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EXECUTIVE SUMMARY

This report is the first in a series produced by CSIRO Climate Adaptation Flagship to meet the need for immediate and strategic policy-relevant insights into the vulnerability of Australian agriculture to climate variability and change. This report reviews:

1. alternative models for conceptualising and measuring vulnerability documenting the most operational and accessible methods and models that are publicly available data

2. and collates existing research into the likely impacts of climate change on the physical productivity of Australian agriculture

REVIEW OF VULNERABILITY CONCEPTUAL MODELS

Vulnerability can be conceptualised in many different ways along a continuum from outcome to contextual vulnerability. Outcome vulnerability is characterised by the IPCC (2001) definition of 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes'. In contrast, contextual vulnerability assesses 'the susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt'. These two concepts of vulnerability vary in their: systems of interests; antecedents; conception of climate change; theoretical or disciplinary basis; range of impacts considered; and type of results provided. The outcome-orientated approach works more effectively in more linear or bounded systems, whereas the contextual approach is more relevant to social and environment-linked open systems and traditionally uses more qualitative methods.

Research into the vulnerability of Australian agriculture has focused on quantifying the impacts in response to both climate variability and future change explicitly on agricultural productivity. This is a logical first step, and an essential prerequisite for exploring the economic and social implications of these changes. The early progress of this science means that research exploring the potential future economic and social impacts of climate change is embryonic. There are four categories of current research: biophysical productivity changes, economic impacts, industry and community planning, and research into the adaptive capacity of rural communities. The first three of these translate directly into production and economic impacts on agriculture and are firmly in outcome-vulnerability assessments. Research into the adaptive capacity of rural communities tackles the broader concept of contextual vulnerability.

REVIEW OF MODELS TO ESTIMATE PRODUCTIVITY CHANGES

Research into the impact of climate change on Australian agriculture is still in its infancy and has tended to use outcome vulnerability frameworks informed by predominantly biophysical agricultural models. To understand the breadth of models that have or could be used to understand the vulnerability of agriculture to climate variability and change, two steps were undertaken: a literature search of known or potential models, and a workshop with experts that accessed a range of operational models. The literature and workshop activities revealed that considerable research has been undertaken to understand and quantify the broad-scale impacts of climate change on cropping and pasture productivity across Australia. In research terms, modelling the potential impacts of climate change on dryland cropping is more advanced than pasture related enterprises. Considerably less research and capability are available to understand, model and quantify the potential impacts of climate change on the grazing, dairy, viticulture and horticulture industries. In many instances, simple historical analogues or 'expert opinion' is the basis for estimating productivity impacts.

While climate change studies have been undertaken for both cropping and pasture related industries at the national scale, capabilities and understanding vary regionally. Native pasture productivity impacts of climate change are well understood in tropical and sub-tropical areas. However, less is known about the potential impacts on temperate and improved pastures. The opposite is true for modelling the impacts of climate change on crops. A better understanding of likely impacts is available for winter cropping systems as opposed to summer cropping systems.

Understanding the impacts of climate change on viticulture and horticulture is far more fragmented and regionalised with very limited operational modelling capability.

CONCLUSIONS

Research into the vulnerability of Australian agriculture to climate change is at an early stage of development. So far, most of the research has focused on biophysical productivity, and its sensitivity to changes in climate. Most of the models used to analyse vulnerability follow linear dose-response logic, focus on biophysical processes and are limited in their integration with contextual issues. These models are linear in the sense that they have limited capacity for model mitigation and adaptation options. They tend to predict the future as predetermined by current activities and choices, rather than as dynamically evolving through a continuous series of choices. There have been some initial attempts to integrate biophysical and economic models to predict the economic impacts of climate change on farm incomes and regional economies. Most of this model-based research has focused on broadacre agriculture, and few studies have covered other industries across Australia. Most models are 'run' for specific climate variability scenarios, meaning there's little comparable analysis between models and modelling outputs. Outcome vulnerability is the implicit framework used for this research.

The risk of accepting current methods as the only and best way to analyse vulnerability means some of its critical dimensions could be overlooked; dimensions that alternative perspectives and methods could inform. Very little work is done in Australia on understanding the dimensions of contextual vulnerability that are essential to the resilience of rural communities. The agricultural sector involves a dynamic interaction between ecological, industrial and social processes. It is subject to multiple interacting drivers, including climate change, market forces and threats to the natural resource base. Consequently, the ultimate focus of vulnerability research needs to be on the socioeconomic outcomes of these dynamic interactions, including conservation, production and livelihood options. These have not previously been considered in particular regions and industries. This would operationalise a completely different construct of vulnerability to that currently dominating research: 'vulnerability as the susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt' (Nelson *et al*., 2007).

1. INTRODUCTION

Agriculture is one of the most climate-sensitive sectors of the Australian economy (Hodges and Goesch 2006). The combined and interacting influences of climate variability and change directly affect Australian agriculture through rainfall and temperature conditions on plant and animal production, and indirectly through changes in soils, water, pests, diseases and biodiversity interactions. Climate variability and change are two inextricably linked drivers of climate risk that also contribute to economic risk in agriculture through the variability of commodity prices and input costs that determine Australia's comparative advantage in export markets.

Changes in the physical productivity of agricultural enterprises have significant economic and social consequences. Changes in the relative profitability of alternative farming activities lead to changes in land use, regional investment and infrastructure development, and ultimately the flow of investment between agriculture and other sectors. Changes in industry investment and infrastructure contribute to changes in employment, regional migration and demographic profiles. At each step in this complex hierarchy of interacting impacts, adaptation routinely takes place to reduce the exposure of agricultural activities to climate risk, and their sensitivity to its impacts.

Although agriculture has steadily declined to around three per cent of gross domestic product and employment (ABARE 2007), agriculture and its future under climate change remains central to Australia's national psyche. A historically derived sense of agrarianism preserves an acute concern for the welfare of rural communities even in the face of an increasingly urbanised Australian society (Botterill 2005). Agriculture remains the economic lifeblood of most rural communities. It is also critical for the environment, with farmers actively managing much of Australia's land and water resources.

The prospect of significant climate change has led to an unprecedented transition in climate related policy in Australian agriculture. An immediate policy priority is to identify vulnerable industries and regions (e.g. DAFF 2006). This has translated into an urgent demand for research using existing methods, data and models to provide immediate insights into the vulnerability of rural industries and communities.

The legitimate pressure for immediate research results to identify vulnerable communities and industries in Australian agriculture is partly in tension with, and partly complementary to, the need for more strategic research. Appropriate strategies for reducing vulnerability to climate risk depend critically on the diverse social, environmental and economic contexts in which people in Australian rural communities live and work. At any point in time, existing research methods will always be limited to a subset of possible methods and operating contexts. Pressure to apply or draw inferences from a limited set of existing methods beyond their sphere of relevance carries a risk. At best, this risks constraining the exploration of a greater set of potentially feasible and relevant adaptation opportunities. At worst, it risks institutionalising inappropriate or counter-productive adaptation options. Appropriate adaptation depends on efficiently discovering and matching appropriate strategies and actions for the diverse situations faced by vulnerable rural communities and industries.

This report is the first in a series produced by CSIRO Climate Adaptation Flagship to meet the need for both immediate and strategic policy-relevant insights into the vulnerability of Australian agriculture to climate variability and change. Its objectives are to review:

1. alternative methods for conceptualising and measuring vulnerability by documenting the most operational and accessible methods and models that are publicly available.
2. and collate existing research into the likely impacts of climate change on the physical productivity of Australian agriculture

An important reason for doing this is to inform the application of regional economic models (Heyhoe et al. 2007), particularly in terms of the regions and industries for which projections of agricultural productivity under climate change are available.

The report concludes with a brief review of existing research, and priorities for future research.

2. CONCEPTUAL FRAMEWORKS FOR ASSESSING THE VULNERABILITY TO CLIMATE CHANGE

2.1 Concepts of vulnerability

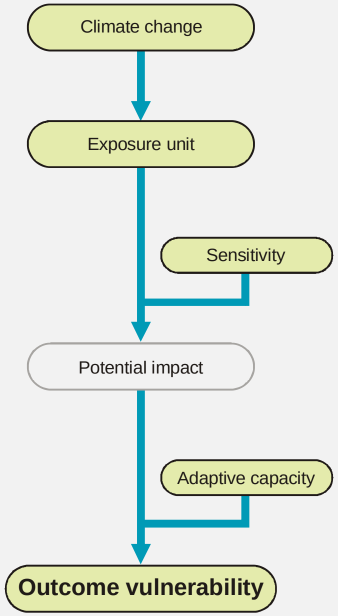
There are alternative frameworks for conceptualising vulnerability to climate change. They have their origins in alternative academic disciplines, and professional fields of practice. The frameworks differ in their unit of analysis (e.g. individual, household or region), methods and language. They are so diverse that it is difficult and controversial to even organise them into a single classification system (various attempts include: Adger 2006, Gallopin 2006, Adger et al. 2007, Adger and Vincent 2005, Alwang et al. 2001, Eakin and Luers 2006, Eriksen and Kelly 2006, Fussel and Klein 2006, D. Nelson et al. 2007, Pelling, 2006, Smit and Skinner 2002, Vincent, 2007). Two attempts at classification that have met with varying success are by Adger and others (notably in Kelly and Adger 2000 and Adger 2006) and further developed by O’Brien et al. (2007). The diversity of conceptual frameworks that have evolved for defining vulnerability reflects that ‘vulnerability is manifest in specific places at specific times’ (Adger, 2006:276). That is, it is context specific, and specific to place, time and the perspective of those assessing it. The context specific nature of vulnerability means that there can be no single, unified or general purpose approach to conceptualising it.

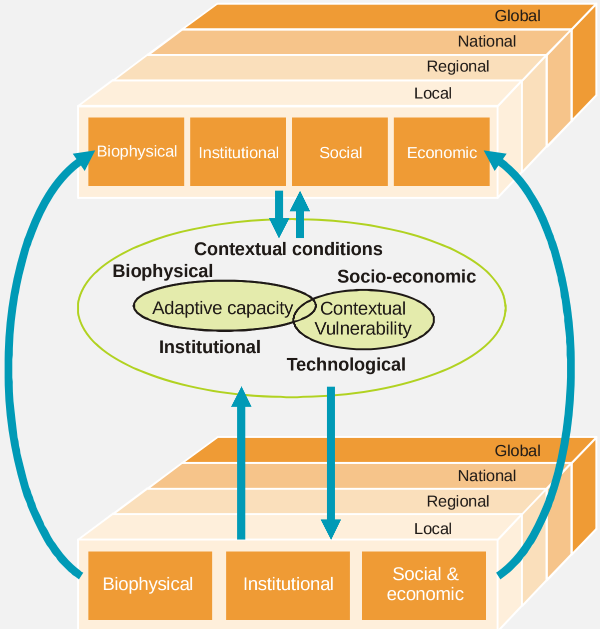
Figure 1 Categories of various approaches to conceptualising vulnerability

Vulnerability approach	Objective
Antecedents	
Vulnerability to famine and food insecurity	Developed to explain vulnerability to famine in the absence of shortages of food or production failures. Described vulnerability as a failure of entitlements and shortage of capabilities.
Vulnerability to hazards	Identification and prediction of vulnerable groups, critical regions through likelihood and consequences of hazard. Application in climate change impacts.
Human ecology	Structural analysis of underlying causes of vulnerability to natural hazards
Pressure and release	Further developed human ecology model to link discrete risks with political economy of resources and normative disaster management and intervention.
Successors	
Vulnerability to climate change and variability	Explaining present social, physical or ecological system vulnerability (primarily) future risks, using wide range of methods and research traditions.
Sustainable livelihoods and vulnerability to poverty	Explains why populations become or stay poor based on analysis of economic factors and social relations.
Vulnerability of social-ecological systems	Explaining the vulnerability of coupled human-environment systems.

Source: Adger, 2006:275

Within this diversity of conceptual frameworks outlined in **Error! Reference source not found.**, several important characteristics consistently emerge. One of these characteristics is the evolution of more integrated systems approaches to measuring vulnerability, evident in Adger's (2006) review of antecedent and successor frameworks. Another characteristic is whether vulnerability is itself the focus of the analysis, or whether it serves as an intermediate step embedded within the process of learning and adaptation. For example, O'Brien et al (2007) suggest the evolution of a continuum of approaches for measuring vulnerability from *outcome* vulnerability to *contextual* vulnerability, broadly consistent with earlier concepts of starting and end-point vulnerability (Kelly and Adger 2000). These two concepts of vulnerability vary in the characteristics attributed to them including: systems of interests; antecedents; concept of climate change; theoretical or disciplinary basis; range of impacts considered; and the type of results provided (**Error! Reference source not found.**).

<table>
<tr><th></th><th>Outcome vulnerability</th><th>Contextual vulnerability</th></tr>
<tr><td>Conceptual frameworks</td><td>

Source: This figure, often attributed to Allen Consulting (2005), is based on much earlier thinking such as that of Holling (1978).</td><td>

Source: Adapted from Smit et al 1999</td></tr>
<tr><td>Systems of interest</td><td>Biophysical, well defined closed systems</td><td>Nature-society, open systems</td></tr>
<tr><td>Antecedent</td><td>Hazard analysis</td><td>Human-security or livelihood interrogation</td></tr>
<tr><td>Construction of climate change</td><td>Problem of human impacts on climate</td><td>Transformative process, which has consequences for society and environment</td></tr>
<tr><td>Theoretical basis</td><td>Physical science</td><td>Social theory and post-positivism</td></tr>
<tr><td>Exogenous impacts</td><td>Single – i.e. climate change</td><td>Multiple – i.e. economy, climate, lifestyles, varying across space and time and scale</td></tr>
<tr><td>Results</td><td>Technologically focused on adaption and mitigation strategies</td><td>Socially focused on increasing current resilience, exploring alternate development pathways, addressing power or equity issues and constraints to respond</td></tr>
</table>

Figure 2 Frameworks for depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability; (b) contextual vulnerability, with indicators of difference

These broad characteristics are useful for identifying the thinking behind specific vulnerability analyses. For example, based on the continuum of O'Brien et al. (2007) the definition of vulnerability used by IPCC (2001) of 'the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, including climate variability and extremes' is an outcome approach. In contrast, D.Nelson et al (2007: 396) define contextual vulnerability: 'as the susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt'.

Alternative concepts of vulnerability are specific to purpose and, as such, are neither better nor worse. For example, addressing the question 'are grain silos vulnerable to predicted climate change given current construction standards?' will be most efficiently addressed by using an outcome-based approach to vulnerability assessment. This is because the physical vulnerability of a silo as a piece of infrastructure may be largely independent of the social, economic or political context. Even in this case, however, the failure of multiple silos is likely to have important social and economic consequences, requiring a contextual approach to vulnerability analysis. This is certainly true of questions like 'what agricultural regions and communities are vulnerable to climate change?' which are entirely dependent on the social, economic and environmental context of each region.

2.2 Vulnerability approaches and methods

The diversity of frameworks for conceptualising vulnerability has resulted in the diversity of methods that have evolved to measure it.
Figure 3 conveys the idea that there are multiple and overlapping ways of measuring vulnerability, regardless of how it is defined. This figure is notional rather than exhaustive. It shows how alternative concepts of vulnerability (from outcome to contextual) support multiple methodological approaches and measurement methods. In general, outcome-oriented vulnerability assessments tend to lean toward reductionist approaches, focusing on a single or well defined group of hazards or drivers of change. This approach works backwards from the hazard relying on the presence of well defined and measurable relationships to explore who and what are likely to be affected, how severe the impacts are likely to be, and what can be done to manage them. In contrast, the contextual approach is constructivist in that it attempts to analyse vulnerability from the perspective of individuals or groups in society. Combining qualitative and quantitative approaches can provide an integrated assessment of the multiple hazards simultaneously faced by these individuals and groups.

As with approaches to conceptualising vulnerability, the appropriate choice of method depends on context. For example, qualitative techniques such as interviews or focus groups are likely to be a very indirect, inefficient and imprecise means of understanding the vulnerability to climate change of a piece of physical infrastructure such as a grain silo. In this case, more direct engineering approaches such as experimental materials testing and structural modelling will be more appropriate. Alternatively, meta-analysis, surveys and landscape readings (Lewis, 1979) are potentially powerful tools for understanding the vulnerability of people living in agricultural regions. This is because multiple interacting psychological, biological and sociological factors in context determine the degree of vulnerability felt.

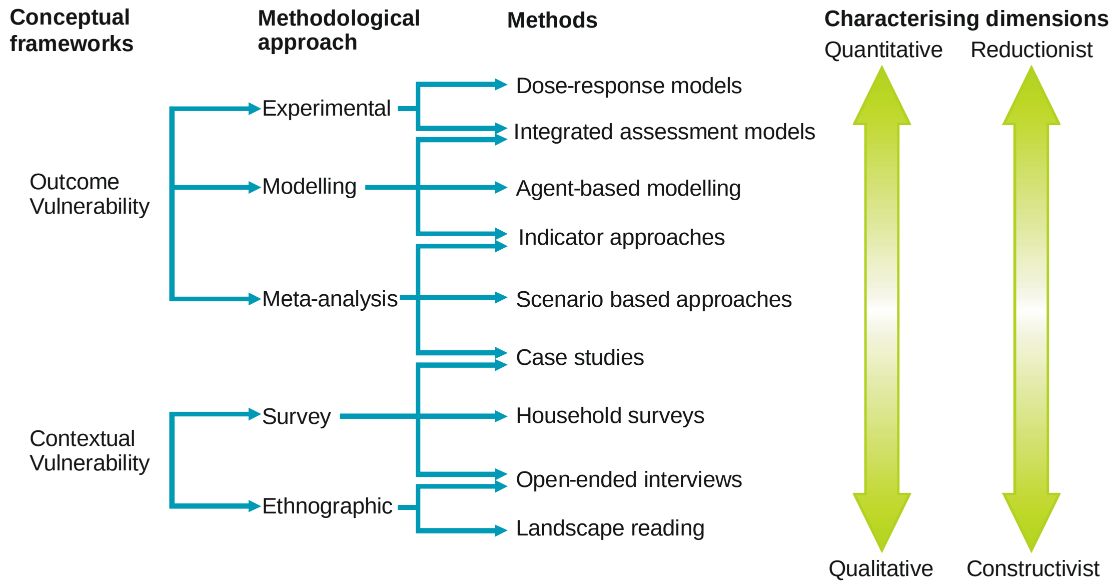


Figure 3 Categorisation of methodologies, methods and characterising dimensions of outcome and context vulnerability

2.3 Vulnerability assessments in Australian agriculture

Research into the vulnerability of Australian agriculture has focused on quantifying the impacts in response to both climate variability and future change explicitly on agricultural productivity. This is a logical first step, and an essential prerequisite for exploring the economic and social implications of these changes. The early progress of this science means that research exploring the potential future economic and social impacts of climate change is embryonic. There are four categories of current research: biophysical productivity changes, economic impacts, industry and community planning, and research into the adaptive capacity of rural communities. The first three of these directly translate into production and economic impacts on agriculture, and are outcome-oriented vulnerability assessments. Research into the adaptive capacity of rural communities tackles the broader concept of contextual vulnerability.

Biophysical productivity – A large number of studies have sought to project changes in the physical productivity of plant and animal growth, yields and physical production, often using agroecological models (e.g. Crimp et al., 2002; 2008 and McKeon et al., 2008). The following two sections of this report attempt to collate the most accessible portions of this research. The methods broadly used are dose-response and experimental or modelling in nature.

Economic impacts – Bioeconomic modelling is used to translate projected future changes in physical productivity into projected changes in economic productivity, farm incomes, land use and regional economic impacts. Work by Kokic et al. (2007) and Nelson et al. (2007) using M-Quantile regression to model the sensitivity of broadacre farm incomes to climate variability is being extended to climate change. Heyhoe et al. (2007) used changes in total factor productivity (as used in Kokic et al., 2006 and Crimp et al., 2008) to model the regional economic impacts of climate change. The

Garnaut report on climate change has applied similar approaches. These methods used are integrated assessment modelling.

Planning – Allen Consulting Group (2005) used a scenario planning approach to conduct a preliminary assessment of Australian agricultural industries to climate change. The methods used were scenario-based approaches and were qualitative.

Adaptive capacity – Nelson et al. (2005) produced a preliminary assessment of the vulnerability of Australian broadacre agriculture to climate variability using rural livelihoods analysis, leading to ongoing research into the adaptive capacity of rural communities (Nelson et al. 2007, forthcoming). The approaches used include survey and modelling.

All studies undertaken to-date in Australia have employed the outcome vulnerability approach and have focused on primarily two methods; modelling (independent or integrated to economic models) and; scenario-based risk assessments. No known work has been undertaken using the contextual vulnerability approach.

3. AVAILABLE MODELS AND CHARACTERISTICS

The origins of this research into vulnerability assessment in Australian agriculture lie in an urgent need to use existing methods to understand the vulnerability of Australian agriculture to climate variability and change. It takes place in the context of rapidly developing science in which it is important to understand the full range of options available to inform policy. An important first step in progressing toward contextual analyses of vulnerability is to understand the availability of research into the likely impacts of climate variability and change on agricultural productivity. This section addresses part of objective two of this project: 'Collate existing and readily accessible literature, data and expert opinion on agricultural productivity changes'. The following section addresses objective two by providing productivity estimates.

To understand the breadth of models used to understand the vulnerability of agriculture to climate variability and change two steps were undertaken:

1. Literature search of known or potential models

2. Workshop with identified experts to assess a range of operational models

3.1 Literature search

The literature search was confined to documented models with a track record of useful application, or a realistic potential for useful application. Over 50 models were identified that have been used in agricultural research applications (Appendix A). The models were collated and assessed using six criteria. Each of these criteria were rated (subjectively by the researchers) for rapid assessment of models that are suitable and available for use in Australian agricultural vulnerability assessments. The criteria included:

1. *Agricultural enterprise*: Climate change can potentially affect all agricultural enterprises but this project's focus was on industries that currently have a key role in Australia's land use and economy. The sectors' significance was determined by their: contribution to employment; number of establishments; and gross value of production. **Error! Reference source not found.** identifies industries including mixed farming (grain-sheep) cattle, sheep, crops, fruit, vegetables and sugarcane as priorities for vulnerability assessment.

Table 1 Ranking of agricultural sector by employment, number of establishments and production

Ranking	Total employment 2000[1]	No. of establishments 2000[1]	Gross value of production 2006[2]
1	Grain-sheep/beef cattle farming	Beef cattle farming	Cattle
2	Grain growing	Grain-sheep/ beef cattle farming	Crops
3	Fruit	Grain growing	Sheep
4	Dairy Cattle	Fruit	Fruit
5	Beef Cattle	Sheep farming	Dairy
6	Sheep farming	Dairy cattle farming	Vegetables
7	Vegetables	Sheep-beef cattle farming	Other livestock
8	Sheep-beef cattle farming	Vegetables	Sugarcane
9	Sugarcane	Sugarcane	

[1] ABS (2001)
[2] ABS (2007)

2. *Scale*: Consideration was given to the most appropriate model scale for assessing the vulnerability of Australian agriculture to climate change. For rapid assessment, a higher rating was given to models that were already capable of operating at a regional scale, rather than point or global scales[1]. Note that while point or higher resolution models can be scaled up, this is not a trivial process and takes time and careful selection of aggregation method. Additionally, global models that operate at very coarse scales may be inadequate for examining the nuances of agricultural systems within Australia.

3. *Operational status*: Currently operational models are more likely to be available for rapid application than those under development or that are no longer supported. As such, higher ratings were given to models known to be operational rather than dormant or not yet applied models.

4. *Accessibility*: Higher rating was given to models that are easy to obtain and use compared to those that are difficult to access and use. However, collaboration could access some complex models, although this is a subjective assessment based on modelling industry knowledge and relationships and not included in assessment.

5. *Validation*: Higher rating was given to models that have been widely validated and tested.

1 Regional scale is considered more appropriate for assessing vulnerability of agricultural activity, as adaptation, mitigation and adaptive capacity occur at regional not point scales.

6. *Data availability*: Higher rating was given to models for which data were readily available, i.e. known or linked data requirements. Therefore, lower ratings were given to models that require very specific and intensive data collection for parameterisation and calibration.

The above six criteria were used to interrogate the known and published models that assess agricultural productivity change to climate variability in Australia. Where relevant, modelers were interviewed to assess each model against these criteria. In total, 31 biophysical models were identified. A subjective assessment of each model's immediate 'potential' for application in Australian agriculture was rated against each of the six criteria. A higher subjective ranking indicated that immediate application to Australia was possible, while a lower ranking indicated that further work on the model was needed before it could be applied in Australia. Models difficult to access, no longer in use and not supported were generally given a lower priority. These literature searches were not exhaustive but captured the models with good potential or that have been in common use in Australia.

The list of models was used to identify workshop participants who apply models or work in related areas. This model information and identifying key agricultural enterprises in Australia helped us to target workshop participants who work in areas where our information was deficient.

Table 2 Shortlisted biophysical agricultural models

MODEL	FOCUS	WHERE APPLIED?	POTENTIAL
APSIM [*Agricultural Production Systems sIMulator]*	Cropping, Beef/sheep, Vegetables, Sugarcane (modules specific to crop type)	Australia	✓
APSFARM [whole farm business simulator)	Cropping	Australia	✓
Oz-Wheat *[crop yield simulation model]*	Wheat	Australia	✓
Crop Syst *[Cropping Systems Simulation Model]*	Cropping (generic crop, parameterisation to define crop)	USA, Europe - some use in Australia	✓
Canegro-DSSAT	Sugarcane	Developed for South Africa	**?**
QCANE *[growth and sugar accumulation in sugarcane]*	Sugarcane	Australia	**?**
AUSSIE GRASS *[Australian Grassland and Rangeland Assessment by Spatial Simulation*]	Beef/sheep	Australia (using appropriate models)	✓
GRASP/CEDAR *[Grass production model]*	Beef/sheep	national but predominantely wet tropics - some temperate	✓
AusFarm *[Farm management model inc. GrassGro-DSS, GrazPlan, GrazFeed]*	Beef/sheep	Australia	✓
GrassGro *[DSS fror mgt of grazing systems]*	Beef/sheep	temperate southern Australia (high rainfall and Mediterranean zone)	✓
IMAGES *[pasture/herbage production model]*	Beef/sheep	Australian chenopod, tussock grassland, shrublands	**?**

MODEL	FOCUS	WHERE APPLIED?	POTENTIAL
ARIDGROW *[pasture/herbage production model]*	Beef/sheep	Arid & semi- arid Australia	**?**
SEESAW *[Simulation of the Ecology and Economics of the Semi Arid Woodlands]*	Beef/sheep	Semi-arid Southern Australia	**X**
FLOW *[Forage FLOW in arid rangelands]*	Beef/sheep	Australian rangelands	**X**
DYNAMOF *[pasture/herbage production model]*	Beef/sheep	Annual and perennial pastures in Northern and Western Victoria	**X**
PGAP *[Pasture Growth and Animal Production]*	Beef/sheep	Western Australia	**?**
WCMOD *[White Clover MODel]*	Beef/sheep		**X**
SGS *[Sustainable Grazing Systems pasture model]*	Beef/sheep, dairy?	Southern Australia?	**?**
RANGEPAK *[DSS for the management of extensive grazing systems)*	Beef/sheep	Arid Australia	**X**
RISKHERD (economic/policy?)	Beef/sheep	Arid Australia	**X**
INSIGHT *[System model for catchment management]*	Beef/sheep, Cropping, Ecological (economic/social/biop hysical)	Lachlan catchment	**X**
GROWEST (& Plus) *[plant growth index simulation model]*	Beef/sheep, Cropping	Australia	**?**
DairyMod *[Dairy Model - linked SGS?]*	Dairy	Irrigation areas Australia	**?**
Plantgro *[Plant growth model]*	Forestry and Horticulture	not regionally specific - measure of plant suitability	✓
APPLE *[Bioeconomic model of an apple orchard]*	Horticulture - apple	tested Qld (Stanthorpe)	**?**
TOMSIM *[TOMato SIMulation]*	Horticulture (glasshouse tomato)	Netherlands	**?**
SAVANNA *[Landscape and Regional Ecosystem Model]*	Ecological (beef/sheep?)	Africa, US, Northern Australia	✓
TREEGRASS *[plant interactions in tree–grass ecosystems*	Ecological	Lamto, Ivory Coast	✓
FLAMES *[Fire model for savannas]*	Ecological	Australian Savanna	✓
LANDIS *[Forest Landscape Disturbance and Succession Model]*	Landscape Ecology	Africa	**?**
CENTURY *[model of carbon and nutrient dynamics]*	Ecosystem	Global and regions worldwide	✓

✓= good potential, rates highly on most or all criteria
? = may have potential but information insufficient to determine more definitively
✕ = Not a high priority for use

3.2 Workshop

The aim of the workshop was to examine future research priorities in understanding the impact of climate change on agricultural productivity by comparing existing research against emerging policy demands (see Appendix B for workshop feedback). A critical part of the workshop was to augment the model list developed through the literature review with additional models and applications. The workshop identified additional models and approaches used or with potential for application to climate change work, these include:

- RangeASSESS: rangeland model used to look at changes in soil carbon
- Steer physiology model: not currently used for climate change work but with the potential to explore impacts of heat stress
- State-contingent model: social/economic model looking at land and water allocation. Further application of this approach is possible.
- THI: Temperature and Humidity Index used to look at milk losses due to changes in heat stress with climate change.
- Vine logic: modified Homocline method used for climate change research in the southern grape growing region.
- Phenological rules: exploration of the change in harvest dates for lettuce and sweet corn by linking phenological rules with APSIM simulation.
- Potato model: could be expanded to investigate climate change impacts and changes in yield.
- Consultant spreadsheets: whole farm spreadsheets have been used for climate change research now, so they could have a role

The workshop focused on the application of these models and the resultant estimates in productivity, as outlined in the following section.

4. AVAILABLE DATA ON PRODUCTIVITY CHANGES

This section addresses part of objective two of this project: 'Collate existing and readily accessible literature, data and expert opinion on agricultural productivity changes'.

Various studies in Australia have estimated the change in agricultural productivity due to climate variability and change. The interpretation of collated literature, data and opinion is a value-laden activity, and can only be resolved against the purposes of specific applications. Depending on the question or issue to be addressed, some of the collated material will be more relevant. We have endeavoured to provide references to the known accessible literature, data and expert opinion and leave the interpretation to those that use the data in future studies.

The literature and workshop activities revealed that considerable research has been undertaken to understand and quantify the broad scale impacts of climate change for both cropping and pasture productivity across Australia. In research terms, modelling the potential impacts of climate change on dryland cropping is more advanced than pasture-related enterprises. Considerably less research and capability are available to understand, model and hence quantify the potential impacts of climate change on the grazing, dairy, viticulture, horticulture industries. Simple historical analogues or 'expert' opinion is, in many instances, the basis for estimates of productivity impacts.

While climate change studies are available for cropping and pasture-related industries at a national scale, capabilities and understanding vary regionally. In terms of native pastures, impacts of climate change are well understood for tropical and sub-tropical areas. However, less is know about the potential impacts on temperate and improved pastures. The opposite is true for modelling the impacts of climate change on crops. A better understanding of likely impacts is available for winter cropping systems as opposed to summer cropping systems.

Understanding of the impacts of climate change on viticulture and horticulture was far more fragmented and regionalised than for cropping and pasture-related industries with very limited operational modelling capability for these.

Table 3 Summary of agricultural productivity knowledge by activity

Agricultural activity		Location	Description	Source references
Cropping	Winter crops	Wheat at national scale	Modelled yield estimates from process and empirical models available for wheat at national and regional scales. No estimates for other crops.	Crimp (2008); Potgeiter et al., (2008);Luo et al., (2007)
	Summer crops	Sorghum at specific sites.	Limited modelled yield estimates at shire scale for sorghum, no estimates for other crops.	Potgeiter et al., (2008)
	Sugar	Queensland	Limited modelled yield estimates available for several sites in S.E. Qld and Mossman but not NSW. Vulnerability to climate change has been assessed in Maryborough specifically. Many other regions and associated supply chains still need specific assessment with modelling capability.	McDonald et al., (2006) and Park (2008)
Horticulture	Fruit & vegetables	Specific crops at specific locations	Mainly expert opinion used, but limited modelled estimates available for: (i) changes in harvest date with climate change for lettuce and sweet corn for three locations in Australia; (ii) macadamia nut yield in response to rainfall changes in existing macadamia production regions, (iii) potato, but no production estimates available with climate change.	Deuter (2008); Deuter et al., (2008)
Livestock	Extensive grazing	National	Modelled yield estimates available for Australia and particularly rangeland systems from process and empirical models. There are several pasture models in use but most estimates have been generated using GRASP. Some old modelling work available looking at the impact on beef yield of pests with climate change.	Crimp et al., (2002), McKeon et al., (2008); Carter and Stone (2006); White et al., (2003)
	Feedlots	Not investigated		
	Pigs	Not investigated		
	Poultry	Not investigated		
Viticulture	Grapes	Southern grape growing region	No process model currently in use besides simple empirical models.	Webb et al., (2007a,b)
	Wine			
Irrigated agriculture	Cotton	Central Queensland	Modelled yield estimates and collated expert opinion and site specific modelling of the impact of pest and disease with climate change	DeVoil et al., (2006); McCray et al., (2007)
	Rice			
	Dairy	Victoria and NSW	Limited estimates of milk and pasture yield with CO_2 changes available for temperate pasture regions (Victoria and NSW). Changes in milk production due to heat stress estimated for the Hunter valley in NSW	Cullen et al., (2007); Jones and Hennessy (2000)

5. WHAT IS DONE IN AUSTRALIA AND WHERE TO FROM HERE?

This report has briefly reviewed alternative approaches for conceptualising and assessing the vulnerability of Australia's agricultural sector to climate variability and change. This provides a useful context for analysing the strengths and limitations of current approaches, and identifying necessary directions for future research.

5.1 Current state of play for vulnerability assessments in agriculture

Research into the vulnerability of Australian agriculture to climate change is at an early stage of development. So far, most of the research has focused on biophysical productivity, and its sensitivity to changes in climate. Most of the models used to analyse vulnerability have followed linear dose-response logic, focus on biophysical processes and are limited in their integration with contextual issues. These models are linear in the sense that they have limited capacity to model mitigation and adaptation options. They tend to predict the future as predetermined by current activities and choices rather than as dynamically evolving through a continuous series of choices. There have been some initial attempts to integrate biophysical and economic models to predict the economic impacts of climate change on farm incomes and regional economies. Most of this model-based research has focused on broadacre agriculture, and few studies have covered other industries across Australia. Most models are 'run' for specific climate variability scenarios, meaning little comparable analysis between models and modelling outputs. Outcome vulnerability is the implicit framework used for this research.

An outcome approach to analysing vulnerability is best suited to well defined, closed-system problems. It has its roots in early approaches to hazards analysis; usually results of this type of vulnerability assessment are around technologically focused adaption and mitigation strategies. These types of vulnerability assessment are particularly useful for operationalising the IPCC's definition of vulnerability to climate change: 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes' (IPCC 2001). This approach has the advantage of using currently available modelling systems to provide immediate insights into the likely impact of climate change in systems, such as broadacre cropping in Australia, that have already been studied in detail over many years. The outcome-vulnerability approaches constrain policy questions to: 'what is the vulnerability of current systems if current management and policy continues?'

The risk of accepting current methods as the only and best way to analyse vulnerability means some of its critical dimensions could be overlooked; dimensions that alternative perspectives and methods could inform. Very little work in Australia is on understanding the dimensions of contextual vulnerability that are essential to the resilience of rural communities. The agricultural sector involves a dynamic interaction between ecological, industrial and social processes. It is subject to multiple interacting drivers, including climate change, market forces and threats to the natural resource base. Consequently, the ultimate focus of vulnerability research needs to be on the socioeconomic outcomes of these dynamic interactions, including conservation, production and livelihood options. These have not previously been considered in particular regions and industries. This would operationalise a completely different construct of vulnerability to that currently dominating research: 'vulnerability as the susceptibility of a system to disturbances determined by exposure to perturbations, sensitivity to perturbations, and the capacity to adapt' (D.Nelson et al 2007; 396).

Embracing a more complete understanding of vulnerability beyond linear impact modelling has potential to reveal new and innovative mitigation and adaptation options. However, the evolution of these options is likely to depend on employing more integrated and holistic methods for operationalising contextual concepts of vulnerability. This means embedding vulnerability science into dynamic social processes which characterise mitigation or adaption to climate change. This has potential to reframe the kind of policy questions that it can support to 'how could Australian rural communities currently dependent on agriculture reorganise their farming and livelihood opportunities to mitigate and adapt to the impacts of climate change?'

5.2 Future research

There are two specific areas of research that need to be undertaken: short term—building on existing models, tools and approaches; and long term—exploring new approaches and tools.

Building on current approaches

Some overall gaps in the current approaches include:

- Expanding productivity and adaptation modelling beyond broadacre cropping and livestock, to industries such as horticulture, viticulture, and dairy
- Including regional gaps in productivity estimates for southern Western Australian grazing and cropping systems and temperate dairy and pasture.
- Considering the economic or social requirements and impacts of land-use change, which includes the ability to shift between land uses (i.e. substitution)

Gaps in current biophysical models include:

- Understanding thresholds of change that influence productivity of single crops or species, as these thresholds or 'tipping points' could be critical in managing current industry investment in certain land-use options (i.e. rainfall, temperature)
- Considering CO_2, changes in growing season, management impact, changes in burning frequency, diseases, pests and parasite impacts on production
- Coupling feedback loops between production and underlying natural assets (i.e. soil, water etc.)
- Incorporating effectively Global Climate Model (GCM) models into current biophysical and economic models

Gaps were also identified in current integrated models, including:

- Understanding interactions between natural resource condition, farming system productivity and management practice
- Understanding the impact of management change (both tactical and strategic) and other drivers of change e.g. carbon trading on land use and productivity
- Understanding and investigating resilience and transformation of farming systems (i.e. what are the 'marginal thresholds' in horticultural systems and how can we manage them?)
- Linking biophysical to social-economic systems to understand impacts of changes elsewhere in the supply chain, e.g. stranded assets—when elements of the supply chain become redundant in response to climate change (processing plants).=
- Dynamic modelling of mitigation and adaptation responses at all scales from management within farming systems, to industry investment and policy.

Some overall gaps were identified within the current research paradigm, including:

- Expanding the scale of models to a land-use perspective; to deal with mixed farming systems and mixed farming regions, accounting for changes to crop species and alternative land uses, (this must recognise that land use changes are driven by changes in economic productivity and profitability)
- Incorporating multiple drivers (apart from climate change) into climate change assessments e.g. demographic changes, 'strong/resilient regions' and 'food miles'
- Coupling models together to address both multiple-scale and land-use outcomes
- Assessing climate variability on decadal or multi-decal timescale, rather than current modelling, which focus on marginal daily time steps (consider a risk-based approach rather than the current modelling approach)
- Making models 'open source' which should then drive research and model development

Exploring new strategic research into vulnerability of agriculture

This review was focused on current modelling approaches to vulnerability, and as such, it did not fully explore all other possible approaches to vulnerability assessments, particularly those based on contextual conceptual frameworks. As such, our recommendations are more generic in this space due to our focus on current capabilities and models. Importantly, our finding was that there was so little work available on contextual assessments of climate variability and change in Australian agriculture that strategic investment into contextual vulnerability research is necessary for policy makers in the future to have the right information to address challenging issues. Areas of future research could include:

- Limiting investment in context-free vulnerability assessments. Vulnerability is experienced by *specific* groups of people in *specific* contexts. Embedding the science of vulnerability assessment in context is the only way to inform practical action by clearly defined industries and social groups.

- Creating a contextual vulnerability research agenda by embedding current linear response modelling into the decision making and policy processes that lead to mitigation and adaptation actions.
- Building multidisciplinary and cross-institutional teams in which social scientists, economists and biophysical scientists work together to understand the processes and governance of change, through various drivers, e.g. climate change, globalisation, resource scarcity.

REFERENCES

ABS, (2001), *Agriculture 1999-2000*, 7113.0

ABS, (2007), *Value of principle agricultural commodities produced*, 2005-06, 7501.0

Adamson, D. Mallawaarachchi, T. and Quiggin, J. (2007), 'Water use and salinity in the Murray-Darling Basin: A state-contingent model, Australian Journal of Agricultural and Resource Economics' in *Journal of Agricultural and Resource Economics*, vol. 51, no.3, pp. 263–83.

Adger, W., (2006), 'Vulnerability' in *Global Environmental Change*, 16:268-281.

Adger, W.N., Agrawala, S., Mirza, M., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B. and Takahashi, K., (2007), 'Assessment of adaptation practices, options, constraints and capacity', *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, UK, pp. 717-743.

Adger, W. and Vincent, K. (2005), 'Uncertainty in adaptive capacity', in *Comptes Rendus Geoscience*, 337:399-410.

Allen Consulting (2005), *Climate Change Risk and Vulnerability: Promoting an efficient adaptation response in Australia*, report to AGO, Department of Environment and heritage, Australia.

Alwang, J., Siegel, P. and Jorgensen, S. (2001), Vulnerability: a view from different disciplines. Social Protection Discussion Paper Series No. 0115, The World Bank, Washington.

Asseng, S., A. Drayb, P. Perezb,c and X. Sua (forthcoming), 'Human-Landscape Interactions in a Salinity-Prone Agricultural Region of the Western Australian Wheat-Belt'. in *Ecological Modelling*.

Bange, M., McRae, D. and Roth, G. (2007), 'Cotton' in *An overview of climate change adaptation in Australian primary industries – impacts, options and priorities*. Report prepared for the National Climate Change Research Strategy for Primary Industries, February 2008.

Botterill, L. (2005), 'Late twentieth century approaches to living with uncertainty: the national drought policy', in L.C. Botterill and D. Wilhite (Eds.) *From disaster response to risk management: Australia's national drought policy*, Springer, Dordrecht, pp. 51-64.

Chilcott, C. R., Dalal, R. C., Parton, W. J., Carter, J. O. and King, A. J. (2007), 'Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. IX. Simulation of soil carbon and nitrogen pools using CENTURY model', in *Australian Journal of Soil Research*, 45 (3), pp. 206-217.

Crimp, S.J., Flood, N.R., Carter, J.O., Conroy, J.P., and McKeon, G.M. (2002), *Evaluation of the Potential Impacts of Climate Change on Native Pasture Production – Implications for livestock carrying capacity*. Australian Greenhouse Office, Canberra. p. 54.

Crimp, S. Howden, M., Power, B., Wang, E., and De Voi, P. (2008), *Global Climate Change impacts on Australia's Wheat Crops*. Report prepared for the Garnaut Climate Change Review Secretariat, March 2008, p. 16.

Crimp, S.J., McKeon, G., Flood, N., Kokic, P., Carter, J., Nelson, R., Stone G. (2008), *Assessing the vulnerability of Australian Agriculture to Climate Change: Developing appropriate methods for examining both impacts and adaptation*. CAF Discussion Paper 12.

Cullen B.R., Eckard R.J., Johnson I.R., Bryant J.R., Rawnsley R.P. (2007), Strategies for increasing resilience of grazing-based dairy systems. In: Chapman DF, Clark DA, MacMillan KL, Nation D (eds.) *Meeting the challenges of pasture-based dairying*. Melbourne, National Dairy Alliance, pp. 541-547.

DAFF (2006) *National Agriculture And Climate Change Action Plan 2006-2009*. Department of Agriculture, Fisheries and Forestry, Canberra.

Deuter, P. (2008), *Defining the Impacts of Climate Change on Horticulture in Australia*. A Report Prepared for the Garnaut Climate Change Review Secretariat, March 2008, p. 18.

Deuter, P. Park, S., White, N. (2008), The development of adaptation strategies for the most vulnerable horticultural regions in Australia. Horticulture Australia report Project Number: AH06019.

Eckard R.J., Dalley D., Crawford M. (2000), Impacts of Potential Management Changes on Greenhouse Gas Emissions and Sequestration from Dairy Production Systems in Australia. In: Keenan R., Bugg A.L. and Ainslie H. (eds), 'Management Options for Carbon Sequestration in Forest, Agricultural and Rangeland Ecosystems'. *Workshop Proceedings, CRC for Greenhouse Accounting*, 25 May 2000, ANU, Canberra. pp. 58-72.

Eckard R.J. (2006), *Greenhouse Gas Emissions and the Australian Red Meat Industry*, Report to Meat and Livestock Australia, March 2006.

Eriksen, S. and Kelly, P. (2006), 'Developing credible vulnerability indicators for climate adaptation policy assessment' in *Mitigation and Adaptation for Strategies for Global Change*, 12, pp. 495-524.

Eakin, H. and Luers, A., (2006), 'Assessing the vulnerability of social-environment systems' in *Annual Review of Environment and Resources*, 31: pp. 365-394.

deVoil, P., Rossing, W. A. H., & Hammer, G. L. (2006), 'Exploring profit - sustainability trade-offs in cropping systems using evolutionary algorithms.' In *Environmental Modelling and Software,* 21(9), pp. 1368-1374.

Fussel, H. and Klein, R. (2006), 'Climate change vulnerability assessments: an evolution of conceptual thinking'. In *Climate Change,* 75: pp. 301-329.

Gallopin, G. (2006), 'Linkages between vulnerability, resilience, and adaptive capacity.' in *Global Environmental Change* 16: pp. 293-303.

Hall, W.B., Carter, J.O., Day, K.A. and McKeon, G.M. (1998a), 'Chapter 2: Models for simulating climate change impacts on native pasture and animal production in northern Australia.' in McKeon, G.M., Carter, J.O., Day, K.A., Hall, W.B. and Howden, S.M.*Evaluation of the impact of climate change in northern Australian grazing industries.* Final report on DAQ139A to RIRDC, pp. 78-112.

Hall, W.B., McKeon, G.M., Carter, J.O. and Day, K.A., Howden, S.M., Scanlan, J.C., Johnston, P.W. and Burrows, W.H. (1998b), 'Climate Change and Queensland's grazing lands: II. An assessment of the impact on animal production from native pastures', in *The Rangeland Journal*. 20: pp. 177-205

Hacker, R.B., Wang, K.M., Richmond, G.S. and Lindner, R.K. (1991), 'IMAGES: An integrated model of an arid grazing ecological system.' in *Agricultural Systems* 37, pp. 119-163.

Hackett, C. and Sands, P. (1979), 'A model of potato development and bulking as an aid to economic decision making'. Acta Hort. (ISHS) 97:397-398. http://www.actahort.org/books/97/97_41.htm

Hackett, C., (1991), PLANTGRO: A software package for coarse prediction of plant growth. CSIRO, Melbourne (Version 1).

Hackett, C., (1996b), INFER: An expert system for estimating the environmental relationships of plants from the conditions they experience, Version 2.3. (Available from the author).

Harris, G. and Hackett, C., (1996), PLANTGRO: A software package for prediction of plant growth. Version 2.1 (Available from Office of Research and International Projects, Griffith University, Nathan Qld 4111, Australia).

Hayman, P., Howden, M. and Nidumolu, U. (2007), 'Climate change and Goyder's Line of reliable rainfall –climate science projections and people's perceptions', In *Proceedings of Greenhouse 2007*, 2-5 October, 2007. Sydney.

Hayman, P., Rebbeck, M., and Bellotti B. (2008), *Managing the Risk of Climate Change in the SE Region*. Report prepared for the ARC Linkage Grant, June 2008.

Hill, M.J., Roxburgh, S.H., McKeon, G.M., Carter, J.O., Barrett, D.J. (2006), 'Analysis of soil carbon outcomes from interaction between climate and grazing pressure in Australian rangelands using Range-ASSESS,' in *Environmental Modelling and Software.* 21(6) pp. 779-801.

Hodges, A., and Goesch, T. (2006), 'Australian Farms: Natural Resource Management in 2004-05.' *ABARE Research Report 06.12*. Australian Bureau of Agricultural and Resource Economics, Canberra.

Holling, C. S. (1978), *Adaptive environmental assessment and management,* John Wiley, New York, New York, USA.

Howden, S.M., McKeon, G.M., Scanlan, J.C., Carter, J.O. and White, D.H. (1993), 'Changing stocking rates and burning management to reduce greenhouse gas emissions from northern Australian grasslands', XVII International Grassland Congress Palmerston North, New Zealand, pp. 1203-5.

Howden, S.M. and Jones, R.N. (2001), *Costs and benefits of CO_2 increase and climate change on the Australian wheat industry* Report to the Australian Greenhouse Office, p 25.

Howden, S.M., McKeon, G.M., Meinke, H., Entel, M. and Flood, N. (2001), 'Impacts of climate change and climate variability on the competitiveness of wheat and beef cattle production in Emerald, north-east Australia' in *Environment International*, 27: pp. 155-160.

IPCC, (2001), *Third Assessment Report*, TS12.

Jones, R. N., and Hennessy, K. J. (2000), *Climate change impacts in the Hunter Valley: a risk assessment of heat stress affecting dairy cattle*, Aspendale: CSIRO Atmospheric Research. iii, p. 22.

Jones, R. N., and Page, C. M. (2001). 'Assessing the risk of climate change on the water resources of the Macquarie River catchment' in MODSIM 2001: International Congress on Modelling and Simulation: proceedings, Australian National University, F. Ghassemi, and others (eds.), Canberra, ACT: Modelling and Simulation Society of Australia and New Zealand. pp. 673-678.

Jones, R. N. (2005), Water resources case study: the Murray-Darling Basin in Australia, in I. Burton, and E. Spanger-Siegfried (eds.) *Adaptation policy frameworks for climate change: developing strategies, policies, and measures*,, Cambridge: Cambridge University Press, pp. 241-244.

Jones, R. N., Chiew, F. H. S., Boughton, W. C., and Zhang, L. (2006), 'Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models', in *Advances in Water Resources*, 29 (10): pp. 1419-1429.

Kirono, D. G. C., Podger, G., Page, C. M., and Jones, R. N. (2006), *Assessment of the impacts of climate change on water supplies*, a consultancy report prepared for Rous Water Regional Water Supply New South Wales Department of Commerce, Aspendale: CSIRO Marine and Atmospheric Research, p. 57..

Kirschbaum, M. U. F., Harms, B., Mathers, N. J. and Dalal, R. C. (2008), 'Soil carbon and nitrogen changes after clearing mulga (Acacia aneura) vegetation in Queensland, Australia: observations, simulations and scenario analysis', in *Soil Biology & Biochemistry*, 40 (2), pp. 392-405.

Lewis, P.F. (1979), 'Axioms for Reading the Landscape: Some Guides to the American Scene', in (ed.) D. W. Meinig *The Interpretation of Ordinary Landscapes: Geographical Essays*, , Oxford University Press: pp. 11-32.

Liedloff, A.C., Cook, G.D. (2007), 'Modelling the effects of rainfall variability and fire on tree populations in an Australian tropical savanna with the Flames simulation model', in *Ecological Modelling*, 201 (2007), pp. 269–282.

Luo, Y., Su, B., Currie, W.S. et al. (2004), 'Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide' in *Bioscience*, 54: pp. 731-739.

Luo, Q., Jones, R.N., Williams, M., Bryan, B. and Bellotti, W. (2005), 'Probabilistic distributions of regional climate change and the application in risk analysis of wheat production', in *Climate Research*, 29, pp. 41-52.

Mallawaarachchi, T., Yainshet, A., Adamson, D., Hone, S., Oliver, M, Kokic, P., Quiggin, J. and Gooday, P. (2007), *Reduced water availability: Impacts on agricultural activities and regional economies in the Murray Darling Basin, ABARE* unpublished client report for the Murray-Darling Commission November 2007.

McRea D., Roth G., Bange M. (2007), *Climate Change in Cotton Catchment Communities A Scoping Stud. Cotton Catchment Communities Cooperative Research Centre*, Report for the Australian Greenhouse Office.

McDonald, G., Park, S. Antony, G., Thorburn, P., Dawson, S. and Harmon, B. (2006), *Future Use of Sunshine Coast Cane Landscapes*, St Lucia. CSIRO Sustainable Ecosystems.

McKeon, G.M., Howden, S.M., Silburn, D.M., Carter, J.O., Clewett, J.F., Hammer, G.L., Johnston, P.W., Lloyd, P.L., Mott, J.J., Walker, B., Weston, E.J. and Willcocks, J.R. (1988), 'The effect of Climate Change on Crop and Pastoral Production in Queensland', in Pearman, G.I. (ed.), *Greenhouse, Planning for Climate Change*. CSIRO Division of Atmospheric Physics, Melbourne. pp. 546-63.

McKeon, G.M., Charles, S.P., Bates, B.C. and Hall, W.B. (1998), 'Chapter 3: Methods for evaluating climate change impacts on pasture growth' in McKeon, G.M., Carter, J.O., Day, K.A., Hall, W.B. and Howden, S.M. *Evaluation of the impact of climate change in northern Australian grazing industries*, Final report on DAQ139A to RIRDC, pp. 113-140.

Moore, A. D., Donnelly, J. R. and Freer, M. (1997), 'GRAZPLAN: Decision Support Systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS' in *Agricultural Systems*, 55(4), pp. 535-582.

Moore, J., (1998), *Tree-grass Modelling Workshop*, NCEAS, Santa Barbara, 10th - 13th May 1998, viewed on Nov, 2008, at: http://www.nceas.ucsb.edu/nceas-web/projects/2062/report1/

Nelson, D., Adger, W. and Brown, K. (2007), 'Adaptation to environmental change: contributions of a resilience framework', in *Annual Review of Environment and Resources* 32: pp. 395-419.

Nelson, R. Kokic, P., Elliston, L. and King, J. (2005), 'Structural adjustment: a vulnerability index for Australian broadacre agriculture', in *Australian Commodities* 12(1): pp. 171-179.

Nelson, R. Kokic, P., Crimp, S., Howden, M., Devoil, P., Meinke, H., McKeon, G. and Nidumolu, U. (forthcoming) 'A preliminary assessment of the vulnerability of Australian agricultural communities to climate variability and change'.

Nidumolu, N. (2007), *Regional bio-economic modelling of dairy sector in a unique island setting: A case of Ile de La Reunion*, Report on the EU Marie Curie 'MODLAIT' project at CIRAD EMVT- Pole Elevage, Saint Pierre, La Réunion 2005-2007, p. 120.

O'Brien, K., Eriksen, S., Nygaard, L., Schldojen, A. (2007), 'Why different interpretations matter in climate change discourses', in *Climate Policy*, 7: pp. 73-88.

Park, S.E. (2008), 'A review of climate change impact and adaptation assessments on the Australian sugarcane industry', *Proceedings of the Australian Society of Sugar Cane Technologists*, 30, pp. 1-9.

Pearson, L., McDonald, G., Park, S., Antony, G., Thorburn, P., Dawson, S., Harmen, B., Heyenga, S. and Horan, H (2007), *Future Use of South East Queensland Cane Landscapes*: Technical Report. St Lucia. CSIRO Sustainable Ecosystems.

Pelling, M. (2006), *Measuring Urban Vulnerability to Natural Disaster Risk: Benchmarks for Sustainability*, Open House International, 31(1): pp. 125-132.

Preston, B. L., and Jones, R. N. (2008), 'Evaluating sources of uncertainty in Australian runoff projections', in *Advances in Water Resources*, 31 (5): pp. 758-775.

Potgieter, A., Doherty, A., Crimp, S., Rodriquez, D., Hammer, G., Meinke, H., Fearweather, H. (2008), 'Examining the likely climate change impacts and adaptation options available to Australian Cereal Crops using the Shire Scale wheat model', Australian Agronomy Conference Adelaide September 2008.

Rodriguez, D., DeVoil, P., Cox, H., Chudleigh, F., Conway, M. and Routley, R. (2006), 'APSFARM: A whole farm systems analysis of economic and environmental indicators of contrasting farm business strategies in Central Queensland', *Proceedings 13th of the Australian Agronomy Conference, at http://www.regional.org.au/au/asa/2006/index.htm.*.

Rogiers, S.Y., Greer, D., Hutton, R., Somers, T., Hutchinson, P. (2006), ‘Managing Semillons susceptibility to heat and drought’ in *Australian and New Zealand GrapeGrower and Winemaker* 515: pp. 24-26.

Schrobback, P., Adamson, D., Quiggin, J. (2008), ‘The options for salinity mitigation in the Murray-Darling Basin’, 52nd Annual Conference of the Australian Agricultural and Resource Economics Society, Canberra, Australia, 5-8 February 2008.

Stephenson, R.A. and Mayer, D.G. ‘Forecasting the Australian macadamia crop’, Proceedings of the NZIAHS/ASHS Conference, August 2007.

Stokes, C., and Howden, M. (2007), *An overview of climate change adaptation in Australian primary industries – impacts, options and priorities*, Report prepared for the National Climate Change Research Strategy for Primary Industries, February 2008.

Simioni, G., Le Roux, X., Gignoux, J., Sinoquet, H. (2000), ‘Treegrass: a 3D, process-based model for simulating plant interactions in tree–grass ecosystems’ in *Ecological Modelling* 131, pp. 47–63.

Sinclair, K. (2007), Seasonal climate forecasts to improve dairy farmers' feedbase management (DAN20) (June 2004 - May 2007).

Smit, B. and Skinner, M. (2002), ‘Adaptation options in agriculture to climate change: a typology’, In *Mitigation and Adaptation for Strategies for Global Change*, 7: pp. 85-114.

Smit, B., Burton, I., Klein, R.J.T. and Street R. (1999), ‘The Science of Adaptation: a framework for assessment’, in *Mitigation and Adaptation Strategies for Global Change* 4(3-4), pp. 199-213.

Vincent, K. (2007), Uncertainty in adaptive capacity and the importance of scale, in *Global Environmental Change* 17: pp. 12-24.

Watson, I. (1999), IMAGES: Simulation for the AussieGRASS project, Boolathana grazing trial 1983-1993. Agriculture Western Australia.

Webb L., Barlow E.W.R., Whetton P. (2007a), ‘Climate change raises the heat on wineries’ in *Australasian Science* 28: pp. 20-22.

Webb L., Whetton P., Barlow E.W.R. (2007b), ‘Modelled impact of future climate change on phenology of wine grapes in Australia’, In *Australian Journal of Grape and Wine Research* 13: pp. 165-175.

APPENDIX A – AUSTRALIAN PRODUCTIVITY ESTIMATES UNDER CLIMATE CHANGE

Table 4 Sugar and cotton productivity models and estimates

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Sugar yield impacts	APSIM	Queensland northern, central and southern coasts	Biophysical	Yes	Validated against historical yields in Mossman; Maryborough; Maroochy and Rocky Point	daily climate data, accurate soils characterisation, accurate management	2030, 2050, 2070 using both low (B1) and high (A1FI) emission scenarios, daily climate files scaled using monthly GCM change anomalies value chain context quantifying adaptation and planting strategies	Estimates of yield changes in regions: Mossman, Maroochy, Rocky Point, Maryborough, QLD	McDonald et al., 2006; Pearson et al., 2007; and Park, 2008.
Cotton yield impacts	APSFarm	Central Queensland	whole farm system, exploring economic and environmental tradeoffs	Yes	Validated against historical yields in this region	daily climate data, accurate soils characterisation, accurate management	No climate change applications yet, but optimisation procedure looking at options for adaptation. Runs made for a hypothetical 'climate change' scenario using wet and dry deciles for alternative farm enterprises i.e. irrigated and rain-fed wheat, irrigated cotton, and irrigated maize for a cotton farm at Wee Waa, NSW.	Assuming that over 10 years, 7 seasons range between dry and average and 3 seasons between average and wet, the resulting NPV ($) would be negative in 26% of the cases. Meaning there is a 26% probability that the project would be unviable. Assuming that over 10 years, 3 seasons range between dry and average; and 7 seasons between average and wet, the NPV ($) would be negative in only 4% of the cases. This means there is a 4% probability that the project would be unviable.	DeVoil et al., 2006
Cotton Yield impacts	Expert opinion - David McRae generated via QLD workshops	Central QLD	Biophysical - participatory approach	No				Cotton yield impacts	Stokes and Howden 2007; Bange et al., 2007
Change in cotton yield due to the impact of Heliothis	AUSFARM		Biophysical, optimisation of management strategies					temperature not an issue but water and disease more problematic	McRae et al., 2007

Table 5 Dryland grazing productivity models and estimates

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in pasture productivity (also livestock carrying capacity, animal production (beef and wool), other components of the grazing system, e.g. runoff, soil loss, frequency of burning, drought risk)	GRASP	Northern Australia and rangelands	Biophysical	Yes (Only available to trained pasture scientists)	The model has been parameterised from a wide range of field data, including pasture growth studies and grazing trials. The output of the model has been compared to grazier estimates of safe carrying capacity to develop models of whole property livestock carrying capacity (Johnston et al. 1996). The model has been used to analyse the variability in livestock carrying capacity at a Statistical Division scale (Crimp et al. 2002). Validated against 0.5 million observations	Parameter files are available for different locations across Australia, as well as average parameter sets that can be used at larger scales. Trained pasture scientists can also carry out simulation experiments for themselves.	Has been used for climate change impact studies since 1987. 116 points modelled across all of Australia. Stat Div scale; Used combination of projection extremes for 2030 and 2070. Climate, soils and tree density data at a national scale used.	% change in pasture productivity and animal numbers	McKeon et al., 1988; 1998; 2008; Crimp et al., 2002; 2008
							The pasture model GRASP was used to simulate pasture and beef production for six locations across northern Australia (Gayndah, Charters Towers, Charleville, Julia Creek in Queensland, and Alice Springs and Kidman Springs in the Northern Territory). The scenarios were from CSIRO 1992 scenario (CIG 1992). Bates et al. (1996) analysed GCM output from the CSIRO 1992 climate change study and a daily weather generator to provide suitable daily climate files for simulating pasture growth. Daily climate data was produced by two approaches: either weather generator WGEN or a simple set of multipliers. This experimental design allowed comparison of whether a simple approach of representative climate change produced similar results to a more sophisticated approach. The scenario tested was called a 'warmer climate' which involved variation between locations in changes in summer and winter rainfall and spatially variable increases in maximum minimum temperature (approximately 3 to 6 degrees depending on location). Given that the scenario was modelled in 1992 it is unlikely to be compatible with the current scenarios.	The outputs that were evaluated were components of the soil water balance including plant transpiration, runoff, drainage, percentage of days with pasture growth index exceeding a threshold (0.05), annual pasture growth, annual pasture nitrogen mineralisation index, percentage coefficient of variation of annual stocking rate, percentage of years when pasture burning occurred, and liveweight gain per ha.	McKeon et al., 1998

Table 5 Dryland grazing productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in pasture productivity (also livestock carrying capacity, animal production (beef and wool), other components of the grazing system, e.g. runoff, soil loss, frequency of burning, drought risk)	GRASP	Northern Australia and rangelands	Biophysical	Yes (Only available to trained pasture scientists)	The model has been parameterised from a wide range of field data, including pasture-growth studies and grazing trials. The output of the model has been compared to grazier estimates of safe carrying capacity to develop models of whole property livestock carrying capacity (Johnston et al. 1996). The model has been used to analyse the variability in livestock carrying capacity at an statistical division scale (Crimp et al. 2002). Validated against 0.5 million observations	Parameter files are available for different locations across Australia, as well as average parameter sets that can be used at larger scales. Trained pasture scientists can also carry out simulation experiments for themselves.	Simulate pasture and beef production for three locations (Gayndah, Charters Towers, Galloway Plains) in the black speargrass zone of coastal Queensland. The climate change was represented as simple modifications to daily climate files. The base period was 1961 to 1990. A simple multiple regression was used to calculate pan evaporation from modified solar radiation, temperature, humidity and calculated vapour pressure deficit. The scenarios were a factorial:CO_2 level (355 & 710 ppm) X Temperatures (Control temp & control temp + 3°C) X Rainfall (90% of control rainfall, control rainfall &110% of control rainfall)	Outputs were percentage of days that the growth index exceeded a threshold (0.05), pasture growth, liveweight gain per head, liveweight gain per ha.	Hall et al., 1998a.
							Simulation for 12 locations across QLD's grazing lands representing the 12 major pasture types in Queensland (O'Rourke et al. 1992): Maryborough, Banana, Galloway Plains, Emerald, Rolleston, Roma, Cunnamulla, Longreach, Cloncurry, Charters Towers, Croydon, Donors Hill. The climate change was represented as simple modifications to daily climate files. The base period ('control') was 1961 to 1990. A simple multiple regression was used to calculate pan evaporation from modified solar radiation, temperature, humidity and calculated vapour pressure deficit. The scenarios were a factorial: CO_2 level (355 & 710 ppm) X Temperatures (Control temp & control temp + 3oC) X Rainfall (90% of control rainfall, control rainfall &110% of control rainfall)	The major outputs were that the growth index exceeded a threshold (0.05), pasture growth, liveweight gain per head, liveweight gain per ha. The major output in the publication is safe carrying capacity. In the second document the carrying capacity and liveweight gain attributes have been converted to liveweight production for the whole of Queensland. Hall et al. 1988b	Hall et al., 1998a and b

Table 5 Dryland grazing productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in soil carbon	Range-ASSESS	Australian rangelands	Biophysical						Hill et. al., 2006
Change in greenhouse gas emissions	GRASSMAN	Tropical and sub-tropical savanna woodlands of northern Australia	Biophysical					Not focused on productivity per se. Management options to reduce greenhouse gas emissions from the tropical grazing system investigated were highly sensitive to the GWPs used, and to the emission definition adopted. A recommendation to reduce emissions by changing burning management would be to *reduce* fire frequency if both direct and indirect GWPs of CO_2, CH_4, N_2O, CO and NO are used in evaluating emissions, but to *increase* fire frequency if only direct GWPs of CO_2, CH_4 and N_2O are used. The ability to reduce greenhouse gas emissions from these systems by reducing stocking rates was also sensitive to the GWPs used. In heavily grazed systems, the relatively small reductions in stocking rate needed to reduce emissions significantly should also reduce the degradation of soils and vegetation, thereby improving the sustainability of these enterprises.	Howden, et. al., 1993

Table 5 Dryland grazing productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in beef production	TICK1	Australia	Biophysical	No - could be revived			2030 and 2100. Two approaches - bottom-up approach using sensitivity analysis and a top-down approach using climate change scenarios from a GCM. Scenario by the CSIRO and represent the best available science as of October 1996 (as presented in the 1996 IPCC) with a resolution of 450 km^2. They differ from more recent scenarios (CSIRO, 2001), which show a potential warming that is 40% greater due mainly to an assumption that sulphate aerosols will be lower than previously estimated.	In the absence of any adaptation measures there was an increase in losses in annual beef production nationally due to climate change impact on ticks of 1186 and 15043 tonnes in 2030 and 2100 respectively compared with present If all producers adopted the optimal breed structure now increase in losses in beef production due to climate change impact on ticks is 2326 and 2983 tonnes in 2030 and 2100 respectively compared with present (assuming optimal breed).	White et al., 2003
Role of trees in production, strips for shading, changes in hydrology, wind, evaporative demand and carbon value and biodiversity	GRASP hybrid	Australia	Biophysical	Yes	Validated against selected datasets (limited)	Climate, soils and pasture sward information	Land type mapping 250 different land types based on climate, soils, etc. in Queensland Extended to WA. Images being used in WA dynamics of shrubs, 4 time steps during the year, tries to look shrub dynamics in response to climate drivers	No productivity estimates produced at this time	Moore 1998

Table 5 Dryland grazing productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in pasture productivity, changes in stream flow, impacts on carrying capacity	AUSSIE GRASS	Australia	Biophysical	Yes	Calibrated with over 0.5 million observations	Climate, soils and tree density nationally	No climate change related productivity estimates produced at this time	AussieGRASS has been used to make estimates of beef production and wool yield for Australia (Carter and Stone 2006, Enhanced forecasting of farm financial performance, MCVP project ABA12).	McKeon, et al 1998
Changes in primary production in a mixed tree grass system	TREEGRASS		Biophysical		Tested for grassy and shrubby areas of Lamto savannas (Ivory Coast)		No climate change related productivity estimates produced at this time	NA	Simioni et al., 2000
Change in pasture productivity, changes stocking rates and herd dynamics	GRASSGRO	Australia	Biophysical	Preliminary Climate change runs have been undertaken	Validated against a range of NSW sites	Climate, soils, and initial flock\herd dynamics	Simple scaling of temperature and rainfall to examine related changes in production and herd dynamics at one site in NSW	changes in production and herd dynamics at one site in NSW	Moore et al., 1997
Change in pasture productivity in a mixed shrub/ grass rangeland system	IMAGES	Australian arid-semi arid rangeland	Biophysical Captures shrub dynamics	not currently used but could be if there was a needs		Rainfall, stocking rate, soil parameters	No climate change related productivity estimates produced	NA	Hacker et al., 1991; Watson 1999
Changes in woody biomass in a fire driven system	FLAMES	Australian savanna	Biophysical capturing tree population dynamics and fire impact	Yes	Tested in Australian Northern savannas (developed using Kapalga fire experiment research)		No climate change related productivity estimates produced?	NA	Liedloff and Cook 2007

Table 6 Irrigated systems productivity models and estimates

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Adaptive capacity – impacts on feedbase, quantity of milk produced	Dairy Mod (whole of farm system model	Largely used in Australian temperate pasture regions	Biophysical	Yes, although limited application to date			Examined impacts of CO_2 on water-use efficiency Using 2030 scenarios (but not looking at any feedbacks or interactions largely an optimisation approach) doesn't consider quantity and quality impacts of heat stress on milk	Milk production linked to pasture production	Cullen et al., 2007; Eckard et al 2000; 2006; Nidumolu 2007; Sinclair 2007
Total water use, salinity levels and flows to the sea. 'Social value' ($)	state-contingent model	Murray Darling Basin	Social-Economic. Land and water allocation through sequential and global maximisation solutions.	Yes		Land-use decisions, land use in basins, water inflows, region-specific gross margin budgets, soil type	Jones et al. (2007) apply the methods of Jones and Page (2001) and Jones and Durack (2005) to derive inflow projections for the Murray–Darling Basin from regional projections of precipitation and temperature derived from various climate models and scenarios. The inflow projections of Jones et al. (2007) are used as the basis of the modelling. Consider two alternative hypothesis; In the first, changes in precipitation are proportional across states of nature, so that a reduction in mean rainfall implies an equi-proportional reduction in the standard deviation. In the second, changes in precipitation are driven primarily by changes in the frequency of drought. Projections are in the form of a probability distribution of changes in inflows for 2030 in which the 5th, 50th and 95th percentiles are reported.	The effects of climate change on the Murray-Darling Basin remain uncertain. The most notable feature of the results is that an assessment of the effects of climate change is sensitive to the state-contingent specification of changes in inflows, and is significantly larger if climate change takes the form of an increase in the frequency of droughts than if inflows decline proportionally in all states of nature. The adverse effects of climate change may be partially, but not entirely, offset by adjustment.	Adamson et al., 2008; Jones 2005; Jones and Page 2001; Jones et al., 2006; Kirono et al., 2006; Mallawaarachchi et al., 2007; Schrobback et al., 2008

Table 6 Irrigated systems productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Changes in risk of losses to milk production through heat stress and $ benefit of installing shade and sprinklers	THI (temperature humidity Index)	Nationally applicable	Biophysical threshold exceedence	easy to calculate	THI threshold calculation validated against long term climate records for Muswellbrook Hunter Valley. Response of dairy cattle to heat stress assessed in NSW and QLD.	Maximum temperature, relative humidity	Probability of heat stress exceeding THI levels between the years 2010 and 2090 using ranges of change for maximum temperature and humidity. Sample at regular intervals between the lower and upper extremes of the IPCC 1996 estimates of global average warming to estimate probability of a particular temperature occurring. Uncertainty measured by comparing local changes in fine (CSIRO DARLAM) and 5 coarse resolution global models. Looks at adaptation by installing shade and sprinklers.	Losses under 2000 climate with no shade were 232 L/cow/year (3.3% annual production). By 2030 milk loss approaches 280 L/cow/year (4% annual production). By 2070 milk loss is 250-400 L/cow/year (-6% annual production).	Jones and Hennessy 2000
Changes in heat stress	AussieGRASS	Nationally applicable	Biophysical	Yes	Validated against observational information on heat stress	Maximum temperature, relative humidity	Current applications have scaled current national heat stress assessments (Using the THI) by increasing maximum temperature by 2.7^{O}C	no linkages to productivity, although a surrogate for milk production and liveweight gain could be established	Howden et al., (2001)

Table 7 Cropping productivity models and estimates

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in wheat yield and crop value	APSIM (Wheat)	Australia	Biophysical and economic	No	Validated against historical state yields	daily climate data, accurate soils characterisation, accurate management	Carbon dioxide concentrations for 2070 were sampled using a uniform distribution across the range of values provided by the Intergovernmental Panel on climate change scenarios (525ppm to 716ppm: IPCC 2000) which relate CO_2 levels to global temperature change	There is a high likelihood of significant yield reductions in Western Australia. In north-eastern Australia there is a high likelihood of moderate increases in yield but also a small probability of substantial yield reductions. Nationally, while median yields are little changed (without adaptation) there is a significant risk to the industry as increases in crop value are limited (to about 10% or $0.4B p.a.) but potential losses are large (about 50% or $2B p.a.). Adaptation strategies of changing planting dates and varieties could be highly effective by offsetting the negative impacts of global change and enhancing positive aspects. The median benefit of these adaptations was about $225M p.a. but with a range of $100M to over $500M p.a.	Howden and Jones 2001
							No specific year although some estimates with 2050 CSIRO climate change predictions. Sensitivity analysis to examine simulated yield responses to a range of temperature, rainfall and CO_2 changes for 10 representative areas across Australia. Simple scaling of existing daily rainfall and temperature records for the period 1957 to 2006. The envelope used limits temperature change to an increase of up to 4°C above current temperatures (0, 1, 2, 3, and 4°C) and +20% to -30% change in rainfall (-30, -20, -10, 0, 10, and 20%), for a series of different CO_2 concentrations, including 350, 450, 550, 650 and 750 ppm	Different responses for different regions. Different results with adaptation via modification to the planting window	Crimp et al., 2008

Table 7 Cropping productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Change in wheat yield and crop value	APSIM (Wheat)	Australia	Biophysical and economic	No	Validated against historical state yields	daily climate data, accurate soils characterisation, accurate management	The vulnerability of wheat production at 8 locations (Cummins, Keith, Lameroo, Minnipa, Naracoorte, Orroroo, Roseworthy, Wanbi) in SA under future climate change was quantitatively evaluated via a risk analysis. Local climate change (monthly temperature change in °C per degree of global warming and monthly rainfall change in percentage change per degree of global warming) and information drawn from the IPCC Special Report on Emission scenarios marker scenarios (SRES) (IPCC 2000) for the year 2080 were used to construct probability distributions of regional climate changes by using a Monte Carlo Random Sampling (MCRS) technique. The local climate change information consists of downscaled outputs of eight General Circulation Models (GCMs) and one Regional Climate Model (RCM) obtained from CSIRO Marine and Atmospheric Research, Australia.	Risk (conditional probability of not exceeding the critical yield thresholds) increased more or less across all locations under the most likely climate change. Wheat production in drier areas such as Minnipa, Orroroo and Wanbi will not be economically viable under the most likely climate change.	Luo et al., 2007
% change in wheat yield, % change in days to maturity and $$	OZ Wheat	Australia	Biophysical and economic	Yes	Validated for wheat growing districts in Australia i.e. 245 shires across wheat-belt	Daily climate data	Sensitivity approach at shire scale using 2020 and 2050 CC simulations. Simplified crop model includes water stress, temperature and rainfall. Not pure biophysical model. The modelling was applied to wheat yield production for the 245 cropping shires across Australia. The model uses daily rainfall and temperature from the beginning of the fallow prior to the crop through to crop maturity. A simple, soil water balance is maintained and the degree of water stress experienced by the crop calculated and used to predict shire scale wheat yield. Benchmark yield distributions were derived from simulations using historical climate data (1901-2007). Yield distributions were then simulated (using the 107 year time series) with adjustments to the climate data to account for low(B1) and high (A1T) CO_2 emission climate change scenarios for 2020 and 2050 climates, relative to a reference climate period i.e. 1961 to 1990. Emission scenarios were generated by CSIRO's CCAM model.	Percentage yield, fallow rainfall changes, days to maturity, changes in-crop rainfall	Potgeiter et al., 2008

Table 7 Cropping productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
% change in sorghum yield	OZ Sorghum	Australia	Biophysical and economic	Yes	Validated for sorghum growing districts in NE Australia, i.e. 31 shires	Daily climate data	Sensitivity approach at shire scale using 2020 and 2050 CC scenarios. Simplified crop model includes water stress, temperature and rainfall. Not pure biophysical model.	Percentage yield, fallow rainfall changes, days to maturity, changes in-crop rainfall	Potgeiter et al., 2008
Business profitability, economic risk, environmental impact, enterprise mix For a mixed crop farm	APSFARM	Australia	Biophysical and economic	Yes	Validated for individual farms in NSW and QLD	Daily climate data, accurate soils characterisation, accurate management	No climate change scenarios run to date but runs for a mixed cropping enterprises (sorghum, wheat, chickpea and maize) have been made using wet (1986-1995) and dry (1996-2005) decades for a 2000 ha cropping farm business near to Emerald, Central Queensland, Australia.	During the dry years it would be difficult to significantly improve the profitability of this farm business, suggesting that even our best growers would be highly vulnerable to increased signals from climate change.	Rodrigues, et al., 2006
Shifts in commercial viability	APSIM (Wheat)	Australia	Biophysical	Yes	Validated against farm production estimates	Daily climate data, accurate soils characterisation, accurate management	Goyder's line approach, sensitivity approach, analogue approach to examine groups of management activities for different rainfall deciles	Regional shifts in productivity	Peter Hayman et al., 2008

Table 7 Cropping productivity cont…

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Wheat yield, Grain nitrogen and protein content	DSSAT3.5 CERES Wheat	Australia	Biophysical	Yes	Validated for many sites overseas and in Australia	Inputs include weather and soil conditions, plant characteristics, and crop management.	Climate change runs for southern Australian wheat belts. One representative site in each agricultural division was selected for running the simulations, i.e. Minnipa for Western, Hawker for Upper North, Port Pirie for Lower North, Roseworthy for Central, Wanbi for Murray Mallee and Keith for Southeast. Four greenhouse gas emission levels and three sensitivity levels of the climate system to increased greenhouse gas concentration were considered. The four greenhouse gas emission levels are denoted by B1, B2, A1, and A2 in the preliminary Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel for Climate Change (IPCC). The assumed atmospheric CO_2 concentration for B1, B2, A1, and A2 scenarios are 532, 561, 646, 720 ppm, respectively for the 2080s. Sensitivity of the climate system to increase of greenhouse gas concentration was defined as Low (1.5 _C), Medium (2.5 _C), and High (4.5 _C) according to the work of IPCC.	Three conclusions can be drawn from thus study. Firstly, wheat yields increase from 13.91 to 46.58% under all CO_2 levels at planting date of 30 May. Yield has a positive relationship with atmospheric CO_2 concentration. Yields increase under different climate change scenarios in most cases (−1.03%39.38% at planting date of 30 May, 10.33%68.03% at planting date of 30 June). Secondly, grain nitrogen content decreases under all CO_2 levels (−26.6% to −10.63%) and under most of climate change scenarios (−20.47% to 5.44%). Grain nitrogen content has a negative relationship with atmospheric CO_2. The decrease under climate change scenarios is less than that under corresponding CO_2 level due to increased temperature, which enhanced soil nitrogen mineralisation. Grain protein content decreased more at drier sites. The combined effects of climate change and increase of atmospheric CO_2 concentration will downgrade wheat quality at least one class at drier sites. Finally, grain yield at planting date of 30 June was significantly enhanced compared with that of planting date of 30 May under the same environmental change condition (same climate change scenarios plus their corresponding CO_2 levels). Excalibur is an early maturity cultivar. Appropriate late sowing is probably beneficial to its growth and development	Luo 2003; 2004; Luo et al., 2005

Table 8 Viticulture and horticulture productivity models and estimates

Industry outcome	Model type	Where applicable	Focus	Operational	Validation	Input data requirement	Current climate change applications		
							Approach e.g. scale, scenarios, year	Productivity estimates	Access
Region most appropriate for production and impacts on grape quality	modified HOMOCLINE method called Vine logic	Southern grape-growing region to Griffith	Biophysical	No		Temperature and rainfall	Leanne – yield and quality linked to mean January temp Victor - Quality and date of harvest	Production increases under dry years and decreases under wet years in a fully irrigated system	Webb et al., 2007a,b; Rogiers et al., 2006
Horticulture regions most appropriate for production in the future, lettuce, sweet corn, etc. (land capability perspective)	Range of phenology rules based on temperature (Peter Deuter) combined with APSIM simulation capability	Could be applied at a national scale	Biophysical	No	Limited validation for lettuce and sweet corn in Gatton region	Temperature threshold information for individual crops and cultivars.	Lettuce – 2020 and 2050 (low (B1) and high (A1FI) emission scenarios considered). Sweet corn has been completed and broccoli being developed	Changes in harvest dates Some linkages to price via an understanding of scheduling	Deuter 2008; Deuter et al., 2008
Temporal variability in production	Macadamias – David Meyer using GRASP	Limited to existing production regions	Biophysical	No	Validated against Northern NSW yields		Not currently used in climate change studies	Changes in nut production in response to rainfall changes	Stephenson and Mayer 2007
Region most appropriate for production quality	Potato model		Biophysical	No			Not currently used in climate change studies	Changes in yield	Hackett and Sands 1979

APPENDIX B – FEEDBACK FROM 22 APRIL WORKSHOP, CANBERRA

Understanding the likely impacts of climate change on Australian agricultural productivity at multiple scales: workshop feedback

This workshop forms part of an ongoing study into the vulnerability of Australian agricultural productivity to climate change. This document summarises the workshop presentations and discussions; including follow-up data. In total 19 people attended the workshop (Table 9) on Tuesday 22 April 2008. These attendees included researchers of both climate variability and change across Australia's agricultural industries.

The aim of the workshop was to examine future research priorities in understanding the impact of climate change on agricultural productivity, by comparing existing research against emerging policy demands. This was achieved through four objectives which structure this document.

1. Discuss current model types and outcomes and how they can contribute to assessing the impact of climate change on Australian agriculture.

2. Collate existing and readily accessible literature, scientific data and expert opinion on agricultural productivity changes to climate change including agroecological modelling systems.

3. Document current models used to undertake productivity estimates, including significant assumptions such as the climate change scenarios used.

4. Identify and prioritise research areas based on current and emerging policy questions.

1. Models to asses impact of climate change on Australian Agriculture

Description of models and characteristics discussed is found in Table 10.

The workshop discussed a variety of models which have been used to assess the impact of climate change on agricultural productivity. The models discussed, largely allow productivity estimates to be determined for single industries only, a small number of models could be used to develop productivity estimates for multiple industries. The workshop discussions focused seven of the top ten nationally ranked industries (in terms of gross value of production; ABARE 2007) and included: grazing, cropping, horticulture, viticulture, dairy, cotton, and sugarcane.

2. Collation of agricultural productivity estimates

Each model was assessed in terms of the following criteria: industry of application, spatial scale of model outputs – "scale", nature of the outputs - "focus", operational readiness, validation undertaken, input data required, outline of current climate change applications (see Appendix A and excel file for further information).

Summary of current model characteristics:

- Models ranged from internationally validated and applied through to expert opinion.
- Most models reviewed provided point based estimates of productivity change only. A range of disparate methods had been developed scale outputs spatially.
- Only a limited number of models provided spatial estimates at a regional or national scale.
- For some industries phenological attributes such the length and start of the growing season was the focus for productivity as opposed to net primary production.
- Many current models while operational in terms of considering climate variability were not designed for climate change related research.
- Significant gaps exist in the ability to provide readily accessible estimates of productivity changes, particularly in the areas of horticulture, viticulture and dairy.

3. Document productivity estimates and assumptions

A description of productivity responses to climate change has been tabulated on an industry basis and is presented in Appendix A.

In summary the key points included:

- The cropping and grazing productivity estimates are further progressed than most other agricultural industries. Both explicit scenario-based productivity changes and empirically based estimates of change have been developed.
- Determining productivity estimates for the remaining industries discussed in this workshop would require an extensive interview process in order to extract industry specific expert knowledge.
- Some scope exists for determining productivity estimates for horticulture, viticulture and dairy in the near although this will require targeted investment to ensure these industry models are further developed.

4. Identify and prioritise future research and emerging policy questions

Workshop identified some gaps in current model development and application:

- Further model development is required in the horticulture, viticulture, dairy and mixed farming enterprises (e.g. grain-sheep/beef and sheep-beef cattle) industries in order to understand basic productivity responses to climate change.
- Changes in productivity were discussed for most of Australia although noted gaps included: south West Australian grazing and cropping; temperate dairy; temperate pasture.
- Most models reviewed provided point-based estimates of productivity change only. A range of disparate methods had been developed scale outputs spatially but this is problematic when comparing or contrasting results.

- The ability to shift between land uses (i.e. substitution) is yet to be a formal element of most of the models examined. There has been little consideration of the economic or social requirements and impacts of such land use change.

The workshop identified a number of gaps in current biophysical modelling knowledge:

- Understanding thresholds of change that influence productivity (i.e. rainfall, temperature, etc.)
- The establishment of basic biophysical relationships is still lacking some industries e.g. many horticultural crops
- Clarifying impact of: CO2, changes in growing season, management impact, changes in burning frequency, diseases, pests and parasite impacts on production have yet to be considered.
- Feedback loops between production and underlying natural assets has yet to be fully coupled in existing models(i.e. soil, water etc.)
- The ability of the models to effectively incorporate Global Climate Model (GCM) scenario information also represents a significant research limitation.

Integration of models with other sciences

Further linking or integration of models and other science disciplines will be required in to address issues such as:

- Understanding interactions between natural resource condition, farming system productivity and management practice.
- Understanding the impact of management change (both tactical and strategic) and other drivers of change e.g. carbon trading on land use and productivity.
- Understanding and investigating resilience and transformation of farming systems, i.e. what are the ‘marginal thresholds’ in horticultural systems and how can we manage them?
- Linking of biophysical to social-economic systems to understand impacts of changes elsewhere in the supply chain e.g. stranded assets - when elements of the supply chain become redundant in response to climate change (processing plants).

Emerging policy questions – vulnerability

An extensive review of relevant literature was undertaken to support and focus the workshop on new policy questions. The review found a growing policy question around vulnerability of Australian agricultural industries, practices and communities to global change. For the purposes of this workshop, vulnerability was defined as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC,2001).

A variety of approaches to assessing vulnerability to climate change were identified at the workshop which could be undertaken with current modelling knowledge and interests. Below is a list of the issues, opportunities and priorities for future reach to address the emerging policy questions, such as vulnerability.

- A number of specific industries could assess the vulnerability of biophysical production to global climate change. There is a need to linearly integrate modelling results of biophysical agricultural models to ‘economic’ or industry models to understand community, regional, economic or whole industry vulnerability
- A land-use perspective was seen as valuable to expand the scale of models to deal with mixed farming systems and mixed farming regions, accounting for change to new crops, new land uses etc, but must recognise that land-use changes are driven by changes in economic productivity and profitability
- Multiple drivers (apart from climate change) are rarely incorporated into climate change assessments e.g. ‘strong regions’ of ‘food miles’
- The ability to couple models together to address both multiple scale and multiple land-use outcomes was identified as a significant research focus in the future.
- Perhaps climate changes on decadal or multi-decal timescale, as such current modelling focusing on marginal daily time steps is based in the wrong area of expansion for future research, perhaps consider a risk-based approach.
- Making models ‘open source’ which should then drive research and model development
- Simple whole farm spreadsheets are being used in climate change conversations now and could have a role in future work.

References

ABS (2007) Value of principle agricultural commodities produced, 2005-06, 7501.0

IPCC (2001) Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

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Table 9 List of participants

Organisation	Name	Industry	Location
ABARE	Edwina Heyhoe	ABS	ACT
ABARE	Sharon Page	ABS	ACT
CSIRO	Sarah Park	Sugarcane & horticulture	Queensland
CSIRO	Craig Miller	Dairy	Queensland
CSIRO	Mark Stafford Smith	grazing	ACT
CSIRO	Mark Howden	various	ACT
CSIRO PI	Andrew Moore	Grazing	ACT
NSW DPI	Ron Hacker	Grazing	NSW
NSW DPI	Helen Fairweather	Irrigation	NSW
QDPI	Peter deVoil	Horticulture	Queensland
QDPI	Andries Potgieter	cropping	Queensland
QDPI	Neil White	Horticulture	Queensland
QDPI	Peter Deuter	Horticulture	Queensland
QLD NRM	Greg McKeon	Cropping	Queensland
SARDI	Peter Hayman	Viticulture & horticulture	SA
WA Agriculture	Chris Chilcott	Pasture & cropping	WA
UniQld	David Adamson	Irrigation	Queensland
CSIRO	Leonie Pearson	Project team	Victoria
CSIRO	Rohan Nelson	Project team	ACT
CSIRO	Jenny Langridge	Project team	ACT
CSIRO	Steve Crimp	Project team	ACT

Table 10 Summary of productivity estimates by commodity

Commodity	Availability of productivity estimates under climate change
Sugar	Limited modelled yield estimates available for several sites in QLD but not NSW. Survey work in QLD Northern, Central and Southern Coasts could fill some gaps although not focused on climate change.
Cotton	Modelled yield estimates and collated expert opinion available for Central Queensland only. Also, site specific modelling of the impact of pest and disease with climate change in Central Queensland.
Dryland Grazing	Modelled yield estimates available for Australia and particularly rangeland systems from process and empirical models. There are several pasture models in use but most estimates have been generated using GRASP. Some old modelling work available looking at the impact on beef yield of pests with climate change.
Dairy	Limited estimates of milk and pasture yield with CO_2 changes available for temperate pasture regions (Victoria and NSW). Changes in milk production due to heat stress estimated for the Hunter valley in NSW.
Cropping	Modelled yield estimates from process and empirical models available for wheat at National and regional scales. Limited modelled yield estimates for sorghum; no estimates for other crops.
Viticulture	Some estimates of production increases under dry years and decreases under wet years in a fully irrigated system in the Southern grape growing region using a simple empirical model. No process model currently in use.
Horticulture	Limited modelled estimates available for changes in harvest date with climate change for lettuce and sweet corn for three locations in Australia. Estimates available for macadamia nut yield in response to rainfall changes in existing macadamia production regions. Some modelling undertaken for potato but no production estimates available with climate change. Potential for developing rules of thumb from expert opinion and using 'living experiments'.
Other	Other models have potential to fill some gaps in information such as the suitability of plants/crops to regions with a changed climate and the impact of climate change on land-use mix and greenhouse emissions. Very limited published data. Some published climate change and water use work in the MDB could be useful. International vegetation models used at a global scale estimate biomass/carbon estimates for Australia at a low resolution.

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