Climate Change and the Economics of Farm Management in the Face of Land Degradation: Dryland Salinity in Western Australia

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Projected changes in climate would affect not only the profitability of agriculture, but also the way it is managed, including the way issues of land conservation are managed. This study provides a detailed analysis of these effects for an extensive dryland farming system in south-west Australia. Using a whole-farm linear programming model, with discrete stochastic programming to represent climate risk, we explore the consequences of several climate scenarios. Climate change may reduce farm profitability in the study region by 50% or more compared to historical climate. Results suggest a decline in the area of crop on farms, due to greater probability of poor seasons and lower probability of very good seasons. The reduced profitability of farms would likely affect the capacity of farmers to adopt some practices that have been recommended to farmers to prevent land degradation through dryland salinization. In particular, establishment of perennial pastures (lucerne or alfalfa, Medicago sativa*), woody perennials ("oil mallees",* Eucalyptus *spp.), and salt-tolerant shrubs for grazing ("saltland pastures",* Atriplex *spp.) may become slightly more attractive in the long run (i.e., relative to other enterprises) but harder to adopt due to their high establishment costs in the context of lower disposable income.*

Les changements climatiques prévus influeraient non seulement sur la rentabilité de l'agriculture, mais aussi sur la gestion, y compris la façon de gérer les questions de conservation des terres. La présente étude offre une analyse détaillée de ces effets sur un système d'aridoculture extensive dans le sud-ouest de l'Australie. À l'aide d'un modèle de programmation linéaire d'une exploitation, comprenant une programmation stochastique discrète pour représenter le risque lié aux changements climatiques, nous avons examiné les conséquences de plusieurs scénarios climatiques. Dans la région à l'étude, un changement climatique pourrait diminuer la rentabilité d'une exploitation de 50 p. 100 ou plus par rapport au climat historique. Les résultats ont laissé supposer un déclin dans le domaine des cultures, en raison de la probabilité accrue de connaître des saisons médiocres et de la probabilité diminuée de connaître saisons exceptionnelles. Une diminution de la rentabilité des exploitations freinerait probablement la capacité des producteurs à adopter certaines pratiques recommandées pour prévenir la dégradation des sols par la salinisation des terres arides. Certaines pratiques, telles que l'établissement de pâturages de plantes fourragères vivaces (luzerne ou Medicago sativa*), de plantes ligneuses vivaces (*Eucalyptus*) et d'arbustes tolérants au sel (*Atriplex*), peuvent devenir un peu plus attrayantes à long terme (c'est-à-dire, comparativement à d'autres pratiques), mais également plus difficiles à adopter en raison des coûts d'établissement élevés dans un contexte de faible revenu disponible.*

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INTRODUCTION

Apart from directly affecting the profitability of agriculture, changes in climate may affect the economics of land degradation associated with agriculture. This study examines the potential economic influence of climate change on management of dryland salinity in Australia. The analysis examines the possible effects of climate change on farms in the region, including influences on farm profit, on the optimal mix of enterprises, and on tactical farm management, in the context of dryland salinity as a land degradation threat and management challenge. The study focuses on extensive farming systems in the south-west of Australia, in which the main farming enterprises are crops (especially wheat) and livestock (mostly sheep). A detailed whole-farm bioeconomic model, MUDAS (Model of an Uncertain Dryland Agricultural System), is used to examine the impacts of possible climate-change scenarios on optimal farm management in the face of climate variability and significant land degradation, in the form of dryland salinity. The case study focuses on the eastern wheatbelt of Western Australia. The key questions addressed are following.

1. What are the potential impacts of projected changes in climate on farm profits and optimal farm management?
2. How might climate change affect the economics of strategies being recommended to manage dryland salinity?

POTENTIAL EFFECTS OF CLIMATE CHANGE ON AUSTRALIAN AGRICULTURE

CSIRO have simulated a number of future climate-change scenarios for regional Australia (CSIRO 2001). Across these scenarios, average annual temperatures are projected to rise by between 0.4 and 2.0°C by 2030 over most of Australia, with slightly less warming in coastal areas. By 2070 further increases in temperatures are projected ranging from 1.0 to 6.0°C. The projected rate of warming is 0.1–0.5°C per decade. By 2030 autumn and winter rainfall is projected to decline by up to 20% and evaporation rates may increase. We note, however, that these scenarios are early estimates of climate change impacts in Australia, and they would have large confidence intervals.

Changes noted in Western Australia over the past 30 years have in part been attributed to the enhanced greenhouse gas effect (Indian Ocean Climate Initiative 2002). Rainfall has declined in the early growing season (May–July), although no significant trends have emerged for the latter part (Aug–Oct) of the normal growing season. There has been a significant decline in the number of winter "rain days" and a decline in rainfall per "rain day." It is interesting that despite these changes, crop yields and total factor productivity in the wheatbelt have increased substantially over the same period (Mullen 2002). An analysis by Nicholls (1997) suggested that 30–50% of Australia's wheat yield increases over the past 20 years are due to climate trends with changes in temperature being the dominant influence. For example, the lower frequency of cold fronts has resulted in a lower incidence of frost (Dracup et al 2003).

Drought frequency and severity may increase in some parts of Australia as average rainfall declines (Pittock 2003). Reyenga et al (2001) note that further change in atmospheric CO_2 levels and climate is likely to alter the distribution of cropping in

Australia given the importance of climate and soil characteristics in determining average yields and the frequency of failed sowings. They suggest that the viability of some cropping regions across Australia may decrease if the number or sequence of poor seasons increases.

The integration of Global Climate Model (GCM) output with farm-level systems modeling analysis has recently begun (Howden and Meinke 2003). Ash et al (2000) note that integration of the different climate-change elements (e.g., rainfall, temperature, and vapor pressure deficit) produces superior analyses of potential climate-change scenarios compared to analyses that only consider rainfall.

The effects of elevated CO_2 levels on agricultural production have been reported in a number of wheat and pasture production studies carried out under experimental conditions. Kimball et al (2002) reported that with nonlimiting supply of water and nutrients, a doubling of CO_2 is estimated to increase yields of C3 crops by 30%, while field-scale experiments under more realistic conditions forecast wheat grain yield increases of only 7% (Hebeisen et al 1997). However, the effect of elevated CO_2 depends on temperature, as explained below.

Amthor (2001) reported that warming in general will reduce the yield of grain crops because of accelerated plant development. He noted that increasing temperatures by a few degrees may offset the positive effect of elevated CO_2. Wheeler et al (1996) also noted that increases in temperature reduced wheat yields but to a lesser degree under elevated CO_2 conditions.

A number of recent studies in Australia have simulated crop and pasture yield forecasts associated with climate change. Howden et al (2001) used simulation models of pasture (GRASP) and crop (I_Wheat) to review the impacts of climate change and climate variability on wheat and beef cattle production in north-east Queensland. If temperatures increased and CO_2 concentration doubled, wheat yields would tend to respond better than grass production.

Reyenga et al (2001) modeled effects of global climate change on a marginal wheat production area using the APSIM (Agricultural Production Systems sIMulator) plant simulation model (McCown et al 1996). APSIM is a detailed process-based simulation model. Reyenga et al (2001) investigated the interactions between elevated CO_2, increasing temperatures and changes to annual precipitation, to evaluate distribution changes in areas used for cropping in north-west South Australia. They suggested that there is a prospect of the area of cropping increasing in South Australia as a result of the CO_2 fertilization effect (assuming no offsetting decline in rainfall).

Van Ittersum et al (2003) also used APSIM to review how changes in CO_2 concentration, temperature and precipitation might affect agricultural production in Western Australia. Their simulation results for the Merredin region are highly relevant to this study, and so are presented in Table 1. The results suggest that moderate temperature increases (up to $+3^\circ$C) together with elevated CO_2 levels at ambient rainfall levels can have positive effects on wheat productivity in Western Australia with decreases in grain yield being offset by extra nitrogen fertilization. They note, however, that if precipitation does decrease (the aspect of climate change about which climate forecasters have most confidence) wheat yields decrease substantially for most conditions modeled. This finding suggests a possible contraction of the Western Australian wheatbelt under these climate-change scenarios.

Table 1. Average simulated effects of climate change on wheat yields at Merredin, on sandy and clay soils at low and high nitrogen fertilizer rates (% of base case yields, base case being for current conditions)

Soil type and nitrogen treatment (kg N/ha)	Scenario				
	550 ppm CO_2	+3°C	550 ppm CO_2 +3°C	550 ppm CO_2 +3°C −25% rain 1[a]	550 ppm CO_2 +3°C −25% rain 2[b]
Sand: N30	117	102	124	77	86
Sand: N150	123	98	124	67	79
Clay: N30	112	110	127	54	81
Clay: N90	134	105	143	47	71

Source: Van Ittersum et al (2003).

[a] 25% decrease in precipitation evenly across the year.

[b] 25% decrease in annual precipitation, made up of +20% in summer/autumn and −35% in winter/spring.

Agricultural Management of Climate Change

The farming system in the eastern wheatbelt of Western Australia involves no irrigation, and so, given its low and variable rainfall level, farmers employ a myriad of tactical and strategic management decisions. These decisions are likely to change in many ways if projected changes to climate come to pass.

Quiggin and Horowitz (2003) argued that the costs of climate change will be primarily adjustment costs. Howden (2003) reviewed key adaptations at the farm level in managing climate change. Risk amelioration approaches included zero tillage, retaining soil residues, extending fallows, changing row spacing, changing planting density, staggering planting times, and erosion control infrastructure. Tactical management opportunities included soil moisture monitoring, climate forecasting, and constant reviewing of market conditions.

Van Ittersum et al (2003) suggested a number of adaptive crop management approaches in managing climate change under elevated CO_2. These included offsetting decreases in grain yield with extra nitrogen fertilization (although we doubt the economic wisdom of such a change), changing to varieties more suited to later sowing dates and expanding the sowing window to take advantage of earlier planting opportunities.

There are a number of options for graziers in managing climate change including changes in pasture management, alteration of stocking rates, varying animal type (sheep, cattle), breed (selecting for more drought resistant stock), and herd dynamics (calves, cows, steers). Fuhrer (2003) reviewed climate management adaptations and included the development of systems that are less prone to soil erosion, the selection of crop cultivars that can adapt to shorter growing seasons and earlier planting dates, changing the timing and amount of fertilizer application, and monitoring pest and disease outbreaks.

Uncertainty in Climate-Change Projections

Howden and Meinke (2003) suggest two significant limitations to climate-change analysis. Firstly, identifying effects of climate change on agricultural production is difficult given the complex interactions between climate and current natural resource management issues like dryland salinization and water allocation processes. (We would add that determining the farm-level consequences of climate change is difficult and complex, even if the climate change is fully predictable.) Secondly, there are high levels of uncertainty inherent in climate-change scenarios due to the large ranges in possible future greenhouse gas emissions; and there is fundamental uncertainty in the science behind the global climate system. They suggest that given these limitations, farmers need more resilient agricultural systems to cope with a broad range of possible climate changes.

Nicholls et al (2003) also question the level of certainty in climate-change predictions, suggesting that some of the climate change noted to date may result from climate variability rather than climate change; particularly in areas like the south-west of Western Australia. Van Ittersum et al (2003) note that changes in climate variability can have more profound effects on crop production and associated risks than changes in mean climate. They report that GCM climate-change scenarios are yet to include the associated risks of climate variability in any climate-change analysis.

Essex and McKitrick (2002) argue that the degree of certainty about climate change expressed by the United Nations Intergovernmental Panel on Climate Change (and many others) is completely unjustified. They argue that science is currently unable to determine what climate changes may or may not be induced by rising CO_2 levels and therefore researchers are unable to predict what effects might result from moderating CO_2 emissions.

In this study, we take a number of climate-change scenarios consistent with the literature, and examine their consequences for farm management, including natural resource management, in a particular region. We treat them as scenarios or projections, rather than predictions.

DRYLAND SALINITY

Dryland salinity (i.e., salinity on nonirrigated land) is seen as one of Australia's most serious environmental and resource management problems. There have been major government programs in place for over a decade aiming to increase farmers' adoption of management practices for salinity prevention.

Salt, mainly sodium chloride, occurs naturally at high levels in the subsoils of most Australian agricultural land. Some of the salts in the landscape have been released from weathering rocks (particularly marine sediments) (National Land and Water Resources Audit 2001), but most have been carried inland from the oceans on prevailing winds and deposited in small amounts (20–200 kg/ha/year) with rainfall and dust (Hingston and Gailitis 1976). Over tens of thousands of years, it has accumulated in subsoils and in Western Australia, for example, it is commonly measured at levels between 100 and 15,000 tonnes per hectare (McFarlane and George 1992).

Prior to European settlement, groundwater tables in Australia were in long-term equilibrium. In agricultural regions, settlers cleared most of the perennial native vegetation and replaced it with annual crop and pasture species, which allow a larger proportion of rainfall to remain unused by plants and to enter the groundwater (George et al 1997; Walker et al 1999). As a result, groundwater tables have risen, dissolving and mobilizing accumulated salts. Patterns and rates of groundwater change vary widely but most bores show a rising trend, except where they have already reached the surface or during periods of low rainfall. Common rates of rise are 10–30 cm/year. Given the geological history and characteristics of the Australian continent, large-scale salinization of land and water resources following clearing for agriculture was inevitable.

The main effects of dryland salinity can be summarized as those on:

(i) *Agriculture through land salinization.* Two million hectares of agricultural land are affected by shallow water tables (Australian Bureau of Statistics 2002b). The most serious problems are currently in the state of Western Australia and to a lesser extent South Australia and Victoria, but increases are predicted in New South Wales and Queensland (National Land and Water Resources Audit 2001).
(ii) *Water resources.* Dryland salinity will contribute to the future salinization of currently fresh rivers, affecting the quantity and quality of irrigation and drinking water (National Land and Water Resources Audit 2001).
(iii) *Infrastructure.* Roads, communication infrastructure, pipelines, and buildings are amongst the infrastructure assets affected. Rising water tables threaten a large number of towns (National Land and Water Resources Audit 2001).
(iv) *Vegetation and biodiversity.* Large areas of remnant vegetation and plantation forests are affected, with increases predicted in all states. In Western Australia it has been estimated that 450 plant species are endemic to low-lying areas in salinity prone regions and are at risk of extinction (Keighery 2000). Aquatic biota are also affected by rising salinity (Kefford et al 2003).
(v) *Flood risk.* Shallow water tables result in increased flood damage to roads, fences, dams, agricultural land, and wetlands (e.g., Bowman and Ruprecht 2000).
(vi) *Aesthetics.* Aesthetic changes occur as a result of all of the above impacts, affecting the sentiment of the broader community and raising political support for policy action.

To prevent onset of shallow water tables, large proportions of land in threatened catchments would need to be revegetated with deep-rooted perennial plants (shrubs, perennial pastures, or trees) (Ghassemi et al 1995; National Land and Water Resources Audit 2001; Pannell 2001). R&D efforts are under way to develop a range of new perennial plant options that are sufficiently economically attractive to prompt widespread adoption in place of traditional agricultural enterprises (Pannell and Ewing 2005).

Where soils are already salinized, remediation is often technically and economically very difficult. For that reason, farmers with large areas of salt-affected land are already trialing and implementing farming systems based on salt-tolerant species (e.g., salt bush, tall wheat grass). R&D is also focused on developing new and improved salt-tolerant options for farmers, potentially including a salt-tolerant grain crop (Pannell and Ewing 2005).

Climate Change and Dryland Salinity

There are a number of links between possible changes in climate and dryland salinity. Any reduction in annual rainfall may result in less groundwater recharge and consequently less dryland salinity risk and water logging (Howden and Meinke 2003). However, if reduced winter rainfall is offset by increased summer rainfall, dryland salinization may actually increase in some parts of the Western Australian wheatbelt.

Van Ittersum et al (2003) simulated “deep drainage” (i.e., additions to ground water) under wheat crops following projected climate change (Table 2). This is relevant because

Table 2. Average simulated effects of climate change on "deep drainage" at Merredin, on sandy and clay soils at low and high nitrogen fertilizer rates (% of base case, base case being for current conditions). Deep drainage for base case was approximately 35 mm/year for sand and 5 mm/year for clay

Soil type and nitrogen treatment (kg N/ha)	550 ppm CO_2	+3°C	550 ppm CO_2 +3°C	550 ppm CO_2 +3°C −25% rain 1[a]	550 ppm CO_2 +3°C −25% rain 2[b]
Sand: N30	101	89	90	21	68
Sand: N150	101	88	88	21	71
Clay: N30	106	74	81	6	72
Clay: N90	110	69	71	6	81

Source: Van Ittersum et al (2003).

[a] 25% decrease in precipitation evenly across the year.

[b] 25% decrease in annual precipitation, made up of +20% in summer/autumn and −35% in winter/spring.

higher deep drainage accelerates the onset of dryland salinity. Deep drainage tended to decrease (10–20%) under higher temperatures, reducing the threat of dryland salinity to some extent. A reduction in precipitation, if distributed proportionately across the year, reduced deep drainage substantially, especially on clay soils. If there is a larger reduction in winter/spring precipitation, partly offset by an increase in summer/autumn, there is a much smaller effect on deep drainage. This highlights the sensitivity of long-run salinity outcomes to relatively small and detailed changes in the climate scenario, which would be extremely difficult to forecast.

Changes in rainfall may also affect the adaptation of perennial plants that are intended to manage salinity. In practice, the influences of climate change on the economics of salinity treatments would be complex, depending on the effects of climate change on the economics of all existing and potential farm enterprises and strategies, and varying by soil type. This study examines, in part, how farmers' usage of perennial plants may change in response to climate change, and so how their ability to manage salinity may be affected. The available perennial plant options may also assist in adapting to climate change, increasing the resilience of the farm in a low rainfall region by maintaining productivity under drying rainfall conditions as well as incorporating the potential for greenhouse gas mitigation with the inclusion of carbon-credit benefits. If available, carbon credits would to some extent encourage the adoption of woody perennial plants (oil mallees and saltland pastures) and thereby enhance the management of dryland salinity. Petersen et al (2003) examined the role and economic impacts of a hypothetical carbon tax in a similar (but higher rainfall) farming system in Western Australia.

THE MODEL

MUDAS is described by Kingwell (1994) and Kingwell et al (1993). The model was substantially revised and augmented for this study. Additional perennial plant options were included (lucerne, oil mallees, and saltland pastures) and production and price parameters were reviewed and updated.

MUDAS uses discrete stochastic programming to represent both biological and economic factors at the whole-farm level. It accounts for weather risk, price risk, and tactical (within-season) decision-making opportunities. The objective function of the standard version of MUDAS involves maximization of expected wealth (given risk neutrality). It is possible to include risk aversion in the model, but it was considered a low priority in this analysis given past findings about its low impact on results (e.g., Pannell et al 2000). A typical MUDAS linear programming matrix has 1,400 rows, 1,700 activities, 32,000 elements and a density of 1.39%.

A key feature of discrete stochastic programming is that it can represent some decisions being made after a state of nature is observed. This is a particularly important aspect of farm management in the eastern wheatbelt of Western Australia. Because the farming system is rain-fed (nonirrigated, dryland), the timing and amount of growing season rainfall are the main determinants of crop and pasture yields. Hence in some unfolding weather-years, it is possible for the farmer to make tactical decisions regarding land and input use that lead either to avoiding losses in poor (or dry) years or boosting profits in good (often wet) years.

The MUDAS model includes decisions on the area to commit to crop or pasture production, sheep flock size and structure, the buying and selling of feed, and the buying and selling of livestock (sheep). To overcome the curse of dimensionality often associated with extensive choice discrete stochastic programming models that extend over several time periods, Kingwell (1994) constructed MUDAS efficiently based on an endless cycle of years, rather than a sequence of discrete length.

Data underpinning the model and analyses based on the MUDAS model have been extensively reviewed and validated in recent years by regional economists, agronomists, and farming systems staff of the Dryland Research Institute (Department of Agriculture Western Australia) based in Merredin, the main town in the eastern wheatbelt of Western Australia.

The Study Region

The region is an inland area of approximately 33,500 km^2, 300 km east of Perth, Western Australia. It has an extensive, broad, flat valley landscape only occasionally interrupted by remnant patches of native eucalypt vegetation. The region has annual average rainfall in the range 290–350 mm and experiences a Mediterranean climate: hot, dry summers, and mild, wet winters. Much of the annual rainfall falls within the winter/spring growing season, typically May–October.

Farming is the main economic activity of the region. Farms have a mix of crops and sheep, although most farms are crop dominant, with over 50% of their arable area allocated to annual crops.

The region was chosen for this study as it is a major crop-producing agricultural region, it has extensive problems with dryland salinity, and it is a low-rainfall region that may be particularly susceptible to any climate change.

Soils in the region can be broadly categorized as follows. The upper valley typically has two soil types: acid sand-plain soils (S1) are relatively infertile and are usually not suitable for crop production whereas (S2) is considered good sand-plain soil that is relatively fertile. Mid-slope, the gravely sands (S3) have a high reactive iron content and require phosphate fertilizers and the duplex soils (S4) are shallow sands overlying yellow or pale clay subsoils. Bordering the valley floor are the (S5) medium-heavy clays with fine textured red and brown loams. On the valley floor are the heavy clay soils (S6 and S7) that can be susceptible to waterlogging and weed infestation depending on their structural stability, with higher stability correlated with higher productivity (usually the addition of gypsum to the S7 soil type). The valley floor can also include saline soil (S8), either adjacent to an existing salt lake system or induced by recent water table rise.

The Farming System

In the past 40 years technology improvements and mechanization have led to substantial increases in farm size and labor productivity. Farms in the area are typically owner operated with no more than one other permanent laborer. Casual or contract labor is usually only utilized to assist with seeding, harvesting, and shearing activities. Average farm size is around 3,750 ha (Australian Bureau of Statistics 2002a).

Wheat, lupins, and barley are the main crop options grown in the region. Other crops like field peas, canola, faba beans, and chickpeas are grown in smaller amounts. Some farmers have also taken an interest in perennial options like oil mallees, lucerne, and saltland pastures (mainly saltbush). Some plantings of saltbush are large, but other than that, plantings of perennials are mainly for trialing and research rather than widespread commercial adoption. Details of new assumptions made with the addition of these three perennial options are provided by John (2005).

Pasture production in the region is mainly to supply feed for sheep but also to bestow advantages upon subsequent crop phases such as disease-break benefits, ease of control of herbicide-resistant weeds, and the supply of biologically fixed nitrogen from leguminous pastures. The quantity and quality of pasture produced is mainly influenced by weather-year, rotation, soil type, grazing pressure, and fertilizer effects. Crops and pastures are commonly grown in rotation, and their sequence is altered in response to seasonal weather and commodity prices.

Most farms in the region include a sheep enterprise. Sheep are raised for wool, live export, and for sale as meat. Recently, price relativities have favored sheep ahead of cropping on some soil classes.

In constructing MUDAS, care was taken to ensure that input prices and levels, overhead and other farm expenses (e.g., household expenses) were consistent with those paid or used by farmers in the region. Stratified regional farm survey data from a local bank and an agricultural consulting firm were used as data source to ensure that MUDAS accurately described farm types in the eastern wheatbelt. Input–output relationships were discussed with regional scientists and extension staff to ensure they properly reflected typical farm experience.

Climate-Change Assumptions

The base case or "standard" climate assumptions of the model are based on daily rainfall records from 1908 to 1994 (Table 3). Two climate-change scenarios are investigated. In climate-change scenario 1, the weather-year probabilities of the standard model were revised according to CSIRO estimates for the period 1970–2000. This period was relatively dry when compared against the region's previous climate for 1904–1969 (Foster 2002), so

Table 3. Weather year probabilities for various climate scenarios

	Climate scenario		
Weather year	Standard: 1908–1994	1: 1970–2000	2: 2000–2030
A (495 mm)[a]	0.0730	0.08361	0.06355
B (338 mm)	0.1250	0.03679	0.03679
C (295 mm)	0.0730	0.04348	0.08361
D (453 mm)	0.0940	0.06689	0.03679
E (318 mm)	0.1150	0.04013	0.04013
F (251 mm)	0.0830	0.06689	0.04682
G (309 mm)	0.1350	0.03345	0.03679
H (385 mm)	0.0940	0.10368	0.08696
I (313 mm)	0.0830	0.06355	0.07692
J (263 mm)	0.00730	0.17057	0.17057
K (272 mm)	0.00520	0.29097	0.32107
Wet years (A,D,H)	0.261	0.254	0.187
Dry years (F,J,K)	0.208	0.528	0.538

[a] The numbers in brackets are the average annual rainfalls in each weather-year class based on the weather-year data used in the standard MUDAS model. Letters refer to labels used in the model.

it represents a relatively modest set of climate changes from the standard model. CSIRO climate models (CSIRO 2001) provided hind-casts of daily rainfall and daily maximum and minimum temperatures for the region. From these data the weather-year probabilities of the MUDAS model were calculated.

Climate-change scenario 2 is based on the same CSIRO models involving simulations representing forecasts of climate change and climate variation over 2000–2030, consistent with CSIRO (2001) projections of climate over that period. Impacts of climate change on crop and pasture yields were also included in the MUDAS models of the three farm types. Crop and pasture yields (including lucerne) were generated by plant simulation models TACT (Abrecht and Robinson 1996) and APSIM calibrated and validated for the eastern wheatbelt region by the Department of Agriculture. Saltbush and oil mallee production levels were assumed to remain unchanged in the climate-change scenarios due to their deep rooted perennial nature and their indigenous ability to survive in variable, low-rainfall conditions.

Note that differences in climate between the scenarios were represented by the changing probabilities of each weather-year type shown in Table 3. When one of the weather-years occurs, it is the same in each scenario, but its probability of occurring is different. With the changes shown, there would be a different distribution of expected rainfall through the year.

Other simplifying assumptions used in this analysis should be noted.

- The influence of increasing CO_2 concentrations over the next 30 years on plant growth is not considered. The analysis only considers the impacts of changes in the amount and pattern of rainfall and maximum and minimum temperatures, as captured in plant growth simulation models. Further, the plant growth simulation models are not

able to capture other beneficial effects such as reduced waterlogging and reduced frost damage.
- The complex interactions between nutrient cycling, soil feedback, insect pest occurrence and plant diseases (Fuhrer 2003), and the decoupling of species interactions (Penuelas and Filella 2001) are not considered.
- Commodity or input price relativities are assumed to be unchanged by climate change.
- No new production or management techniques or enterprises are assumed to be introduced.

These simplifications are likely to result in relatively pessimistic projections for farm profitability, principally due to the exclusion of the CO_2 fertilization effect, the potential for technological adaptation and the benefits of reduced frost incidence. The analysis could be viewed as a worst-case scenario for climate change.

RESULTS AND DISCUSSION

Table 4 highlights the major differences in optimal farm plans for three farm types (representative, alluvial plains, and sand-plain farms, with different proportions of the various soil types) and three possible climate regimes. Given current technologies and enterprise options, as the climate regime becomes increasingly warm and dry, optimal farm plans on all three farm types become characterized by:

- markedly less profit,
- greater areas devoted to pasture and less to crop,
- less tactical alterations of crop and pasture areas from year to year,

Table 4. A summary of optimal farm plans for three types of farms, and for three climate scenarios

Activity		Representative farm			Alluvial plains farm			Sandplain farm		
Climate-change scenario[d] >	Unit	No change	1	2	No change	1	2	No change	1	2
Profit	$'000	211.9	96.7	54.2	216.8	89.9	42.0	218.3	93.2	46.7
Pasture area[a]	%[b]	42	47	49	40	50	51	36	46	49
Crop area	%	52	44	42	57	44	42	57	48	44
Lucerne	%	1	0	0	2	2	1	0.3	0	0
Saltland pasture	%	1	2	4	1	4	5	4	2	3
Oil mallee	%	6	9	8	2	6	6	6	6	6
All perennials[c]	%	8	11	12	5	12	11	10	8	9
Crop tactical adjustments	%	28	21	15	27	19	14	28	22	17
Sheep flock size	hd	7,265	6,355	6,134	7,138	6,862	6,371	6,969	6,577	6,219
Winter stocking rate	dse/ha	3.7	3.6	3.0	4.6	3.7	3.0	4.8	3.8	3.1
Lupins fed	kg/hd	17.0	24.1	27.7	16.7	23.5	27.8	17.7	23.1	27.2

[a] "Pasture" includes lucerne, saltland pasture, and annual pasture.
[b] Percentages of the farm's arable area.
[c] Lucerne + saltland pasture + oil mallees.
[d] See Table 3 for definitions of climate-change scenarios.

Table 5. Profitability and land use for the representative farm

Activity	Unit	Land Use[a]	Base case or "Standard" climate (1908–1994)	Climate-change scenario 1 (1970–2000)	Climate-change scenario 2 (2000–2030)
Profit	$'000		211.9	96.7	54.2
Profit per ha	$/ha		56.5	25.8	14.4
S1	ha	PPPP	638	638	638
S1	ha	OM	112	112	112
S2	ha	WWL	568	470	638
S2	ha	PPPP	70	168	0
S2	ha	OM	112	112	112
S3	ha	WWW	375	329	375
S3	ha	PPPP	0	45	0
S4	ha	WWW	375	375	191
S4	ha	PPPP	0	0	184
S5	ha	PPPW	475	562	562
S5	ha	UUUWWW	105	0	0
S6	ha	PPPP	716	552	538
S6	ha	Salt pasture	34	85	148
S6	ha	OM	0	113	64
S7	ha	PPPP	188	188	188

[a] P = pasture, W = wheat, L = lupins, OM = oil mallee, U = lucerne.

- reduced numbers of sheep, lower stocking rates, and more supplementary grain feeding per head,
- slightly more area allocated to perennial plants (lucerne, saltland pastures, and oil mallees).

Other changes not consistent across farm types or climate regimes are changes in the structure of the sheep flock, changes in the number of sheep agisted and sold, and changes in the area of lupins.

Profit

The analyses indicate that projected climate changes place downward pressure on farm profits for all three farm types included in the analyses. Farm profit declines by approximately 50% moving from the base case to scenario 1 and by approximately 80% moving from the base case to scenario 2 (Table 5).

The main factor influencing the forecast decline in farm profit attributable to climate change is the decrease in crop production as a result of declining crop yields given the increased frequency of dry weather years (F, J, and K). Also the reduced frequency of very favorable weather years reduces the contribution to expected farm profit from tactical alterations in the enterprise mix in these favorable years.

The significant change in probability of poor weather years, in the absence of offsetting benefits such as CO_2 fertilization, technical change, and reduced frost, would substantially influence the viability of many farms in the region, particularly those farms which are currently marginally profitable. The very high profit years (weather years A, B, and D) are considered important for debt repayment and capital purchases. In the event that the probability of these seasons is halved from 0.292 to 0.137 (climate-change scenario 2), some farms in the region may no longer be capable of making the capital investments needed for large-scale cropping. Some of these farms would either run down their machinery assets and/or switch more resources into sheep production that requires less capital expenditure.

Land Use

As noted above, the climate-change scenarios modeled lead to a reduced emphasis on crop production. Underlying the results in Table 4 are detailed sets of optimal land uses for each case. Table 5 shows the underlying land uses for the representative farm only. The changes are complex, and strongly influenced by farming-systems considerations. For example, although pasture area tends to increase as climate change becomes more severe, it does not do so evenly on each soil type. Indeed on soils 2 and 6 the area of pasture decreases. There are two soils for which pasture area increases in climate-change scenario 1, but then decreases in scenario 2. This is driven by the need to manage feed budgets throughout the year, and the introduction of increasing areas of saltland pastures, which compete with annual pasture for land, and then provide feed at different times of the year.

Besides the land use and enterprise changes given in the table, farmers in the Merredin region also use other mechanisms to manage both climate and market uncertainty. These include maintenance of high equity, a preparedness to defer personal expenditures in low-income years, deferment of capital purchases, and liquidation or purchase of off-farm investments.

Salinity Management

Focussing on the use of perennials in Table 5, oil mallees and saltland pasture areas increase slightly, while lucerne area decreases from its initial low level to zero. The slightly enhanced role of oil mallees and saltland pastures is likely to be a result of the assumption that their yields will not diminish in the face of climate change, due to their deep-rooted nature and ability to endure dry periods.

Nevertheless, the effect of the climate-change scenarios on the overall area of perennials is not great. We hypothesized that this reflects the low areas of existing perennial options selected as optimal by the model. Current R&D is likely to provide new perennial management options that can both reduce losses due to salinity and improve profitability in increasingly variable climates scenarios. To examine the potential consequences of such R&D, Table 6 shows results for the representative farm assuming that productivity of oil mallees and saltland pastures are increased by 25% and lucerne increased by 50%.

With more productive perennials, the area of perennials increases to 15–20% of the farm. In this scenario, climate change continues to have a small positive impact on the area of perennials sown, including, in this case, on the area of lucerne. The magnitude of the impact of climate change on the expected total area of perennials is little different to the model with less-productive perennials.

The main effect of the increase in perennial productivity is a substantial fall in the expected area of tactical crop area adjustments, down by 10–20 percentage points. In other

Table 6. A summary of optimal farm plans for the representative farm, if productivity of perennials increased by 25% (oil mallees and saltland pastures) and 50% (lucerne)

Activity		Representative farm			Difference to Table 4		
Climate-change scenario >	Unit	No change	1	2	No change	1	2
Profit	$/000	239.0	113.5	72.1	27.1	16.8	17.9
Pasture area[a]	%[b]	39	43	46	−3	−4	−3
Crop area	%	51	44	42	−1	0	0
Lucerne	%	3	4	4	2	4	4
Saltland pasture	%	2	5	4	2	4	3
Oil mallee	%	10	11	10	4	2	2
All perennials[c]	%	15	20	18	7	9	6
Crop tactical adjustments[a]	%	8	6	5	−20	−15	−10

[a] "Pasture" includes lucerne, saltland pasture, and annual pasture.

[b] Percentages of the farm's arable area.

[c] Lucerne + saltland pasture + oil mallees.

words, the management strategy is more consistent from year to year, and less responsive to climatic variation. When the perennials were less productive, climate change had a substantial effect on the area of tactical adjustments: down from 28 to 15% of the area per year. With more productive perennials, tactical adjustments are already much reduced even without climate change (down to 8%) and the additional effect of climate change is small (a further fall to 5%). The combined effect is a dramatically more stable and consistent farm plan.

An additional impact of climate change on the area of perennials may occur through its impact on the capacity of farmers to adopt new technologies. The substantially lower levels of profit indicated by the model after climate change suggest that farmers may have some difficulty adopting these land uses, especially oil mallees and saltland pastures, which require relatively large capital investment during establishment programs.

On the plus side, it is possible that the projected changes in climate that involve less winter rainfall and higher temperatures will cause a reduction in deep drainage (as long as any increase in summer rainfall is not too large—see Table 2) and therefore a slowing in the rate of spread of salinity.

Comparing Severity of Climate Change and Salinity

The question arises whether dryland salinity or climate change is likely to have the greater impact on farms in this region. Table 7 shows results comparing whole-farm profits with and without climate change and with and without severe dryland salinity. Dryland salinity is represented by the conversion of all of soils 6 and 7 into severely salt-affected land—too saline even for saltland pastures. This would overstate the likely severity of the problem on most farms, but provides an extreme case for comparison.

In broad terms, the two issues have effects of similar magnitude. If the benchmark climate is based on long-term historical records, climate-change scenario 2 would have a greater impact on farm profits than the dryland salinity scenario assumed. On the

Table 7. Whole-farm profits (A$'000) for representative farm with and without climate change and dryland salinity, assuming more productive perennials as per Table 6

	No dryland salinity	Severe dryland salinity	Difference
No climate change	239	145	94
Climate-change scenario 1	114	40	74
Climate-change scenario 2	72	7	65
Difference (No change − 2)	167	138	
Difference (1 − 2)	42	33	

other hand, if we consider climate over 1970–2000 to be the benchmark, the additional projected climate change of scenario 2 would have a smaller effect than the dryland salinity scenario. Given that this salinity scenario probably overstates the severity of salinity for most farmers, the overall impacts of the two changes may be similar.

CONCLUSION

This study examines how expected-profit-maximizing farm plans for three types of farms in the low-rainfall region of the eastern wheatbelt of Western Australia may differ if a projected change in climate occurs. The findings are best viewed as an approximation of the possible impacts of climate change, as several caveats and limitations apply to the analyses. These limitations are likely to cause results to over-state the profit-reducing impacts of climate change. For example, the analyses exclude technological innovation in response to climate change. Also excluded are any beneficial yield impacts from a likely increase in the CO_2 concentration and reductions in frost risk. Notwithstanding these deficiencies, the analyses reveal the substantial size of the technical and financial challenge posed by possible climate change. In the more extreme climate-change scenario modeled, farm profits could be reduced by around 80% compared to historical climate.

Several main findings from the analyses have been highlighted. Although optimal farm plans become less crop dominant, livestock carrying capacity diminishes and more supplementary grain feeding per head is required. There are fewer opportunities for the tactical alteration of crop and pasture areas, as the frequency of favorable weather-years diminishes. Of relevance to salinity management, the perennial plants are shown to be small but robust selections in optimal farm plans in the face of forecast climate change. Improved perennial plant options are likely to play a stronger role in future, both in terms of providing improved salinity management and more resilient agricultural systems to cope with climate change. Climate change may slightly increase the incentive to adopt salinity management practices, but at the same time reduce the financial capacity for adoption due to reductions in financial liquidity. Depending on details of the timing of rainfall, reduced annual rainfall may reduce the onset of dryland salinity.

Overall, climate change is shown to be of broadly similar importance to eastern wheatbelt farmers as dryland salinity, although this depends on the extent to which climate change does actually occur, which remains highly uncertain.

REFERENCES

Abrecht, D. G. and S. Robinson. 1996. TACT: A tactical decision aid using a CERES-based wheat simulation model. *Ecological Modelling* 86: 241–4.

Amthor, J. S. 2001. Effects of atmospheric CO_2 concentration on wheat yield: Review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Research* 73: 1–34.

Ash, A. J., P. O'Reagain, P. McKeon and M. Stafford-Smith. 2000. Managing climate variability in grazing enterprises: A case study of Dalrymple Shire, north-eastern Australia. In *Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems - the Australian Experience*, edited by G. L. Hammer, N. Nichols and C. Mitchell. Dordrecht: Kluwer, pp. 253–70.

Australian Bureau of Statistics. 2002a. *Agricultural Census of Western Australia: Local Government Area Data*. Canberra: Australian Bureau of Statistics.

Australian Bureau of Statistics. 2002b. *Salinity on Australian Farms*, Report 4615.0. Canberra: Australian Bureau of Statistics.

Bowman, S. and J. K. Ruprecht 2000. Blackwood River Catchment Flood Risk Study, Water and Rivers Commission Report No. SWH 29. East Perth: Government of Western Australia.

CSIRO. 2001. *Climate Change Projections for Australia*. Melbourne: CSIRO Atmospheric Research. Available at http://www.dar.csiro.au/publications/projections2001.pdf [accessed April 11, 2005].

Dracup, M., I. Foster, G. Pasqual, D. Stephens and D. Tennant. 2003. Climate forecasting and application for the Western Australian grain belt. Perth: Department of Agriculture Western Australia.

Essex, C. and R. McKitrick. 2002. *Taken by Storm: The Troubled Science, Policy and Politics of Global Warming*. Toronto: Key Porter.

Foster, I. 2002. Climate change projections and impacts for WA. Perth: Department of Agriculture Western Australia. Farmnote 5/2002.

Fuhrer, J. 2003. Agroecosystem responses to combinations of elevated carbon dioxide, ozone and global climate change. *Agriculture, Ecosytems and Environment* 97: 1–20.

George, R., D. McFarlane and R. Nulsen. 1997. Salinity threatens the viability of agriculture and ecosystems in Western Australia. *Journal of Hydrogeology* 5: 6–21.

Ghassemi, F., A. J. Jakeman and H. A. Nix. 1995. *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. Sydney: University of New South Wales Press.

Hebeisen, T., A. Luscher, S. Zanetti, B. U. Fischer, U. Hartwig, M. Frehner, G. R. Hendrey, H. Blum and J. Nosberger. 1997. The different responses of *Trifolium repens L.* and *Lolium perenne L.* grassland to free air CO_2 enrichment and management. *Global Change Biology* 3: 149–60.

Hingston, F. J. and V. Gailitis. 1976. The geographic variation of salt precipitation over Western Australia. *Australian Journal of Soil Research* 14: 319–35.

Howden, S. M. 2003. Climate variability and climate change: Challenges and opportunities for farming an even more sunburnt country. In *Proceedings of the National Drought Forum*. Brisbane, Queensland: Department of Primary Industries, pp. 42–6.

Howden, S. M. and H. Meinke. 2003. Climate change: Challenges and opportunities for Australian agriculture. In: *Proceedings of the Conference on Climate Impacts on Australia's Natural Resources: Current and Future Challenges, Queensland, Australia*. Canberra: Standing Committee on Natural Resource Management. Managing Climate Variability Program, pp. 53–5.

Howden, S. M., G. M. McKeon, M. Entel and N. Flood. 2001. Impacts of climate change and climate variability on the competitiveness of wheat and beef cattle production in Emerald, north-east Australia. *Environment International* 27: 155–60.

Indian Ocean Climate Initiative. 2002. *Climate Variability and Change in South West Western Australia*. Perth: Indian Ocean Climate Initiative.

John, M. 2005. The economics of dryland salinity management in a low-rainfall environment of Western Australia. Ph.D. thesis. University of Western Australia, Perth.

Kefford, B. J., P. J. Pappas and D. Nugegoda. 2003. Relative salinity tolerance of macroinvertebrates from the Barwon River, Victoria, Australia. *Marine and Freshwater Research* 54: 755–65.

Keighery, G. 2000. Wheatbelt wonders under threat. *Landscope* 16: 37–42.

Kimball, B. A., A. Kobayashi and M. Bindi. 2002. Responses of agricultural crops to free-air CO_2 enrichment. *Advanced Agronomy* 77: 293–368.

Kingwell, R. S. 1994. Risk attitude and dryland farm management. *Agricultural Systems* 45: 191–203.

Kingwell R. S., D. J. Pannell and S. Robinson 1993. Tactical responses to seasonal conditions in whole-farm palnning in Western Australia. *Agricultural Economics* 8: 211–26.

McCown, R. L., G. L. Hammer, J. N. G. Hargreaves, D. L. Holzworth and D. M. Freebairn 1996. APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50: 255–71.

McFarlane, D. J. and R. J. George. 1992. Factors affecting dryland salinity in two wheatbelt catchments in Western Australia. *Australian Journal of Soil Research* 30: 85–100.

Mullen, J. 2002. Farm management in the 21st century. *Agribusiness Review* 10(paper 5). Available at http://www.agribusiness.asn.au/Publications_Review/Review_Vol10/Mullen.htm [accessed July 14, 2005].

National Land and Water Resources Audit. 2001. *Australia's Dryland Salinity Assessment, 2000*. Canberra: Land and Water Resources Research and Development Corporation. National Land and Water Resources Audit.

Nicholls, N. 1997. Increased Australian wheat yield due to recent climate trends. *Nature* 387: 484–5.

Nicholls, N., L. Chambers, D. Collins and D. Jones. 2003. Recent Australian climate change. In: *Proceedings of the Conference on Climate Impacts on Australia's Natural Resources: Current and Future Challenges, Queensland, Australia*. Canberra: Standing Committee on Natural Resource Management. Managing Climate Variability Program, pp. 9–11.

Pannell, D. J. 2001. Dryland salinity: Economic, scientific, social and policy dimensions. *Australian Journal of Agricultural and Resource Economics* 45: 517–46.

Pannell, D. J. and M. A. Ewing. 2005. Managing secondary dryland salinity: Options and challenges. *Agricultural Water Management* (forthcoming).

Pannell, D. J., L. R. Malcolm and R. S. Kingwell. 2000. Are we risking too much? Perspectives on risk in farm modelling. *Agricultural Economics* 23: 69–78.

Penuelas, J. and I. Filella. 2001. Responses to a warming world. *Science* 294: 793–5.

Petersen, E., S. Schilizzi and D. Bennett 2003. The impacts of greenhouse gas abatement policies on the predominantly grazing systems of south-western Australia. *Agricultural Systems* 78: 369–86.

Pittock, B. 2003. Climate change and Australia's natural resources: A review. In: *Proceedings of the Conference on Climate Impacts on Australia's Natural Resources: Current and Future Challenges, Queensland, Australia*. Canberra: Standing Committee on Natural Resource Management. Managing Climate Variability Program, pp. 51–2.

Quiggin, J. and J. Horowitz. 2003. Costs of adjustment to climate change. *Australian Journal of Agricultural and Resource Economics* 47: 429–46.

Reyenga, P. J., S. M. Howden, H. Meinke and W. B. Hall. 2001. Global impacts on wheat production along an environmental gradient in south Australia. *Environment International* 27: 195–200.

Van Ittersum, M. K., S. M. Howden and S. Asseng. 2003. Sensitivity of productivity and deep drainage of wheat cropping sytems in a Mediterranean environment to changes in $CO_{2,}$ temperature and precipitation. *Agriculture, Ecosystems and Environment* 97: 255–73.

Walker, G., M. Gilfedder and J. Williams. 1999. Effectiveness of current farming systems in the control of dryland salinity. Canberra: CSIRO Land and Water.

Wheeler, T. R., G. R. Batts, R. H. Ellis, P. Hadley and J. I. L. 1996. Growth and yield of winter wheat crops in response to CO_2 and temperature. *Journal of Agricultural Science* 127: 37–48.