscillation in a double CO_2 climate. J Atmos Sci 68:265–283

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288

Keenan TD, Cleugh HA (eds) (2011) Climate science update: a report to the 2011 Garnaut Review. CAWCR Technical Report No. 036

Kim HY, Lieffering M, Miura S, Kobayashi K, Okada N (2001) Growth and nitrogen uptake of CO_2-enriched rice under field conditions. New Phytol 150:223–229

Kimball BA (1983) Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron J 75:779–788

Kimball BA, Kobayashi K, Bindi M (2002) Responses of agricultural crops to free-air CO_2 enrichment. Adv Agron 77:293–368

Kirono DGC, Tapper NJ (1999) ENSO rainfall variability and impacts on crop production in Indonesia. Phys Geog 20:508–519

Kriticos D, Filmer M (2007) Weeds will thrive on climate change. Farming ahead. Available at http://www.csiro.au/Outcomes/Climate/Adapting/Weeds-will-thrive-on-climate-change.aspx

Kron W, Berz G (2007) Flood disasters and climate change: trends and options—a (re-)insurer's view. In: Lozán JL, Grabl H, Hupfer P, Menzel L, Schönwiese CD (eds) Global change: enough water for all? University of Hamburg, Hamburg, pp 268–273

Krupa SV, Kickert RN (1993) The effects of elevated ultraviolet (UV)-B radiation on agricultural production. Report submitted to the Formal Commission on 'Protecting the Earth's Atmosphere' of the German Parliament, Bonn, Germany, 432 pp

Le Quere C, Raupach MR, Canadell JG, Marland G et al (2009) Trends in the sources and sinks of carbon dioxide. Nature Geo 2:831–836. doi:10.1038/ngeo689

Leakey ADB, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR (2009) Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. J Exp Bot 60:2859–2876. doi:10.1093/jxb/erp096

Lee JS (2011) Combined effect of elevated CO_2 and temperature on the growth and phenology of two annual C3 and C4 weedy species. Agri Eco Environ 140:484–491

Liu DL, Zuo H (2012) Statistical downscaling of daily climate variables for climate for climate change impact assessment over New South Wales, Australia. Clim Chang. doi:10.1007/s10584-012-0464-y

Liu DL, Timbal B, Mo J, Fairweather H (2011) A GIS-based climate change adaptation strategy tool. Int J Clim Chang Strat Man 3:140–155

Lobell DB (2007) Changes in diurnal temperature range and national cereal yields. Agric For Meteorol 145:229–238

Lobell DB, Field CB (2007) Global scale climate–crop yield relationships and the impact of recent warming. Environ Res Lett 2:014002. doi:10.1088/1748-9326/2/1/014002

Lobell DB, Field CB (2008) Estimation of the carbon dioxide (CO_2) fertilization effect using growth rate anomalies of CO_2 and crop yields since 1961. Glob Chang Biol 14:39–45

Loya WM, Pregitzer KS, Karberg NJ, King JS, Giardina JP (2003) Reduction of soil carbon formation by tropospheric ozone under increased carbon dioxide levels. Nature 425:705–707

Lucier A, Palmer M, Mooney H, Nadelhoffer K, Ojima D, Chavez F (2006) Ecosystems and climate change: research priorities for the U.S. Climate Change Science Program. Recommendations from the Scientific Community. Report on an Ecosystems Workshop, prepared for the Ecosystems Interagency Working Group. Special Series No. SS-92-06, University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, 50 pp

Luo Q, Bellotti W, Williams M, Wang E (2009) Adaptation to climate change of wheat growing in South Australia: analysis of management and breeding strategies. Agri Eco Environ 129:261–267

Malone RW, Meek DW, Hatfield JL, Mann ME, Jaquis RJ, Ma L (2009) Quasi-biennial corn yield cycles in Iowa. Agric For Meteorol 149:1087–1094

Marshall GJ (2003) Trends in the southern annular mode from observations and reanalyses. J Clim 16:4134–4143

Marshall GJ, Stott PA, Turner J, Connolley WM, King JC, Lachlan-Cope TA (2004) Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. Geo Res Lett 31:L14205. doi:10.1029/2004GL019952

Marshall NA, Stokes CJ, Howden SM, Nelson RN (2010) Enhancing adaptive capacity. In: Stokes C, Howden M (eds) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO, Collingwood, pp 245–256

Mathhews R, Wassmann R (2003) Modelling the impacts of climate change and methane emission reductions on rice production: a review. Eur J Agron 19:573–598

Meinke H, Stone RC (2005) Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. Clim Chang 70:221–253

Meinke H, Abawi Y, Stone RC, Hammer GL, Potgieter AB, Nelson R, Howden SM, Baethgen W, Selvaraju R (2003) Climate risk management and agriculture in Australia and beyond: linking research to practical outcomes. In: The International Conference on Total Disaster Risk Management Report. Asian Disaster Reduction Center (ADRC) and The United Nations Office for the Coordination of Humanitarian Affairs (OCHA), 2–4 December 2003, Kobe, Japan, pp 83–87

Meinke H, Sivakumar MVK, Motha RP, Nelson R (2007) Preface: climate predictions for better agricultural risk management. Aust J Agric Res 58:935–938

Miller CJ, Howden SM, Jones RN (2010) Intensive livestock industries. In: Stokes C, Howden M (eds) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO, Collingwood, pp 171–185

Moreddu C (2000) Overview of farm household strategies and government intervention. In: OECD (Organization for Economic Cooperation and Development), Income Risk Management in Agriculture, Paris

Moss RH, Edmonds JE, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. doi:10.1038/nature08823

Murray–Darling Basin Authority (2011) The proposed “environmentally sustainable level of take” for surface water of the Murray–Darling Basin: methods and outcomes. MDBA publication no. 226/11, Murray–Darling Basin Authority, Canberra. Available at http://www.mdba.gov.au/

Nakicenovic N, Swart R (eds) (2000) IPCC special report on emissions scenarios. Cambridge University Press, UK, p 570

Nicholls RJ, Tol RSJ (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Phil Trans R Soc A 364:1073–1095

Nicholls RJ, Hanson SE, Lowe J, Vaughan DA, Lenton T, Ganopolski A, Tol RSJ, Vafeidis AT (2006) Metrics for assessing the economic benefits of climate change policies: sea level rise. Report to the OECD, ENV/EPOC/GSP(2006)3/FINAL, Organisation for Economic Co-operation and Development (OECD), 128 pp

Nicholls RJ, Wong PP, Burkett VR, Codignotto JO, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 315–356

Nyenzi B, Lefale PF (2006) El Niño Southern Oscillation (ENSO) and global warming. Adv Geosci 6:95–101

Oladipo EO (1989) The quasi-periodic fluctuations in the drought indices over the North American Great Plains. Nat Haz 2:1–16. doi:10.1007/BF00124754

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112

Ortiz R, Sayre KD, Govaerts B, Gupta R, Subbarao GV, Ban T, Hodson D, Dixon JM, Ortiz-Monasterio JI, Reynolds M (2008) Climate change: can wheat beat the heat? Agri Ecosys Environ 126:46–58

Palmer WC (1965) Meteorological drought. Research Paper No. 45, US Dept. of Commerce, 58. Available at http://www.ncdc.noaa.gov/oa/climate/research/

Parry ML (1978) Climatic change, agriculture and settlement. William Dawson and Sons, Foldestone, p 214. ISBN 0208017224

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob Environ Chang 14:53–67. doi:10.1016/j.gloenvcha.2003.10.008

Parry ML, Rosenzweig C, Livermore M (2005) Climate change, global food supply and risk of hunger. Phil Trans R Soc B 360:2125–2138. doi:10.1098/rstb.2005.1751

Passioura JB (2002) Environmental biology and crop improvement. Funct Plant Biol 29:537–546

Pidwirny M (2006) The carbon cycle. Fundamentals of physical geography, 2nd edn. Available at http://www.physicalgeography.net/fundamentals/9r.html. Accessed 16 January 2012

Pittock AB (1975) Climate change and patterns of variability in Australian rainfall. Search 6:498–504

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10:23–36

Porter JR, Semenov MA (2005) Crop responses to climatic variation. Phil Trans R Soc B 360:2021–2035

Potgieter AB, Hammer GL, Doherty A, de Voil P (2005) A simple regional-scale model for forecasting sorghum yield across North-Eastern Australia. Agric For Meteorol 132:143–153

Potgieter AB, Hammer GL, Doherty A (2006) Oz-wheat: a regional-scale crop yield simulation model for Australian wheat. Queensland Department of Primary Industries & Fisheries, Brisbane. Available at http://www.dpi.qld.gov.au/home.htm

Power S, Colman R (2006) Multi-year predictability in a coupled general circulation model. Clim Dyn 26:247–272

Power S, Casey T, Folland C, Colman A, Mehta V (1999) Inter-decadal modulation of the impact of ENSO on Australia. Clim Dyn 15:319–324

Power S, Haylock M, Colman R, Wang X (2006) The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. J Clim 19:4755–4771

Queensland Government (2006) TC Larry Report, 28March 2006. Available at http://www.disaster.qld.gov.au/news/view.asp?id=1323

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent climate observations compared to projections. Science 316:709–710. doi:10.1126/science.1136843

Raupach MR, Marland G, Ciais P, Le Quéré C, Canadell JG, Klepper G, Field CB (2007) Global and regional drivers of accelerating CO_2 emissions. PNAS 104:10288–10293. doi:10.1073/pnas.0700609104

Reynolds M, Bonnett D, Chapman SC, Furbank RT, Manès Y, Mather DE, Parry MAJ (2011) Raising yield potential of wheat. I. Overview of a consortium approach and breeding strategies. J Exp Bot 62:439–452. doi:10.1093/jxb/erq311

Ronald P (2011) Plant genetics, sustainable agriculture and global food security. Genetics 188:11–20

Rosenzweig C (1985) Potential CO_2-induced climatic effects on North American wheat producing regions. Clim Chang 7:367–389

Rosenzweig C, Hillel D (1995) Climate change and the global harvest: potential impacts on the greenhouse effect on agriculture. Oxford University Press, New York

Rosenzweig C, Hillel D (2008) Climate change and the global harvest: impacts of El Niño and other oscillations on agroecosystems. Oxford University Press, New York

Rosenzweig C, Tubiello FN, Goldberg RA, Mills E, Bloomfield J (2002) Increased crop damage in the US from excess precipitation under climate change. Glob Envion Chang 12:197–202

Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P (2007) Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 79–131

Roudier P, Sultan B, Quirion P, Berg A (2011) The impact of future climate change on West African crop yields: what does the recent literature say? Glob Envi Chang 21:1073–1083. doi:10.1016/j.gloenvcha.2011.04.007

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363

ScienceDaily (2000) Science news: climate change shifts frost seasons & plant growth. Available at http://www.sciencedaily.com/releases/2000/10/001017073120.htm

Scroxton N, Bonham SG, Rickaby REM, Lawrence SHF, Hermoso M, Haywood AM (2011) Persistent El Niño–Southern Oscillation variation during the Pliocene Epoch. Paleoceanography 26 (PA2215):1–13. doi:10.1029/2010PA002097

Shimono H (2011) Earlier rice phenology as a result of climate change can increase the risk of cold damage during reproductive growth in northern Japan. Agric Ecosys Envir 144:201–207

Smit B, Skinner MW (2002) Adaptation options in agriculture to climate change: a typology. Mitig Adapt Strat Glob Chang 7:85–114. doi:10.1023/A:1015862228270

Smith MS, Ash A (2011) Adaptation: reducing risk, gaining opportunity. In: Cleugh H, Smith MS, Battaglia M, Graham P (eds) Climate change: science and solution for Australia. CSIRO, Collingwood, pp 59–72

Solomon S, Plattner G, Knutti R, Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions. PNAS 106:1704–1709. doi:10.1073/pnas.0812721106

Sombroek WG (1990) Soils on a warmer earth: tropical and subtropical regions. In: Scharpenseel HW, Schomaker M, Ayoub A (eds) Soils on a warmer earth. Elsevier, Amsterdam, pp 157–174

Somerville C, Briscoe J (2001) Genetic engineering and water. Science 292:2217

Stephens DJ, Lyons TJ (1998) Variability and trends in sowing dates across the Australian wheatbelt. Aust J Agric Res 49:1111–1118

Stern N (2006) The Stern review on the economic effects of climate change. Review 32:793–798. doi:10.1111/j.1728-4457.2006.00153.x

Stokes C, Howden M (eds) (2010) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO, Collingwood, p 286

Stokes CJ, Crimp S, Gifford R, Ash AJ, Howden SM (2010) Broadacre grazing. In: Stokes C, Howden M (eds) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO, Collingwood, pp 153–170

Stone R, Nicholls N, Hammer G (1996) Frost in Northeast Australia: trends and influences of phases of the Southern Oscillation. J Clim 9:1896–1909

Tao F, Yokozawa M, Xu Y, Hayashi Y, Zhang Z (2006) Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric For Meteorol 138:82–92

Tashiro AH, Wardlaw IF (1990) The response to high temperature shock and humidity changes prior to and during the early stages of grain development in wheat. Aust J Plant Physio 17:551–561

Teramura AH, Sullivan JH (1994) Effects of UV-B radiation on photosynthesis and growth of terrestrial plants. Photosynthesis Res 39:463–473

Teramura AH, Sullivan JH, Ziska LH (1990) Interaction of elevated ultraviolet-B radiation and CO_2 on productivity and photosynthetic characteristics in wheat, rice, and soybean. Plant Physiol 94:470–475

Terjung WH, Hayes JT, O'Rourke PA, Todhunter PE (1984a) Yield responses of crops to changes in environment and management practices: model sensitivity analysis. 1. Maize. Int J Biometeorology 28:261–278

Terjung WH, Hayes JT, O'Rourke PA, Todhunter PE (1984b) Yield responses of crops to changes in environment and management practices: model sensitivity analysis. II. Rice, wheat, and potato. Int J Biometeorology 28:279–292

The National Academies Press (2001) Improving the effectiveness of U.S. climate modeling. Panel on improving the effectiveness of U.S. climate modeling, Commission on Geosciences, Environment and Resources, National Research Council. ISBN: 978-0-309-07257-1. National Research Council, Washington, DC, 142 pp. Available at http://www.nap.edu/

Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B, Wise MA, Clarke LE, Edmonds JA (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. Clim Chang 109:77–94

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677. doi:10.1038/nature01014

Tubiello FN (2005) Climate variability and agriculture: perspectives on current and future challenges. In: Knight B (ed) Impact of climate change, variability and weather fluctuations on crops and their produce markets. Impact Reports, Cambridge

Tubiello FN, Soussana JF, Howden SM (2007) Crop and pasture response to climate change. PNAS 104:19686–19690

UN (2011) United Nations Press Release, Embargoed Until 3 May 2011, 11:00 A.M., New York Time, World population to reach 10 billion by 2100 if fertility in all countries converges to replacement level. Available at http://esa.un.org/wpp/Other-Information/Press_Release_WPP2010.pdf

van Ittersum MK, Howden SM, Asseng S (2003) Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO_2, temperature and precipitation. Agric Ecosys Environ 97:255–273

Vandermeiren K (2005) Impact of rising tropospheric ozone on potato: effects on photosynthesis, growth, productivity and yield quality. Plant Cell Environ 28:982–996

van der Werf W, Keesman K, Burgess P, Graves A, Pilbeam D, Incoll LD, Metselaar K, Mayus M, Stappers R, van Keulen H, Palma J, Dupraz C (2007) Yield-SAFE: a parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems. Ecological Engineering 29:419–433. doi:10.1016/j.ecoleng.2006.09.017

Vines RG (2008) Australian rainfall patterns and the southern oscillation. 2. A regional perspective in relation to Luni-solar (Mn) and Solar-cycle (Sc) signals. Rangel J 30:349–359

Visbeck MH, Hurrell JW, Polvani L, Cullen HM (2001) The North Atlantic Oscillation: past, present, and future. PNAS 98:12876–12877. doi:10.1073/pnas.231391598

Volk M, Bungener P, Contat F, Montani M, Fuhrer J (2006) Grassland yield declined by a quarter in 5 years of free-air ozone fumigation. Glob Chang Biol 12:74–83

Waggoner PE (1983) Agriculture and a climate changed by more carbon dioxide. In: National Research Council, Changing Climate. Report of the Carbon Dioxide Committee, Board of Atmospheric Sciences and Climate. National Academy Press, Washington, DC, pp 383–418

Wheeler TR, Hong TD, Ellis RH, Batts GR, Morison JIL, Hadley P (1996) The duration and rate of grain growth, and harvest index, of wheat (*Triticum aestivum* L.) in response to temperature and CO_2. J Exp Bot 47:623–630

Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Prasad PVV (2000) Temperature variability and the yield of annual crops. Agric Ecosys Environ 82:159–167

White WB, McKeon G, Sytkus J (2003) Australian drought; the interference of multi-spectral global standing modes and traveling waves. Int J Clim 23:631–662. doi:10.1002/joc.895

White JW, Hoogenboom G, Kimball BA, Wall GW (2011) Methodologies for simulating impacts of climate change on crop production. Field Crops Res 124:357–368

Williams GDV, Fautley RA, Jones KH, Stewart RB, Wheaton EE (1988) Estimating effects of climatic change on agriculture in Saskatchewan, Canada. In: Parry ML (ed) The impact of climatic variations on agriculture, vol. 1. Assessment in cool temperate and cold regions. Reidel, Dordrecht, pp 219–379

Wolf J (2002) Comparison of two potato simulation models under climate change. I. Model calibration and sensitivity analyses. Clim Res 21:173–186

Zhang H, Turner NC, Poole ML, Simpson N (2006) Crop production in the high rainfall zones of southern Australia—potential, constraints and opportunities. Aust J Exp Agric 46:1035–1049

Zhao M, Pitman AJ, Chase T (2001) The impact of land cover change on the atmospheric circulation. Clim Dynamics 17:467–477