Assessment of the Possible Impacts of Future Atmospheric Change on South Australian Wheat Production

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A Thesis Submitted for the Degree of Doctor of Philosophy
in

THE UNIVERSITY OF ADELAIDE
AUSTRALIA

Department of Geographical and Environmental Studies

March 2003

Publications during the Candidature

1. Luo, Q., Bellotti, W., Bryan, B., and Williams, M.: 2003, Risk Analysis of Possible Environmental Change Impacts on Wheat Production in South Australia. *Proceedings of the 11th Australian Agronomy Conference*. Geelong, Victoria, Australia, 2 - 6 February 2003.
2. Luo, Q., Williams, M., Bellotti, W. and Bryan, B.: 2003, Quantitative and Visual Assessment of Climate Change Impacts on South Australian Wheat Production. *Agricultural System* **77** (3) 173-186.
3. Luo, Q., Bryan, B., Bellotti, W. and Williams, M.: 2002, Spatial Analysis of Environmental Change Impacts on Wheat Production in Mid-Lower North, South Australia. *Proceedings of the e-future: into the mainstream, the Joint Institution of Surveyors Australia and AURISA Conference*. Adelaide, South Australia, 25-30 November 2002.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

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Acknowledgements

This piece of work has been strongly supported by many people and a number of organizations. Firstly I would like to thank my three supervisors: Professor Martin Williams (Department of Geographical and Environmental Studies), Dr. Bill Bellotti (Department of Agronomy and Farming Systems) and Dr. Brett Bryan (Department of Geographical and Environmental Studies) for their expertise and input to this project. Professor Williams supported me in every possible way including scholarly knowledge in climate and soil science, financial support for computer and software purchases and for the author to develop new research skills, valuable time for carefully checking each chapter of my thesis and for supporting every funding proposal. Your encouragement and care throughout this program are highly appreciated. Thank you, Dr. Bellotti for your precious time, guidance and invaluable insight to this work. You are so keen on this project and come to my office from another campus at regular intervals to instruct me. You are so patient with me for any questions arising from conduct of this research. The regular meeting is very helpful for the successful completion of this project. Your provision of historical climate data, your help in getting the soil profile data and your financial support for the coming agronomy conference must also be acknowledged. The same compliment needs to be extended to my third supervisor: Dr. Bryan. Thank you for your guidance in applying Geographic Information System (GIS) to this PhD project and in research result communication and for digital data acquisition.

Special thanks are extended to Dr. Roger Jones (Atmospheric Research, CSIRO) for his constructive suggestions on the construction of probabilistic environmental change scenarios and for his provision of global warming data, local climate change information and GHG (Greenhouse Gas) emission scenarios for 2080 as well as a software for extracting those local climate change data.

Thanks must go to the Agricultural Production System Research Unit (APSRU) for distributing the APSIM-Wheat model and its technical support to this project. Two people need to be specially mentioned. One is Dr. Enli Wang. He provided me strong technical support for applying APSIM-Wheat Model to this program. The other is Dr. Holger Meinke.

He organized the workshop in which the author was trained to apply APSIM and provided the author some financial support during that training.

I also would like to record my thanks to David Maschmedt (Sustainable Resources, Primary Industries and Resources South Australia (PIRSA)). He provided me with large samples of soil profile data and helped me with the derivation of soil parameters. The authors also would like to thank GIS Manager-Pugh Steven and Dr. Jan Rowland, (Land Information, PIRSA) for providing me the digital soil databases.

Thanks are extended to Dr. Gary Glonek (Department of Mathematics) for his help in Monte Carlo Random Sampling techniques under S-Plus environment. Thanks are also extended to Dr. Ian Cooper (Department of Agronomy and Farming Systems) for his provision of an Excel spreadsheet for calculating the critical yield threshold.

Finally I would like to thank Adelaide University for the Scholarship to complete this project, GISCA for providing me the access to GIS and statistical facilities and the Department of Geographical and Environmental Studies for these three and half years' support.

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Abstract

Two parallel studies: a site specific study and a spatial study were conducted to assess the potential impact of future atmospheric change (climate change plus pCO_2 change) on South Australian wheat production in 2080. Three tools-APSIM-Wheat Module, Monte Carlo Random Sampling techniques and GIS (Geographic Information System) were employed to assess quantitatively and visually the possible impacts of future atmospheric change on median grain yield, median grain nitrogen content and risk. The APSIM-Wheat Module is the core of this study. The Monte Carlo Random Sampling is the key to the construction of the probabilistic atmospheric change scenarios or to the quantification and treatment of uncertainties surrounding impact assessment. Risk analysis corresponding to uncertainty range was conducted through the introduction of a critical yield threshold. GIS is a useful tool to manage spatial climate data and spatial soil data and to present specific/detailed impact information in a map format.

Study results show that the most likely median grain yield in 2080 will decrease (-58% ~ 0%) across all locations and all areas. The most likely grain nitrogen content will decrease or increase (-14% ~ 16%) depending on location and area. A critical yield threshold was calculated based on current costs and wheat production. Risk was assessed as the conditional probability of not exceeding the critical yield threshold for specific locations. The risk of wheat production under the most likely atmospheric change scenario will increase at least one level (section 7.3) in most locations and most areas. These outcomes indicate that South Australian wheat production will face severe challenges from future atmospheric changes. Adaptation strategies to cope with the above adverse effects on South Australian wheat production resulting from future atmospheric changes have been addressed in the form of autonomous adaptation options and planned adaptation strategies. Changes in production activities and management adaptations could play an important role in mitigating the detrimental impacts of atmospheric change.

Results from the spatial study show that large variation of impact outcomes within the same climate division has been found due to variability of plant available water capacity, indicating the necessity of including soil variability in agricultural impact assessment.

Impact assessment based on methodologies adopted in this study is more accurate, complete and comprehensive than previous studies in view of uncertainty quantification and treatment. Adaptation strategies are more applicable, practical, effective and economical in light of probability attachment to impact indicators, in light of risk analysis and in light of spatial analysis.

This study has identified significant risks to the S.A wheat industry in the coming decades due to atmospheric (climate) change. Based on this study, some areas, mainly low rainfall regions, will no longer be viable for wheat production. Even in the higher rainfall areas, wheat production and profitability will be significantly reduced, based on current management practices. Further analyses of management options to reduce the impact of climate change on wheat production are justified based on the results of this study.

1. INTRODUCTION TO ATMOSPHERIC CHANGE AND ITS IMPACT

Atmospheric change including climate change and atmospheric CO_2 concentration (pCO_2) change and its impact on wheat production have attracted considerable attention from governments and scientists over the last two decades due to their importance to people's subsistence and world grain trade. A large number of studies related to this field have been conducted (see Chapter 2). Scientific knowledge on atmospheric change and its impact has been obtained through those studies and can be enhanced and improved through the further development of scientific technology. The release of the IPCC Special Report on Emission Scenarios (SRES) is an example of the research progress made in atmospheric science. This report has focused attention on assessing the possible impacts of future atmospheric change on agricultural production based on greenhouse gas emission scenarios and global warming scenarios provided by SRES. This chapter provides an introduction to this dissertation, which includes three important sections: background of global warming and its impacts; research significance; and research aims and objectives.

1.1 BACKGROUND

1.1.1 Atmospheric change and Its Implication at a Global Scale

It is reported that the globally and annually averaged surface temperature has increased by 0.6±0.2°C over the 20th century. Most of the observed warming is likely to have been due to the increase in greenhouse gas concentration (IPCC, 2001b). Since pre-industrial times, atmospheric CO_2 (one of the most important greenhouse gases) concentration has increased 28% from 280 parts per million volume (ppm) in 1800 to 370ppm in 1999 mainly as a result of human activities such as burning fossil fuels and land use change. Further increases in atmospheric CO_2 concentration will occur with projections from 478ppm to 1099ppm by 2100, given the range of IPCC SRES emissions and uncertainties about the carbon cycle. This range of implied radiative forcing gives rise to an estimated global warming from 1990 to 2100 of 1.4 to 5.8°C, assuming a range of climate sensitivities. The projections indicate that the warming would vary by region, and be accompanied by an increase or decrease in precipitation. In addition, there would be changes in climate variability, and changes in the frequency and intensity of some extreme climate phenomena (IPCC, 2001b).

It is well known to all that atmospheric CO_2 is an essential component for crops to synthesise food, and that climate plays an important role in determining crop growth, development and final yield. Changes in atmospheric CO_2 concentration and climate (atmospheric change) will inevitably change wheat production through both biophysical processes and socioeconomic processes. Increasing atmospheric concentration of CO_2 is likely to directly affect wheat production through the stimulation of photosynthesis (Morison and Gifford, 1984), and through the improvement of water use efficiency (Cure and Acock, 1986) and to indirectly affect wheat production through the impacts of climate change (Howden, 1999a and 1999b). In view of global grain markets and socioeconomic processes, atmospheric change may have significant implications for world grain production patterns, current grain supply-demand relationships, subsistence economies, regional/national economies and human welfare, such as changed income and food supply.

Some regions will benefit more while other regions will benefit less or even endure losses due to the regional divergence of future atmospheric change, which will lead to the alteration of the world wheat production pattern, the supply-demand relationship and global grain market. World grain price is the key summary indicator of the balance between global demand and supply, which determines the access of a majority of the world's population to an adequate diet. It is projected that a mean annual temperature increase of 2.5°C or greater would prompt food prices to increase as a result of slowing in the expansion of global food capacity relative to growth in global food demand (IPCC, 2001a). In light of the possible increase of global grain price and the possible adverse effects of atmospheric change on wheat production, the incomes of vulnerable populations will lower and the absolute number of people at risk of hunger will increase, especially in developing countries where adaptation capacity is limited. It is estimated that the number of hungry and malnourished people in the world may increase, because of atmospheric change, by 10% relative to the baseline (i.e., an additional 80-90 million people) later in the 21st century (Parry et al., 1999). However, some regions (particularly in the arid and semiarid tropics) may be affected more. A decrease of precipitation, an increase in potential evapotranspiration, or higher interannual variability (particularly longer drought) could tip the balance from a meager livelihood to no livelihood at all, and the unique cultures often found in marginal areas could be lost (IPCC, 2001a).

1.1.2 South Australian Climate Change and Its Implication for Local Economy

Impacts of atmospheric change on food production in Australia will be both direct and indirect through changing global supply and demand influenced by atmospheric changes in other parts of the world. A highly variable environment is a feature of current Australian agricultural production such as a highly variable seasonal climate and frequent El Niño Southern Oscillation (ENSO) events. Further atmospheric change will worsen the agricultural production environment. As a result, Australian agriculture will face a severe challenge from future atmospheric change itself and from changes in commodity prices stemming from this atmospheric change.

Projected temperature changes for the South Australian (SA) wheat belt in the year 2070 range from 0.7°C to 5.2°C. Projected growing season rainfall changes vary from -60% to +10%, presenting a decreasing trend, while the non-growing season rainfall change ranges from -35% to +35% (CSIRO, 2001). Enhanced plant growth and water use efficiency due to CO_2 increase may provide initial benefits offsetting any negative impacts due to climate change, although the balance is expected to become negative with warming in excess of 2°C and associated rainfall decrease. Agricultural activities in this state are particularly vulnerable to regional reductions in rainfall. Climate variability is a major factor in the economy of South Australia, principally through the flow-on effects of ENSO-related major droughts on agriculture. Drought frequency and consequent stresses on agriculture are likely to increase due to higher temperatures. Farmers in drought-sensitive parts of the state will be increasingly vulnerable under the condition that interannual droughts will occur more frequently in future or will be more intense. In addition, reliance on exports of agricultural products make this State sensitive to changes in commodity prices induced by changes in the environment elsewhere (IPCC, 2001a). When this scenario is superimposed on the possible exacerbation of soil degradation resulting from atmospheric change, it is apparent that the possible impacts of atmospheric change on agricultural production in SA require rigorous evaluation. Waterlogging, salinisation, acidification, wind and water erosion are already major environmental problems in South Australia and there is no evidence that they are under control. In many parts of this state, thresholds of stability have been exceeded. If present land use is not responsive to greenhouse gas induced climate change, these and other forms of soil degradation are likely to increase, particularly in the wheat belt where decreased soil moisture would make present land use marginal in some areas (Fitzpatrick and Wright, 1993).

1.2 SIGNIFICANCE

Agriculture plays an important role in Australia's economy. It currently accounts for 4% of GDP, but is more important in trade terms, accounting for nearly 30% of total Australian merchandise export. Agriculture exports were worth more than $23 billion in 1996/1997(Department of the Environment: 1997). Wheat is the main cash crop. Wheat exports from Australia take fourth place in the world.

Agriculture has traditionally been a significant component of the South Australia's economy. For example, in the 19th century, wheat and wool were virtually the only farm products produced in South Australia, which could sustain their cost of transport to distant markets. These two products still make up about 40% of the value of farm production today. Agriculture contributes a greater proportion of returns to the State's economy than that of virtually any other State in Australia. Statistical information shows that farm production takes up 34.4% of the value of goods; mines, quarries and gas-fields account for 12.4%; fisheries 1.1%, and manufactured goods 52.1% in the year of 1983-1984 in this state (Griffin and McCaskill, 1986). South Australian agricultural production is dominated by crop production. Australian Bureau of Statistics (ABS) data show that in 2000-2001, it accounted for 75% (26% for wheat) of the value of farm output compared with 11% for wool and other livestock products and 14% for livestock sold for slaughtering.

The impacts of atmospheric change on South Australian wheat production are a key concern to Australia and South Australia because of its importance to the State and national economy.

The importance of wheat production to the State and national economy can be illustrated in two ways: the gross value and the export value. The latter is more important. Over the three years to 1988/89, the average gross value of wheat produced in South Australia was $309 million per year, representing 15% of the gross value of all agricultural production in this state. It is estimated that over 80% of the wheat produced in this state is exported (Dubē and Cook, 1992). Wheat production is a major agricultural industry in South Australia. It consistently earns valuable export income (A$473M in 2000) for the State and supports an important industry and a range of manufacturing, marketing and agribusiness agencies.

Changes in wheat yields and grain quality will have obvious implication in terms of farm economic viability, on risks of starvation in subsistence economies and on international grain trade. Comprehensive studies of the possible impacts of climate change on wheat production are potentially beneficial to both farm management to ensure sustainable development of agriculture and policy making whether in agricultural production or in environmental diplomacy.

1.3 RESEARCH AIM AND OBJECTIVES

1.3.1 Research Aim

The aim of this study is to assess the vulnerability of South Australian wheat production to future environmental change. In order to obtain accurate and comprehensive information on the possible impacts of future atmospheric change on South Australian wheat production, and in order to provide practical, applicable, economical and effective adaptation strategies, quantitative, statistical and visual tools were used including the APSIM-Wheat Model, Monte Carlo statistical techniques and GIS.

Four impact indicators: median grain yield, median grain nitrogen content, risk (economic viability) of wheat production, and failure to sow a crop were selected as criteria for evaluating objectives. Yield is the most important economic property of a crop, and embodies the development level of agricultural technology and the environmental condition for crop production in a certain area. Grain protein content is another important economic property of wheat. Many overseas consumers are now specifying minimum protein levels in wheat and in 1989 the Australian Wheat Board (AWB) introduced a sliding scale of payments for protein levels between 8% and 14%. (Dubē and Cook, 1992). Risk is a synthesized indicator, which scales the economic viability of wheat production in a certain area. Failure to sow a crop is used to study the possible effects of different atmospheric change scenarios on the number of years where soil moisture is inadequate to allow crops to be sown and/or establish successfully.

1.3.2 Research Objectives

To meet the aims of this study five research objectives were defined:

(1) To identify, quantify and manage uncertainties encompassing atmospheric change impact assessment from the projection of greenhouse gas emissions, the projection of global warming, and projection of local climate change by applying Monte Carlo Random Sampling techniques;

(2) To assess the combined effects of atmospheric change (climate change plus atmospheric CO_2 change) on median grain yield, on median grain nitrogen content, and on risk of wheat production;

(3) To assess the individual effects of atmospheric change (rainfall, temperature and atmospheric CO_2 change) on median grain yield, on failure to sow a crop and on risk of wheat production at two locations of the site-specific study;

(4) To visually assess the combined impacts of atmospheric change on median grain yield, median grain nitrogen content and on risk of wheat production by using Geographic Information System (GIS) technology through a spatial study with soil variability taken into account; and

(5) To address adaptation strategies aimed at minimizing adverse effects and taking advantage of new opportunities presented by atmospheric change based on this study.

There are three important aspects to this study. Firstly, probability was attached to atmospheric change scenarios and attached to impact indicators such as median grain yield, median grain nitrogen content and risk. Secondly, risk analysis was conducted in this study through the determination of critical grain yield threshold, which moves impact assessment beyond simple sensitivity and vulnerability assessment towards the goal of forecasting specific impacts under expected atmospheric change. Lastly, the importance of spatial variability of atmospheric change impact outcomes was considered. The three aspects are important because they are innovative.

1.4 CONCLUSION

There is growing acceptance that global temperature has increased over the last century due to the increase of atmospheric pCO_2 as a result of anthropogenic activities such as fossil fuel burning and land use change etc. Projected atmospheric pCO_2 will increase from 478 ppm to 1099 ppm by 2100 based on IPCC SRES emission scenarios. Corresponding to this range of atmospheric CO_2 concentration, 1.4 to 5.8°C of global warming was estimated from 1990 to 2100. This magnitude of global warming will severely affect regional and local climate systems. Agricultural activities such as wheat production, which is closely associated and sensitive to regional/local climate, will definitely be affected by a changed climate system. Changes in regional wheat production will have significant consequences for other parts of the world whether in the production industry or in the socioeconomic sector. Frequent drought and soil degradation are current environmental problems faced by South Australian wheat production. Future atmospheric change will exacerbate these problems and will bring about challenges for the South Australian wheat industry. The comprehensive and deep assessment of the impact of atmospheric change on South Australian wheat production will have far-reaching significance for the South Australian economy as well as for people's welfare elsewhere. Because of this, research aims/objectives are set out. The next chapter reviews climate change impacts on world wide wheat production. From this review, specific research needs for assessing the impact of atmospheric change on South Australian wheat production are identified.

2. CLIMATE CHANGE IMPACTS ON WHEAT PRODUCTION: A REVIEW

Thoroughly reviewing previous studies is the first step in conducting new research and in providing a base on which to identify their limitations and research problems and to put forward further research needs and priorities. Along with climate change studies, climate change impact studies on agriculture have been extensively pursued for many years, especially since the 1990s. With greater understanding of climate change and of the interactions between climate change and crops, and with the development of reliable and accurate crop models, climate change impact studies are becoming more comprehensive and in-depth, although there are still some uncertainties and methodological problems. The history of the development of assessment tools such as crop models and of the approaches for constructing climate change scenarios is traced. A large number of wheat impact studies, which employed those crop models and approaches for constructing climate change scenarios were reviewed. Further research needs/research priorities are identified according to the incompleteness of previous studies. The focus of this study is defined, based on resources available for this research.

2.1 CROP MODELS

Crop models are the main tools for quantifying the possible impacts of climate change on wheat production. Two types of model were used in assessing possible impacts of climate change on wheat production: empirical models and mechanistic models. Empirical models, also known as statistical models or regression models or static models, were used in the earlier climate change impact studies. Most applications of statistical models introduce weather and climate effects in a highly simplified fashion and thus are unable to simulate the effects of the extremes of weather as it varies on a daily basis, as is possible with dynamic crop growth models. This kind of model was used to summarise past data, to interpolate within the range of past data. The disadvantage of this kind of model is its insufficiency for extrapolative prediction or for explanatory interpretation (cause and effect). An example of this approach is the study conducted by the National Defense University in which the long-term effects of climate change on crop yields and agricultural production were evaluated with a relatively simple cause-and effect approach (NDU, 1980).

Mechanistic models or dynamic models involving crop response to daily or more frequent changes in environment were developed in step with computer science and technology. Mechanistic models are mixtures of mechanism and empiricism. Mechanistic models are generally considered to be based on physical and physiological processes, and consider cause and effect at the process level. That is why they are also called process-oriented models. Material (C, N, and water) and energy are usually included. As a tool to assess the vulnerability and adaptation of agriculture to climate change, process models are more accurate, because of the more realistic the mechanisms in dynamic models. Mechanistic models are divided into two categories: simple models (universal models) and comprehensive mechanistic models. Simple models are easy to comprehend, easy to use and apply, and require fewer inputs which corresponded to the level of computer science and technology at that stage. However, they are limited in modelling feedback mechanisms; limited in ability to describe genotype differences; limited in use for process-level physiology; and limited in ability to respond to a wide range of cultural management practices. Comprehensive, mechanistic models consider processes at a level that facilitates the interaction of plant physiologists with the modelling team. These mechanistic models generally are better able to model genotype × environment differences (G×E), to include intrinsic feedback and to handle variable cultural management conditions. This category of models unavoidably has its own limitations such as being more difficulty to understand, to use and apply; has more input requirements; may show instability of output and is sometimes impractical in field situations. Limitations related to model inputs can be attributed to the cost of obtaining data including purchase of data and instruments for measuring data; spatial variability of soil; the technical knowledge required for some inputs (parameterisation); temporal variability (e.g., pest outbreak); and data quality (e.g., poorly calibrated sensors) (Boote et al., 1996).

Comprehensive mechanistic models, such as the Crop-Environment Resource Synthesis-Wheat model (CERES-Wheat) and the Agricultural Production System Simulator-Wheat model (APSIM-Wheat), have been developed and extensively used to simulate the possible effects of climate change and/or increased pCO_2 on wheat production. Comprehensive mechanistic models have become the main tool in analysing the potential impacts of climate change on agriculture. Normally, the outputs from equilibrium and/or transient General

Circulation Models (GCMs) with climate variability considered (or not) are combined with dynamic crop models with the CO_2 fertilisation effect taken into account (or not) by using a Stochastic Weather Generator or the built-in functionality of the crop model (Luo and Lin, 1999) to quantify the possible impacts of climate change and increased pCO_2 on wheat production.

2.2 CLIMATE CHANGE SCENARIOS AND THEIR CONSTRUCTION

Because of the uncertainties surrounding prediction of climate change, it is common to employ climate scenarios (Wigley, 1987; Lamb, 1987) to estimate the impacts of climate change on a system. Climate scenarios are sets of climatic perturbations which are used with impact models to test the sensitivity of the system to the prescribed changes. Scenarios are often devised by changing an original set of climatological data by prescribed anomalies. These anomalies may be arbitrary settings of climate change, or may be derived from GCMs or from historical climate (Rosenzweig and Iglesias, 1998).

Two approaches have been developed and used in climate change impact studies. One assumes that the change of each weather variable is unrelated to the change of the other variables. This approach is normally applied through sensitivity analysis studies, in which the user modifies the weather conditions through a fixed ratio or sets the weather variables to constant values. Generally, arbitrary incremental changes of climate (for example, a temperature increase of 2°C or 4°C and/or a rainfall change of ±20%) were specified for temperature and precipitation and uniformly applied to the baseline climate to explore the response of crop production systems to changed climate with the aid of crop models (McKeon et al., 1988; Wang et al., 1992; Aggarwal and Sinha, 1993; Tubiello et al., 1995; Menzhulin et al., 1995; Seino, 1995; Rosenzweig and Iglesias, 1998). Single climate variables (Aggarwal and Sinha, 1993; Tubiello et al., 1995) or combinations of climatic variables (McKeon et al., 1988) were considered in sensitivity studies. Sensitivity studies were the main method used in the earlier agricultural impact assessment work. With the development of GCMs, they accompanied GCM based climate change scenarios in later impact studies (Barry and Geng, 1995; Baethgen and Magrin, 1995; Brklacich and Stewart, 1995; Menzhulin et al., 1995;

Seino, 1995; Rosenzweig and Iglesias, 1998). While the arbitrary sensitivity tests are dissociated from the processes that influence climate, they simulate a controlled experiment and provide better understanding of the factors affecting crop model responses. They can also help to identify climatic thresholds of critical impacts. Sensitivity studies allow the consideration of the question: 'What type, magnitude, and rate of climate change would seriously perturb the wheat production system.

The other approach is to create climate change scenarios based on equilibrium and/or transient GCMs experiment. An equilibrium climate experiment is an experiment in which a climate model is allowed to fully adjust to a change in radiative forcing. Such experiments provide information on the difference between the initial and final states of the model, but not on the time-dependent response. If the forcing is allowed to evolve gradually according to a prescribed emission scenario, the time dependent response of a climate model may be analysed. Such experiment is called a transient climate experiment (IPCC, 2001b).

GCMs provide the most advanced tool for projecting the potential climatic consequences of increasing radiatively active trace gases in a consistent manner. GCMs were extensively used to create climate change scenarios because they produce climate variables that are internally consistent (i.e., the climate variables within the scenario should vary in a physically realistic way) (Wigley, 1987). Thus they are more realistic and allow for comparisons between or among regions (Rosenzweig and Iglesias, 1998). Monthly climate change scenarios were generated by GCMs, which were then applied to the historical weather data to generate future weather conditions by using certain techniques. Mean monthly changes in temperature, precipitation, and solar radiation from the appropriate GCMs' grid box are applied to observed daily climate records to create climate change scenarios for each site. These GCM-modified weather files are then used as input files by the crop models (Rosenzweig and Iglesias, 1998; Hoogenboom et al., 1995).

Two problems have arisen from using the direct output of GCMs in constructing climate change scenarios. One is the coarse spatial resolution of GCMs with grid-points spaced around 500km or more apart, which is too coarse for regional agricultural impact assessment if the estimated change in climate is affected by sub-grid scale surface features such as topography, lake and coast etc. Crop models simulate processes regulating growth and development at fine scales (a few kilometers or even finer scale, for example where two or more soil types exist in a single paddock it may be appropriate to parameterise the soil module for the different soil types) (Robert, 1993; Barrow and Semenov, 1995; Easterling et al., 1998). Two alternative options exist to counteract with this problem. One is statistical downscaling techniques with which to produce finer scale regional climate change information for impact study. The other is the nesting of Limited Area Models (LAM 60X60 km) into GCMs, which can enhance the spatial resolution of GCMs as LAMs may represent surface characteristics more effectively. Studies using statistical downscaling techniques and nested limited area numerical models to increase the resolution of GCM scenarios of climate change have shown large simulated yield discrepancies between coarse resolution (GCMs) and fine resolution (downscaled) climate change scenarios (Mearns et al., 1999, 2001).

The second problem is lower temporal resolution of GCMs. Although GCMs today can produce output with various temporal resolutions such as annual, seasonal, monthly, daily and even hourly, the temporal resolution for the climate change impact community to access and apply is normally monthly climate change. It is uncommon to employ hourly and/or daily GCM output for agriculture impact studies because of the extraordinarily large computer memory space required by hourly/daily GCM output and the difficulty in interpreting the higher temporal resolution data over large grid boxes. Some alternative options for representing changes in daily means and variability have been proposed through the crop model internally or by using a stochastic weather generator externally. The management section in the CERES-Wheat model, and the Manager module of APSIM-Wheat provide entries for assigning climate changes to historical climate data with various temporal resolutions (annual, seasonal and monthly). In addition to this, there is a section in the CERES-Wheat model called Sensitivity Study which handles arbitrary climate changes specifically. Three popular weather generators: WGEN (Richardson, 1985), SIMMETEO (Geng and Auburn, 1987), and LARS_WG (Semenov and Barrow, 1997) were developed as a computationally inexpensive tool randomly to generate a long time series of climate change scenarios with high temporal resolution by using the variability, means and other characteristics of historical climate records. The stochastic weather generator provides the ability to include climate variability in mean climate change scenarios for impact studies, and to downscale outputs of GCMs from lower temporal resolution to higher temporal resolution for applying to crop models.

2.3 CASE STUDIES OF GLOBAL IMPACTS ON WHEAT PRODUCTION

Recent wheat production impact assessments have focussed on the following seven aspects and summarised in Table 2.1

- Climate variability
- Transient climate change scenarios
- Effects of climate change
- Direct effects of CO_2 and its combined effects with climate change
- Impacts on grain quality
- Wheat distribution
- Quantitative adaptation

Table 2.1 Worldwide wheat production impacts and the conditions considered

Studies	Countries	Wheat	Yield Change (%)	Crop Model	Climate Change Scenarios	CO_2 Effect	Grain Nitrogen Content	Climate Variability	Adaptation	Market or Economic Issue
Barry and Geng, 1995	USA	Spring wheat	+62 to +125	CERES-Wheat	OSU	No				
Baethgen and Magrin, 1995	Uruguay & Argentina	wheat	Decrease	CERES-Wheat	UKMO	Yes			Yes	
Mearns, 1995	USA	wheat	+44 to +82	CERES-Wheat	RCM nested within GCM	No		Yes		
Tubiello et al., 1995	Canada	Spring wheat	-4 to +8	CERES-Wheat	+2°C	Yes				
Rosenzweig and Iglesias., 1998	Global	wheat	+15 decrease vary	CERES-Wheat	+2°C+CO_2 +4°C+CO_2 Equilibrium GISS, GFDL, UKMO and transient GISS scenarios	Yes			Yes	Yes
Brklacich and Stewart, 1995	Canada	wheat	+40 to +50 -40 to +60	CERES-Wheat	CO_2 alone GISS, GFDL and UKMO+CO_2	Yes			Yes	
Lin, 1996	China	wheat	-21 to +55	CERES-wheat	Equilibrium GISS, GFDL, UKMO (2050)	No			Yes (0)	
Bayasgalan et al., 1996	Mongolia	Spring wheat	-74.3 to +32		Equilibrium GISS-G1 and GFD3-A3	No				
Karim et al., 1996	Bangladesh		-31		Equilibrium CCCM and GFDL	Yes				
Aggarwal and Sinha, 1993	India		Decrease	WTGROWS	+2°C					
Rao and Sinha, 1994	India		Decrease	CERES-Wheat	Equilibrium GFDL, GISS, UKMO and transient GISS	Yes				
Kavalerchik et al., 1995	Kazakhstan	wheat	-12	CERES-Wheat	NA	No				

Table 2.1 Worldwide wheat production impacts and the conditions considered (continued)

Pilifosova et al., 1996	Kazakhstan	Spring wheat	-12 to +56		Equilibrium CCCM, GFD1, and GFD3	No			
		Winter wheat	+17 to +21						
Querish and Iglesias, 1994	Pakistan		Decrease			Yes			
Menzhulin et al., 1995	Russia and Former Soviet Republics		-20	CERES-Wheat	+2°C	Yes		Yes	
			>-30		+4°C				
			-19 to +41		Equilibrium GISS, GFDL, UKMO and transient GISS (national wheat yield change)				
Delécolle et al., 1995	France		-30 to 0	CERES-Wheat	Equilibrium GISS, GFDL, UKMO and transient GISS	Yes		Yes	
			-15 to +7		Climate change +CO_2				
McKeon et al., 1988	Australia	Wheat	-6		+2°C	No			
			+23		Temperature increase plus rainfall change				
Wang et al., 1992	Australia	wheat	+28 to +43		CO_2 alone	Yes		Yes	
			-60 to –25		CO_2 + T (3°C)				
			increase		CO_2 +T (3°C) + late maturity variety				
Reyenga et al., 1998	Australia	wheat	+30 to +40	I-Wheat	CO2 alone	Yes	-12 to -7		Gross margin
Reyenga et al., 1999a	Australia	wheat	+26 to +37	I-Wheat	CO_2 alone		-12 to –11	Yes	
			+9 to +23		CO_2 + T (+2.76 °C)				
			+21 to +33		CO_2+ T(+2.76°C) + R (+)				
			-3 to +6		CO_2+ T(+2.76°C) +R (-)				
			+6 to +26		CO_2 + climate change + fertiliser application		-9 to –8		
Reyenga et al., 1999b	Australia	wheat	+13 to +52	I-Wheat	CO_2 alone	Yes			
			-35 to -10		CO_2 + dry scenarios				
Howden et al., 1999c	Australia	wheat	+12 to +19	I-Wheat	Several typical single scenarios	Yes			

Table 2.1 Worldwide wheat production impacts and the conditions considered (continued)

Howden et al., 1999d	Australia	Wheat	+14	I-Wheat	CO_2 alone	Yes	-12		Yes	+23 to +44
			-2 to +14		CO_2 + climate change		-6 to –5			+13
		Sorghum	+20		CO_2 alone		-2			+23 to +44
			-7 to +17		CO_2 + climate change		+5			+19
		Rotation	+19.5		CO_2alone					+23 to +44
			-24 to +23		CO_2 + climate change					+11
Howden et al., 1999d	Australia	Wheat		I-Wheat	CO_2 alone	Yes	-14 to –10		Yes	+31 to +32
					T (0°C) + R (+20%) +CO_2		-17 to –15			+58 to +68
					T (+4°C) +R (-20%)+CO_2		0 to +9			-27 to –23
Howden et al.,1999a	Australia	wheat	+5 to +43	I-Wheat	CO_2 alone	Yes			Yes	+6 to +70
			+9 to +37		CO_2 + Climate Change		-14 to -4			+5 to +60
			+5 to 46		CO_2 + Climate Change +changing planting window					+28 to +95 (gross margin)
Howden, et al., 1999e	Australia	wheat	-3	I-Wheat	A1-Mid, B2-Mid scenarios	Yes			Yes	
			+3		Climate change + changing planting window					
Seino, 1995	Japan	Wheat		CERES-Wheat	Equilibrium GFDL, UKMO, GISS	Yes			Yes	
Semenov, et al., 1996	UK	Wheat	Decrease		UKHIV equilibrium scenario			Yes		
			Increase		UKTR transient scenario					
Smith et al., 1996	Kazakhstan	Winter Wheat	+17 to +21	CERES-Wheat	GFDL equilibrium/ transient climate change scenario					
		Spring wheat	Decrease							

2.3.1 Climate Variability

Most of the previous studies have just focused on the study of the effects of mean climate change on wheat production. However, there is a growing concern that climate variability (e.g., El Niño frequencies) will increase (Wilson and Hunt, 1997) along with the 'mean' climate change that will have significant consequences for agricultural production. That climate variability has been ignored in most previous studies is partially due to considerable uncertainty regarding how climate variability may change in the future. Assessment based on 'mean' climate change provides limited information on how future climate could affect agriculture.

Explicitly modelling the simultaneous effects of changes in climate variability and climate means is one of the main advances made recently in climate change impact studies. Quite a few studies have included detailed, explicit changes in climate variability (Mearns et al., 1992; Mearns et al., 1995; Rosenzweig et al., 2000). Mearns (1995) emphasised the effects of changing climate variability on wheat yields in the central Great Plains of the United Sates. This research demonstrated that estimates of changes in wheat yields simulated from a scenario that includes changes in variability are very different from changes in yield determined from a scenario that considers only mean climate changes. This study provided an improved understanding on what aspects of climate change are most relevant for determining agricultural impacts. For example, simulations of wheat growth indicate that greater interannual variation of temperature reduced the average grain yield (Semenov and Porter, 1995). Hulme et al. (1999) used a multi-century simulation of the control climate to provide an estimate of variability calculated with two climate change scenarios. Using a wheat model, they show that climate change alone by 2050 produces significant increases in wheat yield under both scenarios for only three northern European countries. By contrast, there were substantial grain yield increases in all ten countries in the study when elevated CO_2 effects on plant growth were added. Greater efforts to take account of the 'noise' of natural variability are indicated in Semenov et al. (1996).

The importance of diurnal climate variability has emerged since the Second Assessment Report (SAR). Observations over land areas during the latter half of last century indicate that the minimum temperature has increased at a rate more than 50% greater than that of the maximum. Dhakhwa and Campbell (1998) conclude that, compared to equal day-night warming, differential warming leads to less water loss through evapotranspiration and better water use efficiency. This is likely to enhance photosynthesis, crop growth, and yield, although at a possible loss of nutritional quality (Murray, 1997). The possible mechanisms for maximum temperature and minimum temperature warming differences are currently debated and predictions about whether the asymmetry in daytime and night time warming will continue, await better computer models (Karl et al., 1997).

2.3.2 Transient Climate Change Scenarios

The doubled CO_2 climate change scenarios used in most studies have assumed an abrupt doubling of the pCO_2 in the atmosphere and then have allowed the simulated climate to come to a new equilibrium. This step change in atmosphere is unrealistic, since trace gases are increasing gradually. Recent evidence from GCM experiments incorporating time-dependent greenhouse-gas forcing suggests that there may be important differences between the equilibrium and transient responses, based in part on differential warming of land and ocean areas. The transient scenario does simulate the response of gradually increasing radiatively active gases and is more realistic in this respect (Rosenzweig and Iglesias, 1998; Reilly and Schimmelpfennig, 1999).

Substantial progress has been made in the development of transient (time-evolving) scenarios of climate change for use in agricultural impact assessment. Many crop models contain cumulative functions that retain environmental information over consecutive years (e.g., water balance, soil nutrients). This factor alone could account for substantial yield response differences between transient and equilibrium climate change scenarios. A few studies have deliberately compared simulated yields using transient and equilibrium climate change scenarios. Using the UKHIv equilibrium scenario with increased interannual variability at Rothamsted, Semenov et al. (1996) simulated a loss of wheat yield relative to present with two crop models and no change with a third. With the UKTR transient scenario, all three models showed yield increases relative to present. The U.S. Country Studies Program (Smith et al., 1996) used the CERES model to simulate larger average increases in winter wheat across

Kazakhstan with the GFDL transient climate scenario (for the tenth decade) (+21% winter wheat yield) than when using the GFDL equilibrium climate change scenario (+17% winter wheat yield). Spring wheat yields were decreased with both scenarios, but once again the yields simulated with the transient scenario were not as adversely affected as the ones simulated with the equilibrium climate change.

Menzhulin et al. (1995) studied the possible impacts of 3 equilibrium climate change scenarios (GISS, GFDL, UKMO) and 3 levels of GISS transient climate change scenarios for 2010, 2030 and 2050 respectively on wheat yield with CO_2 induced physiological effects taken into account. The simulated result showed that yield for winter wheat increased from 9 to 41% with the most increase under the equilibrium GISS scenario and least increase under the equilibrium UKMO model. Spring wheat yield decreased under equilibrium UKMO and GFDL scenarios, but increased under other scenarios. Yield responses for winter wheat and spring wheat under equilibrium climate change scenarios and transient climate change scenarios are quite different. Rosenzweig and Iglesias (1998) also found wheat yields to be less adversely affected by transient climate change than equilibrium climate change. Similar conclusions were reached by Delécolle et al. (1995). Lack of consistency in the application of climate change scenarios to impact modelling between studies gives competing explanations about differences in impact estimates between the two types of climate change scenarios.

2.3.3 Effects of Climate Change

Research on the effects of climate change on agriculture has been extensive for many years. Previous modelling studies have mainly looked at the impacts of climate change (indirect effect of greenhouse gases) on wheat production due to the limited wheat model used. McKeon et al. (1988) assessed climate change only (i.e., no CO_2 change) on wheat yields in Queensland, Australia and concluded that scenarios of temperature increase (+2°C) would decrease yields by 6% or rainfall change plus temperature increase (winter rain -20%, summer rain +30%) would increase yields by 23%. There was a tripling of soil loss under the full climate change scenario.

The impact of climate change on wheat yield simulated for several locations in India using the dynamic crop growth model WTGROWS indicated that productivity was dependent on the magnitude of temperature change. In North India a 1°C rise in the mean temperature had no significant effect on potential yields, though an increase of 2°C reduced potential grain yields at most places (Aggarwal and Sinha, 1993). Barry and Geng (1995) explored the possible response of spring wheat to doubled CO_2 in California. An increase of 62%~125% of spring wheat yields was found due to the increase of rainfall and temperature during winter months.

Bayasgalan et al. (1996) researched the effect of climate change (GISS-G1, GFDL-A3) on the yields of Mongolian spring wheat. The result showed that the production of spring wheat could be reduced significantly due to higher evapotranspiration. Simulated adaptive options, such as a change in planting dates, using different varieties of spring wheat, and applying the ideal amount of nitrogen fertiliser at the optimum time, are potential responses that could modify the effects.

Pilifosova et al. (1996) estimated the possible effects of climate change on yields of spring wheat and winter wheat in Kazakhstan. Reductions of spring wheat yield are anticipated to be 56% under CCCM, 51% under GFD3, and 12% under GFD1 scenarios. Winter wheat yield could increase about 21% under GFD1 and 17% under GFD3 and CCCM scenarios. Confronted with this situation, the following adaptation alternatives are recommended: changing planting dates; switching from spring wheat to winter wheat; irrigating; increasing the fallow area; implementing snow reserving; switching to more suitable wheat varieties; applying fertiliser, pesticides, and weed control; and last, applying zonal growing technology. Similar studies can also be found in Kavalerchik et al. (1995) and Lin (1996).

The physiological effects of CO_2 have not been considered in modelling climate change impacts on wheat production until they had been well studied under controlled environments.

2.3.4 Direct Effect of CO_2 and Its Combined Effects with Climate Change

The increase in atmospheric pCO_2 will have a significant effect on crop production, especially for C_3 plants, by the stimulation of photosynthesis (Cure and Acock, 1986) and improvement of water use efficiency (Morison and Gifford, 1984) and through climate change (indirect effect).

The CO_2 fertilisation effect has been investigated since the 1970s under controlled environments. Under doubled CO_2, wheat yields are estimated to increase from 8% to 50% with least increase in well-watered conditions, and with most increase in water-stressed canopies (Gifford, 1977; Chaudhuri et al., 1989; Pinter et al., 1996; Reilly et al., 1996). 8% to 36% increases were observed for wheat biomass (Lawlor and Mitchell, 1991; Cure, 1985; Gifford, 1977; Sionit et al., 1981a) with larger responses correlating with higher nutrient levels under doubled CO_2 (Poorter, 1993; Poorter, 1998). Increases of 50% to 54% for photosynthesis were also estimated (Gifford, 1977; Akita and Moss, 1973; Chmora et al., 1976; Havelka et al., 1984; Teramura et al., 1990) with the doubling of CO_2. These wide ranges of response for yield, biomass and photosynthesis are largely dependent on factors such as nutrient levels (Sionit et al., 1981a), water stress (Chaudhuri et al., 1989) and light (Gifford, 1977). Development stage is an important factor as well (Fisher and Aguilar, 1976), with responses to CO_2 depending on such factors as availability of assimilates during grain filling (Sionit et al., 1981b).

The reduction in stomatal conductance with increasing CO_2 level is also well documented (eg. Morison, 1987). The reduced stomatal conductance under enhanced pCO_2 is likely to reduce water loss but maintain photosynthesis due to higher water potentials (Nie et al., 1992, Knapp et al., 1993) and higher internal CO_2 levels (Morison 1987, Nie et al., 1992) resulting in an increase in transpiration efficiency (TE). TE has been found to increase by 50-80% with doubling of CO_2 in controlled spaced plant experiments (Morison and Gifford 1984, Samarakoon et al., 1995). However, Morison (1985) argues that the TE of an entire crop is likely to be lower due to numerous feedbacks which would occur in the field in crop canopies and he suggested that a 40% increase may be more likely. When wheat was grown as a canopy crop in glasshouse under 340 and 660ppm CO_2, TE increased by 33% under elevated CO_2 (Gifford and Morison, 1993). If this result is translated to a doubling of CO_2 from 350 to 700ppm it represent a 37% increase in TE. The level of enhancement of TE is supported by free-air carbon dioxide experiments with crops with full canopies (Grossman et al., 1995). In the model the transpiration efficiency coefficient (Tanner and Sinclair 1983) was increased by 37% for a doubling of CO_2 with a linear response assumed at intermediate CO_2 concentrations (Eamus and Jarvis 1989). More work is needed in order to predict reliably the full impact of increasing CO_2 on the TE of crops in the field.

Elevated atmospheric CO_2 levels tend to reduce leaf nitrogen concentrations of wheat (Hocking and Meyer 1991; Rogers et al., 1996) due to the change in the balance between the photosynthetic carbon reduction cycle and the photorespiratory cycle (Conroy and Hocking 1993). In particular, there is a consistent reduction in the critical nitrogen concentration (the concentration at which yield drops to 90% of that under optimum nutrition) that has a significant implications for wheat growth and management (Hocking and Meyer 1991, Conroy and Hocking 1993, Rogers et al., 1996).

Wheat models have been improved and modified based on the above findings associated with the response of photosynthesis, evapotranspiration and critical nitrogen concentration to higher levels of CO_2. Ratios have been calculated between measured daily photosynthesis/ evapotranspiration rates for a canopy exposed to a range of high CO_2 values, based on experimental results. The modified wheat models were widely used to study the CO_2 fertilisation effect alone or the combined effects of increased CO_2 and climate change on wheat production.

The combined effects of increased pCO_2 and climate change on wheat production have been reported in many simulation studies. Wang et al. (1992) assessed the interactive impacts of changes in CO_2 concentration and climate on wheat yields in Victoria. They suggested that doubling of pCO_2 to 700ppm would increase yields by 28% to 43%, but that simultaneous increases in temperature of 3°C would decrease yields by 25 to 60% using current cultivars or a substantial increase in yield if a late-developing variety from Queensland was used. Responses to rainfall change were cultivar dependent. Work by Howden et al. (1999c) shows that CO_2 and climate change scenarios gave a range of wheat yields from +12% to +29% in Emerald, NE Queensland, Australia.

Rao and Sinha (1994) used the CERES-Wheat simulation model and scenarios from three equilibrium GCMs (GISS, GFDL and UKMO) and from the transient GISS model to assess the physiological effects of increased CO_2 levels. They showed that in all simulations wheat yields were lower than those in the current climate, even with the beneficial effects of CO_2 on crop yield; and yield reductions were due to a shortening of the wheat-growing season, resulting from temperature increase. Wheat yield decreases could have serious impacts on the food security of India, in view of the increasing population and its demand for grains. Most of the wheat production in India comes from the northern plains, where it is almost impossible to increase the present area of wheat under irrigation.

Qureshi and Iglesias (1994) used GCMs and dynamic crop models to estimate the potential agricultural effects of climate change in Pakistan. Under present climate conditions, wheat is currently under stress due to high temperatures and arid conditions. Projected climate change caused simulated wheat yields to decrease dramatically in the major areas of agricultural production, even under fully irrigated conditions. Decreases in modelled grain yields were caused primarily by temperature increases that shortened the duration of the life cycle of the crop, particularly the grain-filling period. These decreases were somewhat counteracted by the beneficial physiological CO_2 effects on crop growth. Adaptation strategies that were considered in the analysis included development of more heat resistant cultivars, delayed planting, and other changes in farming practices. Together, these adaptation strategies offset some, but not all, of the yield losses estimated to occur with the changed climate.

Seino (1995) estimated wheat yield changes from -41% to +6.3% under future climate change in Japan. Advancing planting dates and application of supplemental irrigation are possible adaptation strategies of management systems to climate change. Introduction of new crops and /or new cultivars better adapted to the climate change conditions would be required. In a later study, Karim et al. (1996) have also shown that wheat yields are vulnerable to climate change in Bangladesh. The preliminary vulnerability assessments based on the DSSAT model for $2xCO_2$ conditions showed that the spring wheat and winter wheat yields would decrease by 12% in Northern Kazakhstan. But the crop model of KazNIGMI gave spring wheat yields twice below those of 1991 if the warming is 2-3°C compared with current climate.

Brklacich and Stewart (1995) assessed the possible impacts of climate change and increased CO_2 on wheat yield in the Canadian Prairies. Their results show that yield responses were sensitive to climate change scenarios and locations; climatic change scenarios tended to reduce and in some cases offset the beneficial effects stemming from elevated CO_2 levels; the effectiveness of response strategies varied according to the location, climatic change scenarios and selected response strategies.

Baethgen and Magrin (1995) evaluated the impacts of climate change on wheat production in Uruguay and the Pampas for a wide range of soil and crop management strategies including planting dates, cultivar types, fertiliser management, and tillage practices. Simulated results show that wheat production is much more sensitive to temperature increase than to the rainfall change; crop yields under expected climate condition were lower, more variable, and showed a lower response to N fertiliser than under current climatic conditions. Best strategies to adapt to climate change conditions included earlier planting dates and optimum N fertilisation.

Tubiello et al. (1995) studied the interactions of CO_2, temperature and management practices on spring wheat in the Canadian wheat belt using the CERES-Wheat model. Research results show that rainfed crops were more sensitive to CO_2 increase than irrigated ones. On the other hand, low nitrogen applications depressed the ability of the wheat crop to respond positively to CO_2 increase. These results are consistent with the findings observed under controlled environmental conditions. In general, the positive effects of CO_2 on grain yield were found to be almost completely counterbalanced by the negative effects of high temperatures. Depending on how temperature minima and maxima were increased, yield changes averaged across management practices ranged from -4% to +8%.

Delécolle et al. (1995) examined wheat and maize yields in France. They found first, that season lengths for wheat are shortened under climate change scenarios. Second, wheat yields decrease under climate change alone, but the decrease can be somewhat counteracted by direct CO_2 effects, up to a $5^{\circ}C$ temperature increase. Third, water use decreases under climate change. Last, planting window changes were explored in an effort to adapt to the potential negative impacts from climate change.

Sensitivity studies and climate change impact studies were also conducted in Russia and the former Soviet Republics (Menzhulin et al., 1995). Four conclusions were drawn. First, a 2°C increase in temperature decreased yield by an average of about 20% while a temperature increase of 4°C resulted in a yield decrease of >30%. Second, changes by ±20% in the precipitation had a smaller effect on the simulated yields than the changes in temperature. Third, the projected national wheat yield change for Russia and the former Soviet Republics is around -19%~+41% when the CO_2 fertilisation effect is considered. Finally, small changes in sowing date do not appear to have large impacts on yields, whereas irrigation could have a dramatic effect on spring wheat yields.

A global agricultural sensitivity and impact study was conducted and summarised by Rosenzweig and Iglesias (1998). For sensitivity tests, crops averaged over all sites showed an increasingly negative response to increased temperatures, with percentage decreases in yields approximately doubling from the +2°C to +4°C without CO_2 fertilisation effects considered. Wheat yields increased about 15% with a 2°C temperature rise, but decreased at 4°C with CO_2 direct effects considered, indicating a possible threshold of compensation of direct CO_2 effects for temperature increases between 2°C and 4°C as simulated in wheat models. In the impact study, climate change scenarios without CO_2 physiological effects caused decreases in simulated crop yields in many cases, while the direct effects of CO_2 mitigated the negative effects primarily in mid and high latitudes. Potential changes in crop yields varied for the GISS, GFDL, and UKMO climate change scenarios. Changes in crop yields in the higher latitudes were less severe than crop yields in lower latitudes. In some cases, yield changes in mid and high latitudes were positive. The GISS and GFDL climate change scenarios produced a range of yield changes from +30% to –30%, although there were regional differences. The GISS scenario is, in general, more detrimental to crop yields in Asia and South America, and the GFDL scenario is more harmful in North America and the former USSR. The UKMO climate change scenario, which has the greatest warming (5.2°C global surface air temperature increase), generally causes the largest yield declines (up to 50%). A series of adaptation strategies were suggested such as irrigation, shifting the planting window, fertiliser application, and cultivar selection as well as exploiting new environmental resources for wheat production. With the existing pool of cultivars and current resources of water and fertiliser, agricultural adaptation to climate change seems likely in high and mid-latitude countries, but seems out of reach for nations in the low latitudes.

2.3.5 Impacts on Grain Quality

One of the obvious advances achieved recently in wheat production impact studies is the possibility of including effects of climate change and increased CO_2 on wheat grain quality as well as grain yield impact studied simultaneously. Australia is in the leading place in the study of grain quality impacts resulting from climate change and rising atmospheric pCO_2, both in controlled environments and in simulation studies.

In controlled environment experiments, elevated CO_2, reduced the protein content of grain and flour by 9-13% (Hocking and Meyer, 1991, Conroy et al., 1994, Rogers et al., 1996). Grain grown at high CO_2 produced poorer dough of lower extensibility and decreased loaf volume (Blumentahl et al., 1996), but the physiochemical properties of wheat starch during grain fill were not significantly modified (Tester et al., 1995). Increase in daily average temperature above 30°C, even applied for periods of up to three days, tended to decrease dough strength (Randall and Moss, 1990). Hence for bread making, the quality of flour produced from wheat grain degrades when developed at high temperatures and elevated CO_2.

Reyenga et al. (1999a) studied grain yield and grain quality impacts under wet, dry and most likely climate change scenarios with pCO_2 set to 700ppm in the Burnett region, Queensland, Australia. Mean wheat yields were increased by +26% to +37% depending on variety under doubled CO_2, with yields increasing by 50% in dry years and 20% in wetter years. Higher temperature under the climate change scenarios moderated the yield gains achieved with increased pCO_2 and in some instances reversed them under the reduced rainfall scenario. The status of the region as a producer of prime hard wheat may be at risk due to reduced grain nitrogen levels from 8 to 9% with fertiliser and 11-12% without fertilisation under doubled CO_2 and the increased likelihood of "heat shock" in the climate scenarios used. Adaptations may be needed to counteract the changes in wheat quality associated with elevated CO_2 and temperature such as breeding of heat tolerant cultivars, changing planting windows as well as changes in fertiliser management.

Howden et al. (1999d) explored the response of grain nitrogen content to fertiliser application rates (80, 125,175,225,275,325,375 kg/ha) under several temperature and rainfall scenarios (temperature increase 2°C and 4°C; rainfall change ±20%). Findings from this study are summarised as follows. As temperatures increased, less fertiliser was required due to increased soil nitrogen mineralisation rates. The amount needed to maintain grain nitrogen level differed between rainfall scenarios with more fertiliser being required in the higher rainfall scenarios. Doubling of CO_2 alone resulted in a 31% increase in gross margins (defined as the difference between the total value of production and the variable costs). Gross margins increased with increased rainfall. Under baseline scenarios, increasing fertilisation application rates resulted in higher gross margins. This however, was not the case under all climate change scenarios. Gross margins continued to increase with additional fertiliser under 0° C temperature change but began to decline at fertiliser levels greater than 275 and 225 kg/ha under the 2°C and 4°C scenarios respectively. This analysis suggests that if climate change results in no change or some increases in rainfall, farmers could adapt to reductions in grain protein content through application of fertiliser without a reduction in their gross margins. However if there is a significant reduction in rainfall, gross margins could also be significantly reduced under all fertiliser regimes, notwithstanding the CO_2 fertilisation effect.

Howden et al. (1999d) also compared the separate responses of monoculture of wheat (in winter) and sorghum (in summer) with a rotation system of wheat-sorghum in Dalby, Queensland, Australia. Some preliminary results included: Increased CO_2 levels enhanced yields in both the single crop (wheat 14%; sorghum20%) and the rotation system (wheat 25%; sorghum 14%). Gross margins were also increased 23-44%. The combined effects of elevated CO_2 and climate change on yields were wheat +14%, sorghum+17%, and rotation+23% under the wet scenario but decreases of 2%, 7%, and 24% under the dry scenario respectively. Climate change in addition to elevated CO_2 resulted in increases in the gross margins of wheat by +13%, sorghum+19% and rotation system+11%, with this increasing by 23%, 36% and 34%, respectively, under the wet scenario. The impact of the dry scenario on gross margins was more severe in the rotation system (-16%) than under the single crop system (wheat-2%, sorghum-13%). Increased CO_2 decreased the nitrogen content of both wheat (-12%) and sorghum grain (-2%), but under warmer temperatures this was offset marginally in wheat (-5~-

6%) and completely in sorghum (+5%) due to increased soil nitrogen mineralisation rates. If in addition to warming there is a reduction in rainfall, the impact is likely to be greater for rotation systems than for single crop systems as there is not a fallow in which to store soil moisture. When the adaptation strategy of shifting the wheat planting window to earlier combined with using a slower-maturing wheat variety was applied to the rotation system, the benefits were marginal and even negative under some scenarios. This occurred because of the intense water requirements leaving little opportunity for storage of moisture between crops and hence a direct trade-off between the success of one crop to the disadvantage of the following one.

Another study by Howden et al. (1999a) indicates that CO_2 alone will increase site yields by 5 to 43%; yields increase by 9-37% for the combined effects of climate change and CO_2 with current practice maintained; and yields increase 13-46% for the combined effects with the planting window changed. Site-specific results were aggregated to stand for national yield change. Doubling CO_2 increased national yields by 25%. If climate change was included in the assessment the yield changes were +20% or +26% if the planting windows were modified. Some adaptation strategies were put forward: choice of cultivar, changing the sowing window, increasing the fertilisation rate and crop/pasture rotation, breeding of new cultivars, soil surface and fallow management, and more broadly changes in industries.

A later reanalysis of Australian wheat cropping suggests marked declines in yields in Western Australia (-13% without adaptation to -6% with adaptation), a small decrease (-2%) in South Australia and a small to moderate increase (2 to 30%) in the other wheat-cropping states under the latest mid-range scenarios (A1-Mid and B2-Mid). Nationally, the suggested impact of climate changes against current yields was –3% but this increased to +3% if adaptation *via* planting window changes occurs. The higher change scenario (A2-high) would have much greater impacts on wheat cropping with cropping most likely to become unviable over entire regions-particularly in Western Australia (Howden et al., 1999e).

2.3.6 Impacts on Wheat Distribution

Impacts from climate change and rising pCO_2 concentration will also be manifest in changes in wheat distribution. The potential impacts of climate on wheat distribution have also been studied in Australia. Hammer et al. (1987) assessed the likely distribution of wheat growing regions in eastern Australia under climate change and concluded that some further expansion of cropping areas was likely. Reyenga et al. (1998) studied the possible movement of the crop frontier in New South Wales and indicated that there is a high probability for wheat to move from its current frontier to the west. Doubling CO_2 significantly increased average yields 30% to 40%; while grain nitrogen content decreased from -7% to -12%. Another study by Reyenga et al. (1999b) showed that the cropping boundary across South Australia will move northwards under most climate change scenarios except under the dry scenario. Wheat yields increase from 13% to 52% with the response to doubled CO_2 greatest at drier sites. Under the dry scenario, wheat yield declined by 10-35% resulting in the retreat of the boundary from its current position.

2.3.7 Other Advances

In addition to the above advances made in wheat production impact studies, progress on adaptation and economic study have also received attention. Earlier impact studies are pure impact assessments without any consideration of adaptation strategies (Mckeon et al., 1988; Aggarwal and Sinha, 1993; Rao and Sinha, 1994; Kavalerchik et al., 1995; Barry and Geng, 1995; Tubiello et al., 1995; Karim et al., 1996). Later studies incorporated adaptation strategies to changed environments. But adaptation strategies, at this stage, were analysed qualitatively for different groups of people ranging from farmers and scientists to government officials (Lin, 1996; Pilifosova et al., 1996). A recent advance made in the wheat production impact assessment is the quantification of adaptation strategies (Wang et al., 1992; Baethgen and Magrin, 1995; Brklacich and Stewart, 1995; Menzhulin et al., 1995; Delécolle et al., 1995; Seino, 1995; Bayasgalan et al., 1996; Querish and Iglesias, 1996; Rosenzweig and Iglesias, 1998; Reyenga et al., 1999a; Howden et al., 1999a; 1999d; and 1999e). Much work should be done in the near future in addressing uncertainties associated with adaptability. A few studies have considered the economic consequences resulting from wheat production impacts.

Howden et al. (1999a; 1999d) and Reyenga et al. (1998) studied the impacts of climate change and doubled pCO_2 on gross margins across the Australian wheat belt.

2.4 UNCERTAINTIES/LIMITATIONS, FURTHER RESEARCH NEEDS AND FOCUS OF THIS PROJECT

Uncertainties and limitations have been identified based on previous impact studies. Further research priorities are suggested below.

2.4.1 Living with Uncertainties and Limitations

Even with these substantial studies, there still remain many uncertainties and methodological problems, which impede accurate assessment of agricultural impact from atmospheric change.

Uncertainties exist and propagate from each step of atmospheric change impact assessment from the projections of greenhouse gas emissions, the projections of global climate change, the projections of regional climate change and with all three propagating through to impact assessments.

Quite different outputs from different GCMs make it very hard for scientists to make decisions about the accuracy of GCMs and the selection of model to include in impact studies. Faced with this dilemma, it is natural to apply several single scenarios to explore the possible impacts of climate change on wheat production. Most of the literature reviewed here has adopted this approach. Assessment results derived from single scenarios are fairly precise but are conditional on those single scenarios only, are unlikely to be representative of other possible futures and are highly speculative. This is confirmed by the fact that simulated crop model results vary considerably among GCMs (Luo and Lin, 1999). The outcomes are plausible but contain no information as to their likelihood. There are no confidence limits as to the possibility of these outcomes, nor how the results fit into broader ranges of uncertainty and what those ranges of uncertainty may be. Uncertainties have simply been mentioned qualitatively and incompletely and not quantitatively and explicitly characterised and measured. While appropriate for testing sensitivity and vulnerability of a particular system, this methodology is poorly suited for planning or policy purposes.

Updated climate change projections/scenarios are expressed as upper and lower limits that correspond to the uncertainty range quantified. Projected ranges are constructed from two or more scenarios where one or more sources of uncertainty may be acknowledged. A range of projections will always be more likely to encompass what will actually transpire than a single scenario (IPCC, 2001a). This advance provides a prerequisite for applying a range of climate change scenarios to wheat impact assessment. However, the resulting range of outcomes arising from the high and low ends of the range of regional climate change is often too large to be of real use for planning or policy purposes although certain levels of probability can be attached to the regional climate change (Jones, 2000b).

Adaptations based on these two methods are normally too generic and broad and therefore impractical and useless for planning and policymakers.

Limitations existed in mainly three categories: spatial variability of impacts, crop model functionality, and the method of constructing climate change scenarios.

Poor Spatial Coverage of Study Area Mechanistic crop models have been widely used to enhance our understanding of crop response to climate change. So far, relatively little attention has been paid to problems involved in spatial aggregation of model results. Most studies compromise between maintaining a high level of detail with relatively few sites. The consequence of this approach is the need to infer changes in production over a broad area from studies at just a few sites. In reality, there may be two or more soil types in a single paddock. It is appropriate to parameterise the soil model for different soil types.

Applicability of Wheat Models A number of limitations existed in applying the wheat model to atmospheric change impact studies.

(1) Empirically derived simple relationship was employed in impact studies. Wheat models have not been tested under changed CO_2 concentration and climate conditions. Models

simulate crop phenological and morphological development as observed in ambient CO_2 concentrations. Changes in plant structure and growth stages caused by different CO_2 levels are not included in the numerical studies of climate change impacts (Tubiello et al., 1995). Biophysical relationships may or may not hold under changed conditions. (evapotranspiration is not likely to maintain its current relationship with maximum temperature under climate change), particularly the higher temperatures predicted for global warming. Most of the data used to derive the relationship in the crop models were obtained with temperatures below 35°C whereas the projected temperatures for doubled CO_2 are often 35°C or 40°C during the growing period (Curry et al., 1990; Rosenzweig et al., 1998). The biophysical relationships are simplified to cumulative growing degree days, and so miss effects of variability and extreme events on crops (Reilly and Schimmelpfennig, 1999). Effects of increases in foliage temperature (Idso et al., 1987) as a result of elevated CO_2 were not computed or used to modify plant growth processes. However, evidence from Allen (1990) indicates that increase in CO_2 to 800ppm could cause plant temperature to be 2-3°C higher than if they were under 330ppm for the same climate condition. The relation between vapor pressure deficit and evapotranspiration, and other factors require expanded models. The effect of high temperature on pollen viability and the interaction between temperature, drought, and increased CO_2 concentration need further research (Hoogenboom et al., 1995).

(2) The reliability of experimental evidence: modifications to photosynthetic and evapotranspirational processes are based on experimental evidence. But experimental evidence produces widely varying crop responses to elevated CO_2. The magnitude of the CO_2 fertilisation effect and water use efficiency should be resolved. In addition there are interactions between elevated CO_2, temperature, moisture deficit, and other environmental factors (such as nutrient availability and tropospheric ozone), but few experiments have been conducted to quantify confidently these interactive effects (Reilly and Schimmelpfennig, 1999). The extent and occurrence of physiological adaptation of the photosynthetic apparatus to long term exposure to high CO_2 concentration are still unsolved (Rotter and Van de Geijn, 1999).

(3) The incapacity in incorporating changed soil processes and other soil problems into impact studies. Crop response models treat soils but not the processes by which soil water and soil fertility may change as environment changes (Reilly, 1999). Agricultural production systems may face severe challenges due to the potential exacerbation of soil condition such as soil erosion, salinity and acidification, which have not been integrated into the wheat model.

(4) The incapacity in simulating the effects of diseases, pests and weeds on wheat. The impact of pests, weeds and diseases on agriculture is a significant factor in determining crop yields that was not modelled in wheat impact studies. Changes in CO_2 concentrations and climate may affect the distribution and pest-plant interaction of pests and diseases and the competitive balance between weeds and crops (Sutherst, 1995; Reilly, 1999). However, it is not possible to predict how these changes will affect yields at this time.

(5) Biophysical models (wheat model) have not been integrated with socioeconomic models to explore possible adaptation strategies based on cost-benefit analyses.

(6) The unrealistic setting of doubled CO_2 concentration in crop models. Crop simulations adopt a ‘step’ increase in CO_2 concentrations rather than a more realistic ‘transient’ increase which results in progressive changes to factors such as the soil carbon/nitrogen dynamics (Reyenga et al., 1999b). The ‘step’ increase and progressive increase of CO_2 concentration will bring quite different consequences to crop yields.

(7) Impact on wheat grain protein content and CO_2 fertilisation effect in most studies have been overlooked.

(8) Impact studies are limited to current agricultural technologies. Wheat models simulate the current range of agricultural technologies available around the world. They do not include potential improvements in such technology, but may be used to test the effects of some potential improvements, such as improved varieties and irrigation schedules (Rosenzweig and Iglesias, 1998).

Construction of Climate Change Scenarios Direct use of the outputs of GCMs has been applied to many impact studies. A problem associated with this approach is the lower resolution of GCM. To what extent can the outputs of GCMs represent climate change information at smaller scale or regional level? Another limitation in the construction of climate change scenarios is that potentially increased climate variability was not incorporated into future climate change scenarios for impact assessment. However, changes in climate variability are more relevant to wheat production than the change in the "mean climate". Mean climate change provides only limited information on how future climate could affect agriculture. Additional information on changed variability effects is needed to further elucidate uncertainties in our knowledge of possible impacts of climate change (Mearns *et al.*, 1995).

2.4.2 Further Research Needs

Existing uncertainties and limitations in projecting wheat production impact as identified in section 2.4.1suggest seven critical, high-priority research needs:

(1) *Identification, Quantification and Treatment of Uncertainties.* With the further scientific understanding of climate change and the improvement of computing technology, uncertainties surrounding agricultural impact assessment can be identified, quantified and managed through statistical techniques. Uncertainty measures could provide an estimate of confidence limits on model results and would be of value in the application of these results in risk and policy analyses (Leavesley, 1994). Risk analyses and risk treatment have emerged recently in this field of research and focus on the utility/treatement of ranges of uncertainty in atmospheric change impact assessment. Rather than being the end result, levels of impact can be addressed in the initial stages of risk assessment. These levels of impact then become the criteria against which risk can be evaluated in the light of system uncertainties. In the context of atmospheric change impacts, these criteria are referred to as thresholds-the point where a stimulus leads to a significant response (Parry et al., 1996). If the uncertainties surrounding projected atmospheric change and its effect on particular impacts can be treated, then the probability of threshold exceedance can be calculated and the consequences of that exceedance (i.e. risk) can be assessed (Jones, 2000c). Risk

assessment presents a completely new area for scientists to obtain a more accurate understanding of atmospheric change impacts. This method will lay a sound basis for adopting better adaptation and mitigation strategies to cope with atmospheric change.

(2) *Increase of Geographical Density of Simulation Sites.* Geographical density for simulation sites should be sufficient to provide great confidence in their representativeness of the area studied. New data sets organised at increasing spatial scales and application of Geographic Information System (GIS) technology are needed to obtain more insight into the validity of extrapolating local crop response data to regional or global scales (Easterling, 1996; Reilly and Schimmelpfennig, 1999; Reilly, 1999; Rotter and Van de Geijn, 1999). Using these spatial data resources predictions can be made about wheat impacts on a much finer spatial scale. Impact results based on this approach within agricultural regions would be of invaluable assistance to local agencies and individuals who need detailed and accurate information for long term agricultural planning.

(3) *Development and broad application of integrated agricultural modelling efforts (those that consider interactions of biophysical and socioeconomic factors), and modelling approaches particularly applicable at the regional scale, including increased attention to validation, testing, and comparison of alternative approaches.* Effects of atmospheric change on soil, pests/weeds/diseases, effects of atmospheric change on grain yield and grain quality in monoculture and rotation systems, consideration of the direct effects of increased pCO_2 and other environment changes, and quantitative adaptation options and economic responses should be an integrated part of the models rather than treated on an ad hoc basis or as a separate modelling exercise. Inclusion of these multiple, joint effects may significantly change our "mean" estimate of impacts, and more careful attention to scale and validation should help to reduce the range of estimates for specific regions and countries across different methodologies.

(4) *Integration of climate variability into climate change scenarios.* Most of previous studies have just focused on the evaluation of the effects of mean climate change on wheat production. However, there is a growing concern that climate variability will increase

along with the 'mean' climate change that will have significant consequences for agricultural production. Explicitly modelling the simultaneous effects of changes in climate variability and climate means is a trend in future agricultural impact assessment.

(5) *Development and broad application of higher spatial resolution output* of *GCMs.* Downscaled outputs of GCMs or outputs of Regional Climate Models (RCMs) should be produced and applied to impact studies.

(6) *Strength risk assessment studies*, which utilise projected ranges of uncertainties, need to be involved in the determination of critical impact threshold and provide conditional probability of exceeding the critical impact threshold.

(7) Extensively conduct experimental studies to solve problems as stated in the first two points of section 2.4.1.2.2.

2.4.3 Focus of This Research and Introduction to Risk Assessment

Based on 2.4.1, and 2.4.2, three areas have been chosen as the research content of this study. One is the identification, quantification and treatment of uncertainties associated with projected range of atmospheric pCO_2, projected range of global warming and projected ranges of local climate change per degree of global warming through the use of statistical techniques (Chapter 6). The next is risk analysis (Chapter 7). Risk analysis was conducted through the introduction of critical yield threshold and implemented in both the site-specific study and the spatial study. The other is the spatial variability analysis of simulated results through a spatial study (Chapter 4 and Chapter 7). This study attempts to overcome the limitations of previous studies and seek to provide a refined and improved assessment of the impact of atmospheric change on wheat production. Figure 2.1 gives each Chapter's content of this study.

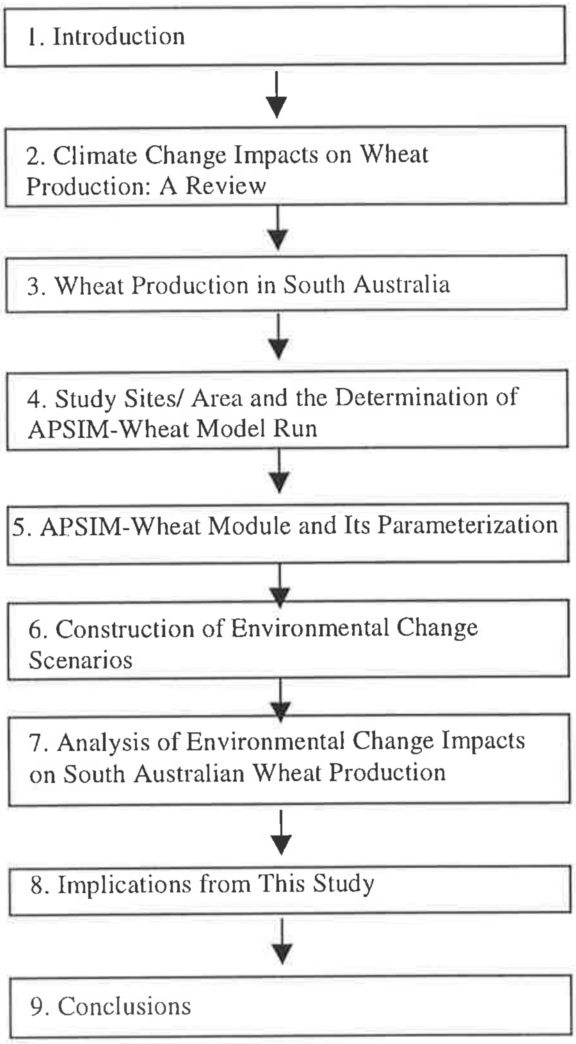


Figure 2.1 Chapters outlines

Risk itself is defined by the US Presidential/Congressional Commission on Risk Assessment and Risk Management (USPCC RARM) as the probability that a substance or situation will produce harm under specified conditions. Risk is a combination of two factors: the probability that an adverse event will occur; the consequence of the adverse event (USPCC RARM, 1997). Risk analysis is the process of assessing these two factors. Risk treatment is applied to reduce the consequences of adverse events identified by risk analysis. The enhanced greenhouse gas effect and its accompanying effect-climate change can be identified as environmental risk in the sense that the wheat production is directly exposed to risk from these effects (adapted from Jones, 2000c). Risk treatment/risk assessment is the process of identifying, evaluating, selecting and implementing actions to reduce risk to ecosystems

(USPCC RARM, 1997). Risk assessment encompasses an analysis phase and an implementation phase: risk treatment.

Several requirements should be met when conducting risk assessment:

- Key environmental variables forcing an exposure unit at a particular location can be identified and used as input for an impact model (Chapter 5). An exposure unit is defined as the sector, location or activity being assessed for impacts under atmospheric change (Carter et al., 1994).
- Those variables can be expressed in terms of a projected range with high and low extremes with a given probability distribution function. Present techniques allow ranges of atmospheric change to be constructed, and allow the upper and lower limits of quantifiable atmospheric change to be estimated (Chapter 6).
- An impact threshold forced by those key environmental variables can be quantified with reference to their projected ranges (Chapter 7).
- A conditional probability of that threshold being exceeded can be calculated on the basis of explicitly referenced assumptions linking key environmental variables and impact model (Chapter 7).
- Adaptation and/or mitigation options can be assessed to reduce the exposure of that threshold to atmospheric change (Chapter 8).

Seven steps involved in environmental impact risk assessment:

(1) Identify the *key environmental variables* affecting the exposure units being assessed

(2) Create *scenarios* and /or projected ranges for key environmental variables

(3) Carry out an *impact analysis* to assess the relationship between atmospheric change and impacts

(4) Identify the impact *thresholds* to be analysed for risk

(5) Carry out *risk* analysis

(6) Evaluate risk and identify feedbacks likely to result in *autonomous adaptations*

(7) Analyse proposed adaptations and recommend *planned adaptation* options

These seven steps are in sequence order and shown in Figure 2.2. Each step or several steps corresponds to a particular chapter of this project. The first step corresponds to Chapter 5. Step 2 corresponds to chapter 6. The following three steps are included in Chapter 7. The last two steps are discussed in Chapter 8 (See Figure 2.2).

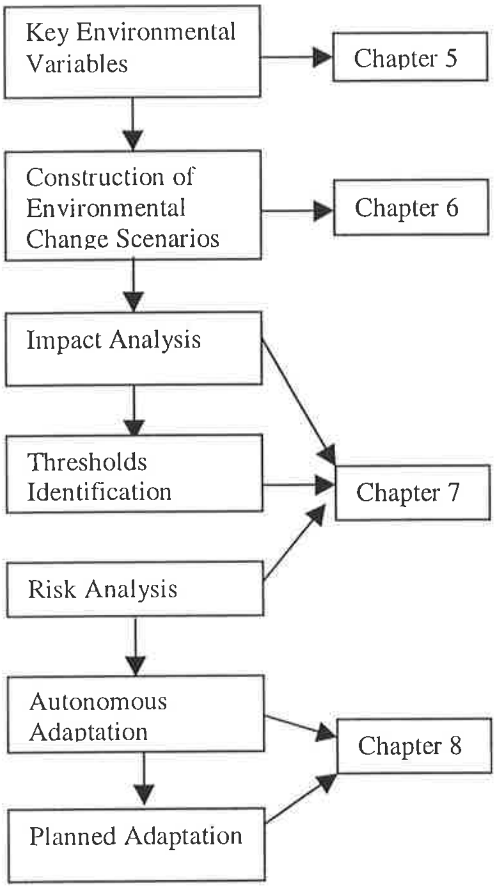


Figure 2.2 Seven steps of risk assessment (adapted from Jones, 2000c)

2.5 CONCLUSION

This chapter reviewed the research progress in atmospheric change impact on worldwide wheat production in view of the evolution of assessment tools (crop models), in view of the refinement of the construction of climate change scenarios, and in view of more impact indicators and environmental factors considered. Crop simulation models have evolved from simple to complex, from static to dynamic, and are much more reliable and flexible. Climate change scenarios have evolved from arbitrary climate changes to GCM based equilibrium and/or transient climate change scenarios and then to regional climate change scenarios. Impact studies have developed from isolating climate change effects to analysing interactions.

Impact indicators are increasingly considered from earlier work on grain yield alone, to now include both grain yield and grain quality. Based on this review, uncertainties and research problems associated with previous studies have been identified; further research needs and research priorities have been put forward; focuses of this study have been defined; approaches to conduct this project were introduced. Chapter 3 provides background to South Australian wheat production: the physical environment, wheat distribution, highlights of wheat production including the wheat yield and production area, agricultural technologies developed and cultural and management measures evolved. The ensuring chapters deal with methodology (Chapter 4,5,6), result analysis (Chapter 7), and risk management (Chapter 8).

3. THE SOUTH AUSTRALIAN ENVIRONMENT AND WHEAT PRODUCTION

South Australia has a relatively long history of wheat production. It can be regarded as the origin of wheat production in Australia. Outstanding achievements have been made during last two centuries whether in wheat yield or in expansion of wheat production due to the development of agricultural technology in this State, especially the development of agricultural mechanisation. It is the significant role played by South Australia in the national wheat industry that encouraged the author to choose South Australia as the study area. Before moving to the details of this study, I discuss the South Australian environment in relation to wheat production. I first describe the South Australian physical environment. Factors that limit wheat distribution, growth and development, are then elucidated, followed by a brief analysis of fluctuations in wheat yields and production area in this State. The history of agricultural technology and the highlights of wheat production in South Australia are reviewed in the next section. Traditional and current cultivation and management procedures accumulated through long experience are reviewed in the last section.

3.1 THE SOUTH AUSTRALIAN ENVIRONMENT

Climate and soil are the dominant factors that determine wheat distribution, the physiological processes of wheat growth and development and final grain yield and quality. Any variation in climate and soil may bring about significant variation in wheat production.

3.1.1 Climate

South Australia has a Mediterranean-type climate with mild wet winters and hot dry summers. It receives the lowest rainfall of any Australian State. The dominant weather features are the eastward moving high and low pressure systems and the seasonally varying northerly continental and tropical influences. Typically two seasons, winter and summer, are recognised. The highest rainfall occurs along the southern coasts and the Mount Lofty Ranges (with an average annual rainfall of 1200 mm in the vicinity of Mount Lofty). The lowest rainfall occurs in the region of Lake Eyre where the average annual totals are less than 150 mm (Griffin and McCaskill, 1986). Figure 3.1 shows the rainfall isohyet across South Australia.

Most of the rain in the southern districts of the State falls during the winter months when the subtropical high-pressure belt is displaced to the north over the Australian continent. Migratory low pressure systems are thus able to extend further to the north, allowing strong cold frontal activity to penetrate across the southern areas. A two-to- three-day cycle of easterly moving high and low pressure systems is a familiar weather pattern in Southern Australia (Griffin and McCaskill, 1986).

During the summer months of December to March, the subtropical high-pressure belt is displaced to the south of the continent, and frontal activity results in northerly to south to south-east wind changes, or summer ‘cool changes’, with little or no rain. Summer rainfall is generally low over the state, but significant summer rainfall events can occur episodically. Occasionally, however, unstable moist air masses at middle to lower levels of the atmosphere from the north-east or north-west, associated with tropical weather systems over northern Australia, can produce thunderstorms and heavy rainfall in the north of the State. Very heavy summer falls in the north are often caused by incursions of the summer monsoon troughs and/or rain depressions, which are generally the remnants of tropical cyclones. More locally, the orographic influence of the Flinders Ranges can be decisive in some of these situations (Griffin and McCaskill, 1986).

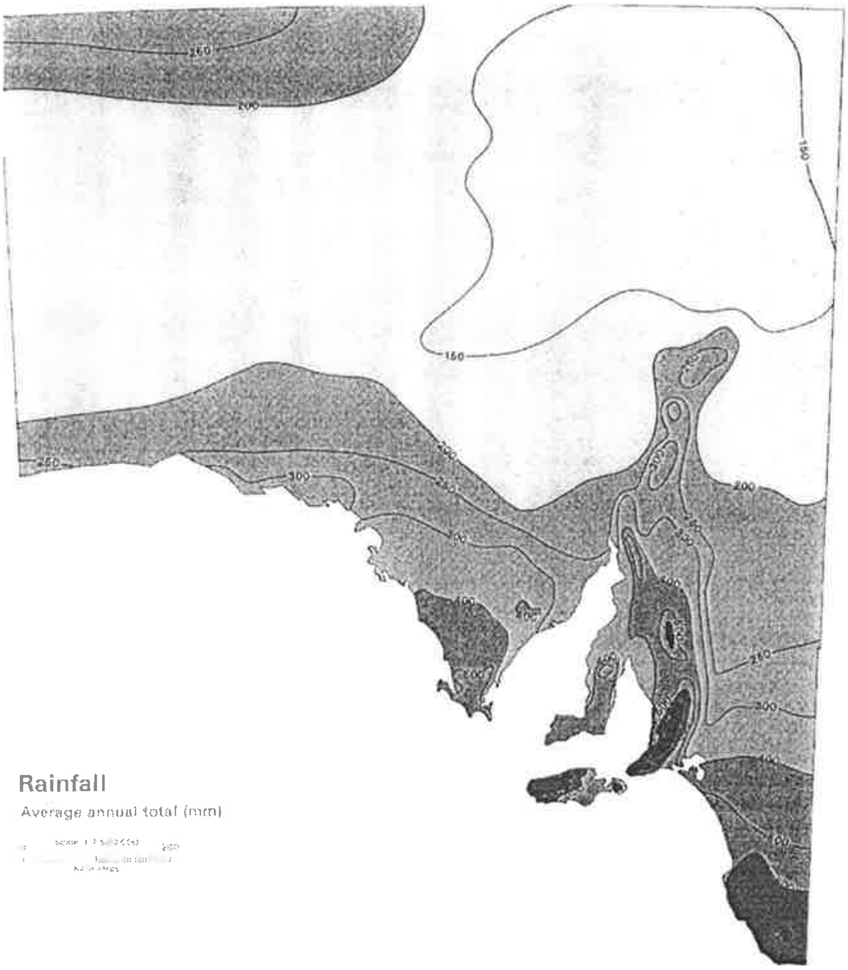


Figure 3.1 Rainfall isohyet across South Australia. Source (Griffin and McCaskill, 1986).

3.1.2 Soil

Five main groups with 16 subgroups have been classified for South Australian soils (Griffin and McCaskill, 1986). Group A-Sandy Soil includes shallow sands, deep sands, bleached sands and calcareous sands. Shallow loams and friable loams form another soil group-Loam Soils (Group B). Of these, friable loams are the most prized agricultural soil in the State. The third group is Clay Soils, and include self-mulching cracking clays, massive surfaced cracking clays, saline clays and clays. These three groups have profiles of uniform texture. The next group are the Earth Soils comprising red massive earths and calcareous earths that have a gradational texture profile. The last group is Duplex Soils, which have contrasted texture profiles. This group consists of crusty red duplex soils, hard red duplex soils (red-brown earths which are the most important agricultural soils in this state), hard yellow, brown, and red soils with bleached subsurface and ironstone gravelly soils.

South Australia is pre-dominantly a land of sands and calcium carbonate (lime) with relatively small areas of loam and clay. The prevalent sandy and carbonate soils have poor water holding characteristics including poor acceptance of moisture, low storage within the body of the soil and its subsequent release to plants.

Seven factors are identified which affect the availability of moisture and land use/management in South Australia. First is the hard-setting surface that seals readily under the impact of raindrops, leading to erosion in heavy storms. Second is the water repellent character of certain sand soils which are not readily wetted by rain due to certain fungi which 'waterproof' the sand grains. Third is the shallow soil depth. Fourth is the calcareous material that ranges from hardened sheets of calcrete to loose boulders. Next is the salinity and sodicity of the soils; particularly of subsoils; and finally, the seasonal shrinkage and swelling of clays when dry and wet (Griffin and McCaskill, 1986).

3.2 WHEAT DISTRIBUTION IN SOUTH AUSTRALIA

There are a number of factors such as climate, soil, topography, plant disease, insect pests and economic conditions, which determine the wheat belt boundaries. Of them, climate and soil play a critical role in determining where wheat can grow. The relationship between environmental components (rainfall, temperature photoperiod, solar radiation and soil) and wheat growth are elucidated below.

3.2.1 Rainfall/Soil Moisture Influences Timing of Start of Growing Season, Growth, Development and Final Grain Yield

Rainfall is the most important factor in wheat production. Wheat grows best in areas that have a cool season with good rains and a hot harvesting period with little rain. Low humidity is preferable as high humidity levels encourage disease in the wheat plant. Most of the wheat in Australia is grown in areas with an annual rainfall of 250mm-500mm. But the rainfall in the "growing period" (May-October, when rainfall should be 200 to 380mm) is more important than the annual total. By far the most relevant factor in explaining the location of the major wheat-growing areas is the fact that they are all in 4-6 months "growing period" regions. This means that climatic conditions in these regions provide at least 4 consecutive months with sufficient moisture in the soil for germination of the seed, growing of the plant and maturing of the grain (Donath and McGarrity, 1976). In South Australia summer rainfall is sporadic and non-effective for plant growth so that the main growing season is the short, cool autumn-winter-spring season with rainfall of 150-410 mm in the cereal-livestock zone which comprises about 15% of the State's area. The length of the growing season is determined mainly by the timing of the opening rains and the duration of the rainfall over the winter and spring (Zubaidi, 1996). Figure 3.2 shows the rainfall variability over 111 years (1889-1999) at Minnipa.

Winters in South Australia are uniformly cool, resulting in slow crop development, development of cold hardiness, and later ear emergence with lower frost risk. The slow development of wheat leads to a delay of the final phase of grain filling into a period of both high temperatures and severe moisture stress during the late spring-early summer drought. Water availability for the final phase is largely dependent on soil water storage from crop-season rainfall in this state. Water stress has a marked effect on yield of wheat by reducing grain number and reducing photosynthetic rate in South Australia because it generally coincides with the start of flowering and grain filling. In addition to the direct effects, low water availability during grain filling also markedly reduces grain quality. Soil moisture stress depresses the accumulation of starch more severely than that of protein. As a result, the duration of grain filling is reduced and hence grain size is reduced (Wurst, 1999a).

Apart from absolute limits to the timing and duration of the crop cycle set by seasonal water availability, there are four major constraints on south Australian wheat crop systems (Pratley, 1994).

- The timing of sowing rains (opening rain)
- The duration of the mid-winter depression in temperature and solar radiation
- The rapid increase in temperature and evaporation rate during spring and early summer

- The timing of earliest safe ear emergence date as set by frost occurrence

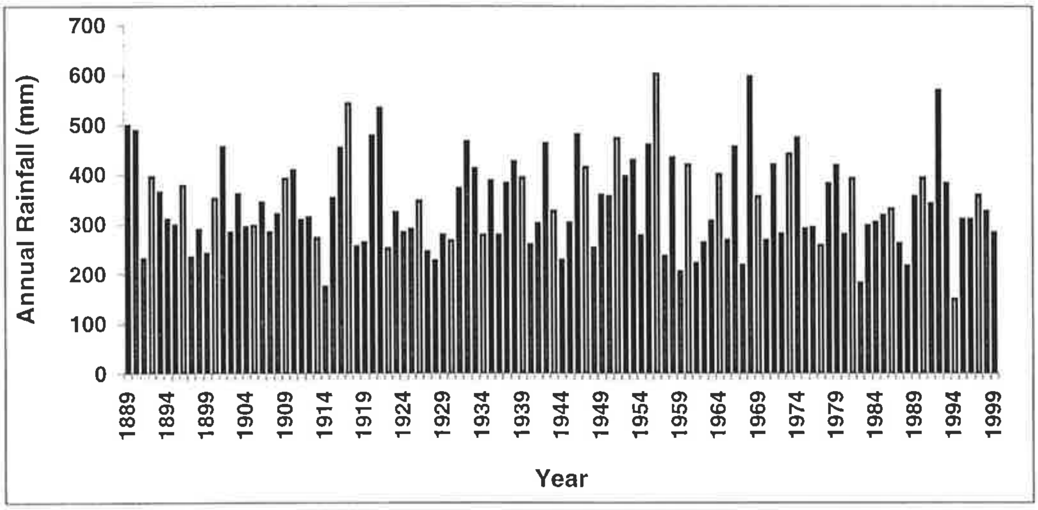


Figure 3.2 Rainfall variability over 111 years from 1889 to 1999 at Minnipa

3.2.2 Temperature, Photoperiod and Radiation Influences Phenological Development and Wheat Growth

Temperature, photoperiod and solar radiation are other determinants that affect wheat production. In South Australia, wheat is sown soon after the opening rains in autumn and early winter, undergoing vegetative growth under conditions of short days and cool to cold temperatures. The commencement of each phenological stage (except for sowing to germination, which is driven by temperature and soil water content) is determined by accumulation of thermal time. Tillering and vegetative growth occurs during September-October at a time when rainfall is declining, days are lengthened and potential evapotranspiration rates are increasing. Floral initiation and inflorescence occur under conditions of increasing daylength, temperature and solar radiation during late winter-early spring, while heading, anthesis and grain filling occur under a combination of high temperatures and rapidly rising water stress during late spring and early summer. For the three development phases: sowing to floral initiation, floral initiation to anthesis and anthesis to maturity, growth and development during the first two is largely governed by the thermal and light regimes, particularly the thermal regime. In the final phase, anthesis to maturity, the moisture regime imposes the major constraint (Pratley, 1994).

3.2.3 Wheat Soil

The influence of soil also plays a part in determining where wheat is grown. The soils of the South Australia wheat zone in their virgin state are predominantly old, weathered and naturally infertile. Their physical state and texture vary widely. The nutritional status of the soil profile is low by world standards and highly variable between soils. Apart from a deficiency in N and P, many of these soils are deficient in a number of micro-nutrients, particularly zinc, copper, and manganese. As well, boron toxicity is widespread, and many of the soils in South Australia are sodic. The subsoils are typically less fertile and can be structurally poorer than the surface horizons. The surface soils, however, are fragile due to excessive cultivation and are often vulnerable to wind and water erosion (Dubē and Cook, 1992; Zubaidi, 1996).

There are two most important wheat belt soils: the red-brown earths which are characterised by a vegetation of open savanna, and soils in scrub country known as Mallee, which are generally alkaline and of light texture. The red-brown earths are found on the drier margins of the podsols, where the rainfall is lower and there is significantly less leaching. These soils have developed in what is known as the winter rainfall areas in a belt of country defined by a rainfall ranging from 400mm to 635mm. The red-brown earths are mildly acidic to neutral pH in the surface and sub-surface layers. These soils also have low to moderate amounts of P and N. It was on these red-brown earths of South Australia that many of the practices and techniques associated with modern wheat production were evolved (Donath and McGarrity, 1976).

Mallee soils are found in the semi-arid region of South Australia, which derives its name from the small eucalypt that grows in these areas. It occurs where the rainfall declines from the open woodland of the red-brown earths. These soils have surface soils of sandy or loamy textures. Mallee soils with sandy surface texture are low in organic matter and N, and have a low water holding capacity so that they are liable to water and wind erosion. Mallee soils with loamy surface textures have a higher level of organic matter and N, a better water holding capacity and are more alkaline. These Mallee soils, on the whole, are not very fertile, tending to show a deficiency in phosphorous and being low in organic matter. Apart from the nutritional problems of these two types of soils, they often have poor physical structure, which results in transient waterlogging, surface crusting and poor emergence (Donath and McGarrity, 1976).

In South Australia, the main wheat production areas are found in the Statistical Divisions of Western (Eyre Peninsula), Upper North, Lower North, Central, Murray Mallee and Southeast. The main localities are Minnipa, Cummins, Orroroo, Kapunda, Roseworthy, Renmark, Wanbi, Lameroo, Keith, and Naracoorte. Wheat growing in this State has extended into areas with an average annual rainfall of only about 200mm, but the bulk of the wheat belt is within the 250mm and 500mm annual isohyets (Donath and McGarrity, 1976).

3.3 FLUCTUATION OF WHEAT YIELD AND WHEAT PRODUCTION AREA IN SOUTH AUSTRALIA

From the beginnings of European settlement, wheat has been the mainstay for the South Australian farmer, although the mixture of products diversified greatly during the 20th century. The seasons of 1883-1884 and 1933-1934 mark the end of two major phases of rapid expansion of wheat growing on newly cleared land. Average grain yield fell steadily during the 19th century as the natural soil fertility became depleted, and farmers spread into drier areas. There was a steep rise early in the 20th century with the wide spread adoption of phosphate fertiliser. Yield fell again in the 1920s as soil nitrogen became depleted through over cropping. The rise after 1940 reflected the retreat from marginal areas and the build-up of nitrogen, which followed from the use of legumes and increased livestock. Between the 1960s and 1980s, the area of wheat expanded again but the long-term trend of yield has been on a plateau (Griffin and McCaskill, 1986). There is no obvious change in sowing acreage and yield since the 1990s, although yield variability still exists due to interannual rainfall variation. The fluctuation of wheat yield and production area through the periods of 1840-1984 and 1983-1996 is illustrated in Figures 3.3 and 3.4 respectively. The expansion of wheat production and the yield fluctuations reflect the improvements in agricultural mechanisation levels, the improvement of agricultural production technology, soil nutrient status, rainfall variability and economic factors.

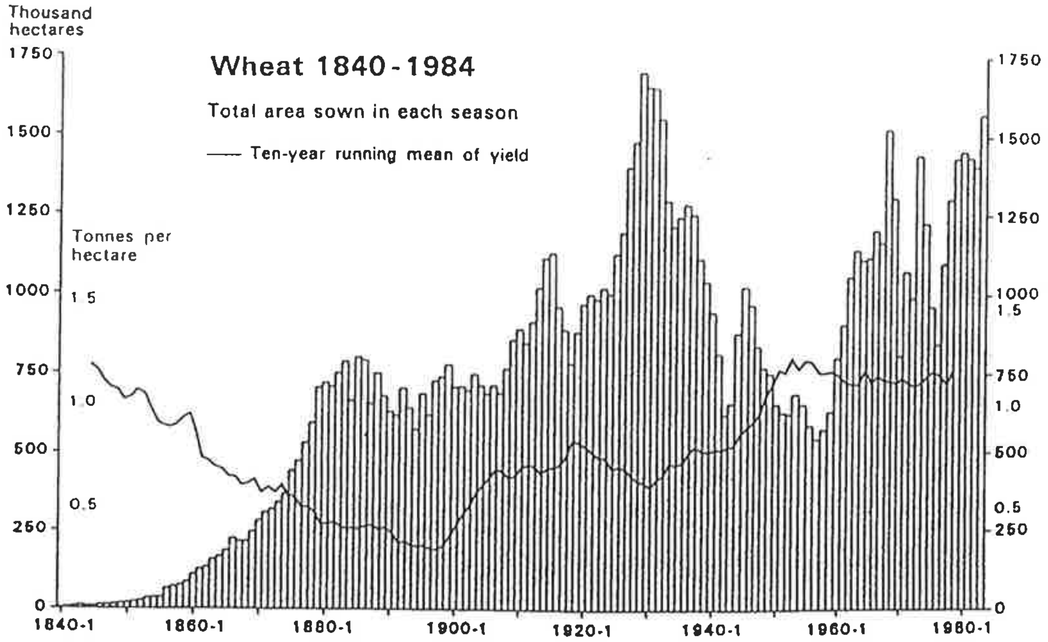


Figure 3.3 Fluctuation of wheat grain yield and production area between 1840 and 1984 in South Australia. Source (Griffin and McCaskill, 1986).

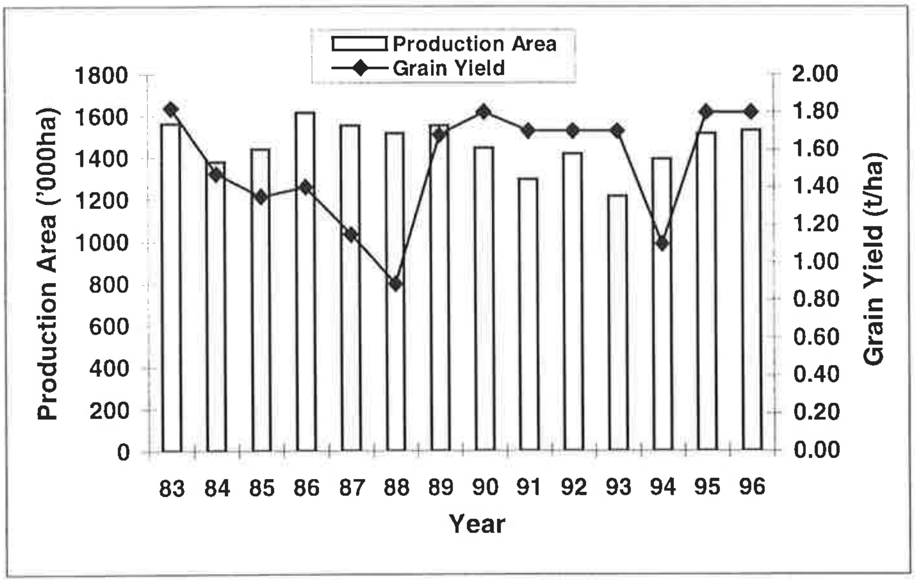


Figure 3.4 Fluctuation of wheat grain yield and production area between 1983 and 1996 for South Australia (ABS, 2000).

3.4 SIGNIFICANT ROLES PLAYED BY SOUTH AUSTRALIA IN THE HISTORY OF THE NATIONAL WHEAT INDUSTRY

The important role of South Australia in the Australian wheat industry can be traced to the earlier 1840s. It is specifically embodied in the breakthrough in agricultural mechanisation levels, the improvement of agricultural production technology and the lead provided by South Australia which made the wheat industry what it is today.

3.4.1 Turning-Points of Development in Wheat Industry

South Australians on farms and in workshops have made important contributions to Australia's list of farm machinery innovations. In 1843, J.W. Bull and G. Ridley developed the grain stripper, paving the way for successful export-oriented wheat farming in the 1850s. It was reported that the stripper could reduce the cost of harvesting to one twentieth of the previous cost. This marked a major and far-reaching breakthrough in the mechanisation of the industry. This reaping machine was successfully used during the harvest of 1844. With some modifications, this reaping machine became the foremost harvester in Australia for the ensuing half century until the invention of the combine harvester.

In the next half of the 19^{th} century, the main location of wheat growing had shifted from the coastal areas to inland districts and the industry had become of vital significance to the economy of the continent. But one particularly difficult problem was encountered in the Mallee country while expanding wheat production: This took the form of underground obstructions, mainly old roots and boulders that buckled and bent ploughshares. This Mallee country was good wheat land, but most of it was unusable because of these obstructions until Robert. B. Smith at Kalkabury near Maitland on Yorke Peninsula, invented the ingenious 'stump-jump' plough in 1876 that opened up vast tracts of land for wheat growing and contributed immensely to the eventual development of inland Australia. The stump-jump mechanism, a 'folk invention' from South Australia's Yorke Peninsula, is now widely used on farm machinery throughout Australia and in some western States of the USA. This development was perhaps the most decisive South Australian innovation (Griffin and McCaskill, 1986; Donath and McGarrity, 1976).

3.4.2 Development of Agricultural Production Technology

Another boost to South Australia's position of dominance in the wheat industry came when a method of combating ball smut or bunt-a serious wheat plant disease-was adopted throughout the country. A South Australian, John Reynell, had long advocated that the seeds which carried the disease spores be 'pickled' in copper sulfate. By 1843, this method was in general use, and both the areas sown to wheat and yield increased dramatically. Reynell's method was still being used on a wide scale until about 1916 when copper and mercurial fungicides became popular with growers.

Professor Custance at Roseworthy Agricultural College discovered that phosphate fertiliser application could restore soil fertility. His successor, Professor W. Lowrie, disseminated this discovery to farmers: dressing of 30-40kg/ha drilled with wheat crop became a standard farm operation. By 1901 two factories were established for the manufacture of super-phosphate in South Australia (Donath and McGarrity, 1976).

Another South Australian innovation was the domestication of first sub clover and second, annual medics as annual pasture legumes that could be grown in rotation with cereals, the so called ley farming system. This system improved soil fertility and cereal grain yield and diversified farm income through wool and meat production.

Undoubtedly these technologies and innovations have made a great contribution to the development of the national wheat industry. The part played by South Australians was paramount.

3.4.3 The Leading Position Taken by the South Australian Wheat Industry

In 1853, South Australian farmers planted 31,200ha of wheat and, in that year overtook New South Wales as Australia's main wheat-growing state. By 1854, more than 40% of Australia's wheat area was sown on South Australian farms. Nine years earlier, and only a mere seven years after settlement, South Australia found itself with an exportable surplus of wheat and supplies were sent to Victoria and Western Australia. This remarkable early success of South Australian wheat growing is one of the most significant aspects of the development of the industry in Australia. Favored by easily cleared land, settlement spread rapidly. In addition, access to sea transport by means of the deeply penetrating St Vincent and Spencer gulfs was relatively easy. South Australia became the granary of the continent and also the birth place of its modern wheat industry (Donath and McGarrity, 1976).

3.5 NORMAL CULTURAL AND MANAGEMENT MEASURES OF WHEAT

The industry made tremendous strides in the field of mechanisation, but this also brought about many environmental problems such as wind and water erosion; and decline of soil fertility. As a consequence, wheat yields slumped dramatically from around 0.22 tonnes/ha in the mid-1850s to less than 0.06 tonnes/ha in 1889, 1890 and 1891.

Measures taken to prevent the continued deterioration of the soil and to restore its fertility at the end of the 19th century include: conserving the soil by mechanical means such as contour cultivation (minimising runoff from rain helping to combat erosion); crop rotation; fallowing (increase in the soil moisture content of the soil, accumulate reasonable amount of nitrogen for the following crop in the short term); and adding phosphate fertiliser to the soil.

The fallow system practised by most South Australian farmers by the early 20th century was a simple wheat-fallow system with few livestock. After a year of fallow with frequent cultivation to suppress weeds and, it was believed, to conserve moisture, wheat was sown with superphosphate following the first autumn rains. However this system was exploitative, and by the 1930s had led to deteriorated soil structure, depleted fertility, and wind and water erosion.

Farm methods have become more refined in order to pursue high profits in conditions of degraded soil. More efficient and broader practices in cultivation method (i.e. rotation system), residue and tillage management etc. were applied later on to ameliorate soil physical structure and improve soil fertility (Donath and McGarrity, 1976; Griffin and McCaskill, 1986).

3.5.1 Rotation System

It was recognised that in order to maximise yields and minimise the build-up in disease levels, successive crops should not be the same or similar species. Wheat production in South Australia is grown in rotation with annual legume pastures and other crops. The pasture is usually sown under the final cereal crop. This type of farming is often referred to as clover-ley or medic-ley farming. "Ley" means pasture. Pasture has several functions as listed below. First, it can enhance soil fertility (the amount of nitrogen symbiotically fixed by legume crops and pastures usually range from 60kg-120kg of N/ha/year). Secondly, it can ameliorate soil structure and lastly, it can contribute to weed and disease control (subterranean clover and lucerne leys are largely responsible for the suppression of skeleton weed (*Chondrilla juncea*) to manageable levels for crop production) (Donath and McGarrity, 1976; Pratley, 1994).

Legumes, notably subterranean clover (*Trifolium subterraneum*) and various species of medics (*Medicago* species) originated in the Mediterranean, and were introduced fortuitously to South Australia, possibly by the 1870s. They spread over much of the cereal zone when farmers began sowing superphosphate with their wheat, and grew as volunteer pastures on land which was not immediately ploughed up after the grain harvest. The medics and clovers are particular useful because they set hard seed at the end of the spring, evade the summer drought, and germinate in the next autumn, or the next but one. These pasture legumes, which are stimulated by superphosphate dressings, obtain nitrogen from the air and return it to the soil through decaying plant material and droppings of grazing animals.

Subterranean clover and the medics provided the basis for a ley system of farming in which grains and medic are alternated, with the pasture phase supporting livestock, especially prime lambs. The spread of the ley system was accelerated by the replacement of horse-teams by tractors after the Second World War and by the high wool prices of 1950s. It was a cheap and effective method of restoring structure and fertility to the worn-out wheatlands and of raising the yields of grain harvests, the number of livestock and the weight of fleeces. The South Australian experience was soon applied to other summer-dry farming areas of Australia. The particularly ley system ranks among the most important Australian agricultural innovations of the 20th century (Griffin and McCaskill, 1986).

In the past decade there has been an increase in cropping intensity with the introduction of more cropping options such as canola, chickpeas, lentils, vetch etc. Changes are related to the relative profitability of grains and livestock products, which have driven this move to greater cropping intensity (Bellotti, 2001).

The rotations practised tend to be flexible (being related to forecast commodity prices) and vary appreciably both between and within regions, being mainly a reflection of the soils and climate and availability of adapted crop and pasture species. In the more favoured areas, more grain legume and cereal cash crops are grown, whereas in the lower rainfall area, less intensive ley farming rotations are prevalent forms of land use (Donath and McGarrity, 1976; Dubē and Cook, 1992).

In the wetter parts (annual rainfall greater than 400mm) of the South Australian wheat belt, subterranean clover together with Wimmera rye grass pastures are rotated with wheat. This pasture is maintained for 3-4 years, and then crops are grown for 2-4 years. In the drier parts of the wheat belt subterranean clover is replaced by medic. Increasingly, however, lucerne (*Medicago sativa*) is being used because it extends the grazing period each year and its deep taproot provides an opportunity to utilise deep soil moisture. Greater options are now available to farmers with the development of improved cultivars, particularly, of burr medic (*M. polymorpha*), murex medic (*M. murex*) and serradella (*Ornithopus compressus*).

In the past, farming systems have evolved with the particular economic and biological conditions of the time. This indicates that in the future, faced with atmospheric change, we can expect that farming systems will continue to evolve to optimise available resources. For example, reduced rainfall requires a shift in crop species grown or a shift from cropping to livestock.

3.5.2 Tillage, Stubble Management and Fallow

From the mid 1970s a discernable trend towards more intensive cropping occurred, together with a wider adoption of reduced tillage and trash retention systems for land preparation. Up until the 1970s in Australia, seedbed preparation involved numerous passes with cultivation equipment. The traditional tillage practice resulted in breaking down organic matter; degrading soil surface structure; increasing erodibility and creating compaction layers at plough depth. Since that time, attention has been directed towards reduced tillage, minimum tillage, zero tillage and no tillage/direct drill techniques, which preserve soil structure. Reduced tillage is a one pass prior to seeding with a full cut. Minimum tillage facilitates crop establishment by enabling the timing of operations to be optimised. Zero tillage applies to sowing seeds into a narrow slot created using a disc seeder. No tillage applies to sowing a crop without prior cultivation and with very little soil disturbance at seeding, using narrow points (PIRSA, 1999).

Three types of stubble management are practised in South Australia to preserve soil physical structure and soil fertility. The incorporation of the stubble within the upper layers of soil is one form of residue management. Burning stubble is another and is a quick, inexpensive and effective way of removing the stubble, which can also reduce disease carry over but at the expense of reduced soil fertility over the long term. The maintenance of the residues from the previous crop on the soil surface with the succeeding crop being sown through the bulk material is the other method for managing residues. This method is called stubble retention.

The amount of cereal straw returned each year has been of the order of 1-2.5 t/ha with smaller amounts from the other crops in rotations.

Fallow has been an integral part of farming in the lower rainfall area (annual rainfall less than 350mm) of South Australia. But the increased use of reducing tillage systems, the retention of crop residues and the wide-spread adoption of annual legume pasture ley have made fallow less important (Donath and McGarrity, 1976).

3.5.3 Sowing and Fertiliser Management

The date of actual sowing will ultimately be determined by the moisture conditions of the soil. It is found that the cultivars of cereals have an optimum sowing date that results in good seed set, a long grain filling period and high grain yields. Sowing late reduces yield due to a high evapotranspirative demand and depletion of soil water during flowering and grain filling (French et al., 1979; Connor et al., 1992).

Research has also clarified the appropriate depth for drilling the seed into the soil (25-50mm) (Coleman, 1996). Optimum yield and quality has often been found to occur at 160-180 plants/m^2 depending on expected growing season rainfall, higher sowing density for higher rainfall environments.

Soil nitrogen is an important factor that affects wheat yield and grain quality. Nitrogen fertiliser recommendations, including the application method, rates and time, are available for all wheat growing regions. 40kg N/ha in mid-higher rainfall areas and 20kg N/ha in low rainfall areas are commonly practised. Broadcast and deep banding are two parallel methods for fertiliser application in South Australia. Broadcasting nitrogen fertiliser is normally ahead of the seeding operation. This requires either additional labour or the need for contractors, increasing cost and risk of nitrogen losses, especially where the fertiliser was spread two or three days ahead of the sowing operation.

An increasing number of growers are moving towards deep placement (15cm) of fertiliser where they are applying more than 20kg N/ha. It is recommended that when applying more than 25kg N/ha, a minimum separation of 3.5 cm is required between the N and seed. Deep banding of urea has proven very successful where higher amounts of nitrogen fertiliser are required in direct drilling systems which ensure soil conservation, timeliness of sowing and reduced machinery, tractor and labour hours (PIRSA, 1999; Wurst, 1999b).

Nitrogen application time is usually before or at seeding. Applications around mid-tillering and pre-flowering are also possible in order to influence tiller production and to assure high levels of grain protein content.

3.6 CONCLUSION

Compared with other States, South Australia has a poorer environment (lower annual rainfall and poor soil conditions) for wheat production. However, great achievement has been made throughout the history of wheat production whether in wheat yield or in wheat production area. These significant achievements are attributed to the invention and adoption of advanced agricultural technologies (agricultural production technologies and agricultural mechanisation technologies) in this State. Any great change in wheat yield and in wheat production area is associated with the renovation of agricultural technology. Advanced agricultural technologies also greatly pushed forward the development of the wheat industry in other States. The higher degree of agricultural mechanisation also had side effects on South Australian wheat production such as wind/water erosion, which led to the decrease of grain yield. Faced with the poorer environment and the consequences of advanced agricultural mechanisation, adaptations have been taken to assure sustainable development of wheat production in this state. This can be demonstrated by the evolution of the cultural and management measures such as the ley system. The plateauing of the average wheat yield since 1960 is a key reason why South Australia must adapt to future atmospheric change. This chapter provided a context for selection of study sites and for assessing wheat production in South Australia. The next three chapters are about methodologies of this study including study site/area, assessment tool: APSIM-Wheat model and its parameterisation.

4. STUDY SITES/AREA AND DETERMINATION OF NUMBER OF SIMULATION RUNS

This research involved in two parallel studies: a site-specific study and a spatial study. They differ from each other in scope, object (point for site-specific study, area for spatial study), data format requirement, study emphasis, and analytical tools employed. These differences are summarised in Table 4.1. Figure 4.1 describes the procedures followed in these two parallel studies. However, these two parallel studies share most of the approaches employed in this project such as the construction of atmospheric change scenarios and the parameterisation of the APSIM-Wheat model while maintaining their own features in managing climate and soil data, the number of atmospheric change scenarios used and in results communication. This chapter introduces the study sites and study area associated with these two parallel studies. The number of simulation runs for the spatial study across the study area was also determined in this chapter based on the analysis of spatial climatic and soil data, which is an essential step before parameterising the APSIM-Wheat model. The number of simulation run for the site-specific study is straightforward: one location corresponds to one simulation run.

Table 4.1 Difference between site-specific study and spatial study

	Site-Specific Study	**Spatial Study**
Study Scope	state wide	east/west strip crossing Central, Lower North and Murray Mallee agricultural regions
Study Object	point-based	area-based
Spatial Soil Variability	no	yes
Study Emphasis	risk analysis	risk analysis and spatial analysis
Analysis Tool	statistical software	GIS
Visualisation Method	point Based, 5 dimensional response surface	spatial data visualisation: map
Advantage	• probability attached to projected yield change • very wide areal coverage	•providing more precise information on wheat production impact •Probability attached to projected yield change
Disadvantage	coarse spatial resolution	digital soil map is required

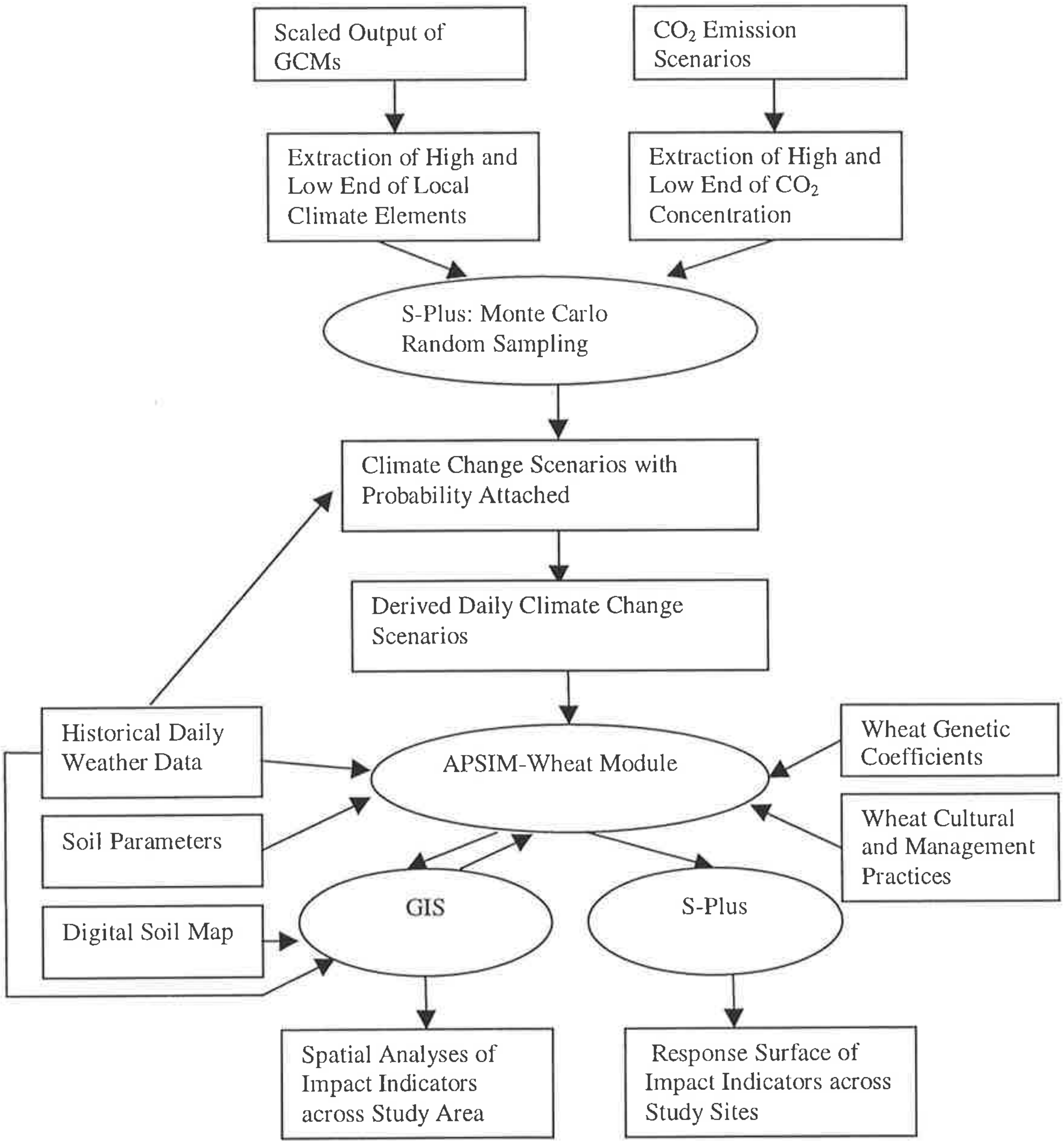


Figure 4.1 Procedures employed by site-specific study and spatial study

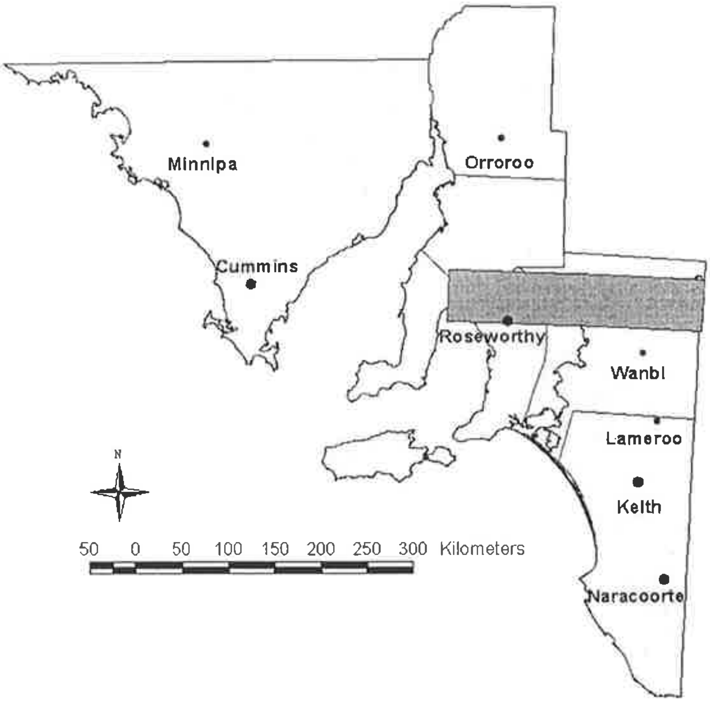


Figure 4.2 Location of study sites and study area. Smaller dots indicated drier sites, larger dots denote wetter sites. The dark grey strip is the scope for spatial study.

4.1 STUDY SITES AND AREA

As indicated in Table 4.1, the site-specific study and the spatial study have different study object/study scope. The study sites and area corresponding to the site-specific study and the spatial study are described below.

4.1.1 Study Sites for the Site-Specific Study

In the site-specific Study, 8 localities (Cummins, Keith, Lameroo, Minnipa, Naracoorte, Orroroo, Roseworthy, Wanbi) across the South Australian wheat belt were chosen. These eight sites are representative of each agricultural region. Minnipa and Cummins are representative of the Western agricultural region. Orroroo represents the Upper North agricultural region. Roseworthy belongs to the Central agricultural region, Lameroo and Wanbi are from the Murray Mallee agricultural region. Keith and Naracoorte are physically located in the Southeast agricultural area.

These eight sites have different annual rainfall. Cummins, Keith, Naracoorte and Roseworthy have wetter climates with an annual rainfall of 430-580mm. The other four sites are drier with annual rainfall ranging from 305 to 390mm. Table 4.2 gives the coordinates and annual rainfall for each location. Figure 4.2 presents the geographical location of these eight sites.

Table 4.2 Coordinates and annual rainfall of study sites

Study Sites	Latitude	Longitude	Annual Average Rainfall (mm)
Wanbi	-34.78	140.27	303.8
Orroroo	-32.74	138.61	341.9
Minnipa	-32.86	135.15	362.2
Lameroo	-35.33	140.52	388.4
Cummins	-34.27	135.73	430.5
Roseworthy	-34.53	138.69	440.3
Keith	-36.10	140.35	467.9
Naracoorte	-36.96	140.74	578.3

4.1.2 Study Area for Spatial study

The area for the spatial study stretches E/W from 138° to 141°E and N/S from 34°S to 34.5°S. The relative position of this area in the South Australian wheat belt is indicated as dark grey in Figure 4.2. It traverses three agricultural regions (Lower North, Central and Murray Mallee) and is composed of 6 map sheets of 1:100,000 scale: Wakefield, Kapunda, Eudunda, Morgan, Moorook, and Renmark. Quite different annual rainfall is received in different parts of this area. Wakefield (individual station) receives an annual rainfall of 337 mm. Kapunda and Eudunda receive the highest annual rainfall ranging from 451 to 495 mm. Morgan, Moorook and Renmark receive the lowest annual rainfall, from 248 to 261 mm. Soil conditions vary spatially.

4.2 SPATIAL DATA ANALYSIS

Increasing density of study sites is one of the purposes of this study to consider the importance of soil variability to the assessment of atmospheric change on wheat production. A GIS tool was used to manage, analyse and process spatial climatic and soil data. The number of APSIM-Wheat runs across the study area for the spatial study was determined through analysing the spatially climatic and soil data and through some geoprocesses such as union, intersection, and dissolve.

4.2.1 Cartography of Spatial Study Area

The 1:100,000 map sheets were downloaded from the AUSLIG website (AUSLIG, 2000) in an Arc/Info format in geographic projection. The data was projected to the Lambert AGD84 projection to match the South Australian Soil Districts Coverage. Six map sheets were selected to form the study area (see dark grey area of Figure 4.2).

4.2.2 Generalisation of Spatial Climatic Data

Higher temporal and higher spatial resolution are needed by crop models for more accurate projected outcomes under atmospheric change. However, at present, there are not enough computing resources for GIS to manage higher spatial and temporal resolution data (daily data for 100 years) simultaneously (mathematically complex and computer-intensive). To overcome this problem, long term series of historical daily climate information (1889-1999) was summarised from 42 stations within and around this study area. The historical daily climate data for these 42 stations were obtained from the SILO climate database (Anon, 2000a). Table 4.3 shows detailed information about coordinates, average annual maximum temperature (MAXT), average annual minimum temperature (MINT), average annual solar radiation (RADI) and annual rainfall (RAIN) for each station. The MAXT, MINT, RADI and RAIN in Table 4.3 were calculated from historical daily climate data (solar radiation data were derived from other variables). This table was then imported into the Arc/View GIS where the climate elements were statistically analysed. The statistical results for those climate components are listed in Table 4.4.

Table 4.3 Coordinates and annual averages of climate variables for each station

Station_Name	Station_ID	Latitude	Longitude	RADI	MAXT	MINT	RAIN
Angaston	023300	-34.50	139.05	16.77	21.88	9.35	559.88
Ardrossan	022000	-34.42	137.92	16.68	22.21	11.40	348.31
Auburn	021001	-34.03	138.68	16.87	21.55	9.07	591.32
Balaklava	021002	-34.15	138.42	17.01	23.02	10.56	382.52
Barmera	024001	-34.25	140.46	17.54	23.98	10.05	247.26
Berri	024025	-34.29	140.60	17.52	24.06	10.23	252.85
Blanche Town	024523	-34.42	139.78	17.32	23.43	9.55	274.09
Eudunda	024511	-34.18	139.09	16.97	21.49	9.21	451.38
Freeling	023325	-34.46	138.81	16.75	21.80	9.80	510.11
Greenock	023305	-34.46	138.93	16.73	21.49	9.27	537.06
Hamley Bridge	023095	-34.36	138.68	16.97	22.94	10.55	430.00
Hoyleton	021026	-34.04	138.56	16.94	22.27	9.64	459.56
Kapunda	23307	-34.34	138.92	16.85	21.97	9.66	494.59
Kingston on Murray	024006	-34.23	140.34	17.55	23.98	9.97	247.51
Loxton	24023	-34.43	140.60	17.39	23.57	9.41	269.17
Mallala	023073	-34.42	138.50	16.89	22.64	10.80	409.09
Manoora	023310	-34.00	138.77	17.12	23.07	9.99	487.96
Marrabel	023311	-34.14	138.88	16.85	21.31	9.09	528.44
Moorook	024010	-34.29	140.37	17.51	23.95	9.89	258.79
Morgan	024578	-34.08	139.65	17.54	23.75	9.91	248.06
Nuriootpa	023321	-34.48	139.00	16.70	21.21	8.93	530.52
Overland Corner	024012	-34.15	140.32	17.67	24.19	10.22	250.37
Owen	023012	-34.27	138.55	16.99	23.01	10.62	420.66
Paskevill	022012	-34.04	137.90	16.88	22.23	10.43	389.48
Point Pass	024526	-34.08	139.05	17.16	22.95	9.89	406.57
Port Wakefield	021044	-34.19	138.15	16.95	22.96	10.98	336.50
Pyap	024013	-34.45	140.49	17.38	23.66	9.49	265.23
Renmark	024016	-34.17	140.75	17.62	24.19	10.80	260.65
Riverton	023314	-34.16	138.75	17.05	22.96	10.17	531.40
Roseworthy	023020	-34.53	138.69	16.85	22.51	10.68	439.48
Saddleworth	023315	-34.09	138.78	17.06	22.88	10.00	495.38
Sedan	024531	-34.57	139.29	16.92	22.74	9.54	305.45
Stockport	023316	-34.33	138.73	16.97	22.91	10.46	450.78
Stockwell	023317	-34.44	139.05	16.68	20.96	8.76	500.71
Sutherlands	024534	-34.16	139.22	17.13	22.61	9.57	292.97
Swan Reach	024535	-34.57	139.60	17.07	23.32	9.55	273.16
Tanunda	23318	-34.53	138.96	16.70	21.78	9.53	548.65
Tarlee	023319	-34.27	138.77	17.01	22.94	10.32	472.99
Truro	024573	-34.41	139.14	16.99	22.67	9.70	495.43
Waikerie	024018	-34.18	139.98	17.63	23.90	9.99	259.41
Watervale	021054	-33.96	138.64	16.69	20.05	7.94	656.32
Wunkar	025024	-34.49	140.30	17.28	23.52	9.24	273.51

It can be seen from Table 4.4 that the spatial variation of rainfall is very large compared to the other three variables. As a result, only rainfall was used to generalise climate divisions. Before the rainfall theme was overlaid with the study area (dark grey area in Figure 4.2), the decimal degree based rainfall feature had been projected to the same projection as the study area. Rainfall was classified into 9 classes with 50 mm intervals and visualised in ArcView (Figure 4.3a).

To further analyse climate data, elevation data (grid data) for the study area was acquired from GISCA, Adelaide University and projected to the Lambert AGD84 to form a new set of elevation data on the basis of study area. This new elevation data set was overlaid with the rainfall data and the study area to analyse the rainfall pattern. Three areas with distinctive, relatively homogenous rainfall were identified: medium rainfall areas, higher rainfall areas and low rainfall areas. Higher rainfall areas corresponded well to the region of higher elevation (Figure 4.3b).

In order to generate the areas with different rainfall patterns as accurately as possible, contour lines were created based on the newly created elevation data set with a 25m interval. Two lines were drawn at distinctive rainfall change intervals (Figure 4.3c). The study area was converted to a line theme and intersected with those two lines. The newly formed line theme was converted to coverage format in ArcInfo GIS. The spatial relationships between features of this coverage were constructed there. The final climate coverage is shown in Figure 4.3c with three divisions (polygons). The three stations chosen to represent the three rainfall divisions are Owen (medium rainfall area), Kapunda (high rainfall area) and Moorook (low rainfall area).

Table 4.4 Statistics for climate elements

Statistical Variables	RADI	MAXT	MINT	RAIN
Mean	17.08	22.73	9.86	401.04
Maximum	17.67	24.19	11.40	656.32
Minimum	16.68	20.05	7.94	247.26
Range	0.99	4.14	3.46	409.06
Variance	0.09	0.97	0.45	14081.25
Standard Deviation	0.30	0.98	0.67	118.66

4.2.3 Digital Soil Map and Its Union with Climate Divisions

The updated digital soil coverage (in Geographic Projection, GDA94 datum, decimal degree and GRS1980 spheroid) was obtained from PIRSA Land Information. It is the best available digital soil database for South Australian agricultural regions. The soil types used in this spatial study are based on common soil units, which are described in the look up table of this coverage. Common soils are the most common types of soil within soil landscape units (Figure 4.4a). There are 43 common soil types with 39 arable in this study area. Therefore data for 39 representative soil profiles were gathered from PIRSA for the spatial study. However, the soil profile data are synthetic soil data as there are no specific data for those common soils.

The digital soil data was firstly projected to Lambert AGD84 projection in order to be overlaid with climate divisions. Projected data were then clipped to the study area. The look up table was joined to the coverage attribute table based on the common field "lanslu" for presenting common soil features.

Common soil theme features were generalised as indicated in Figure 4.4b in order to get unique combinations of soil and climate information. The generalised soil coverage was then intersected with the three climate divisions. Figure 4.4c is the final coverage, comprising 79 unique combinations of soil and climate information. Accordingly 79 simulation runs will be set up under different atmospheric change scenarios.

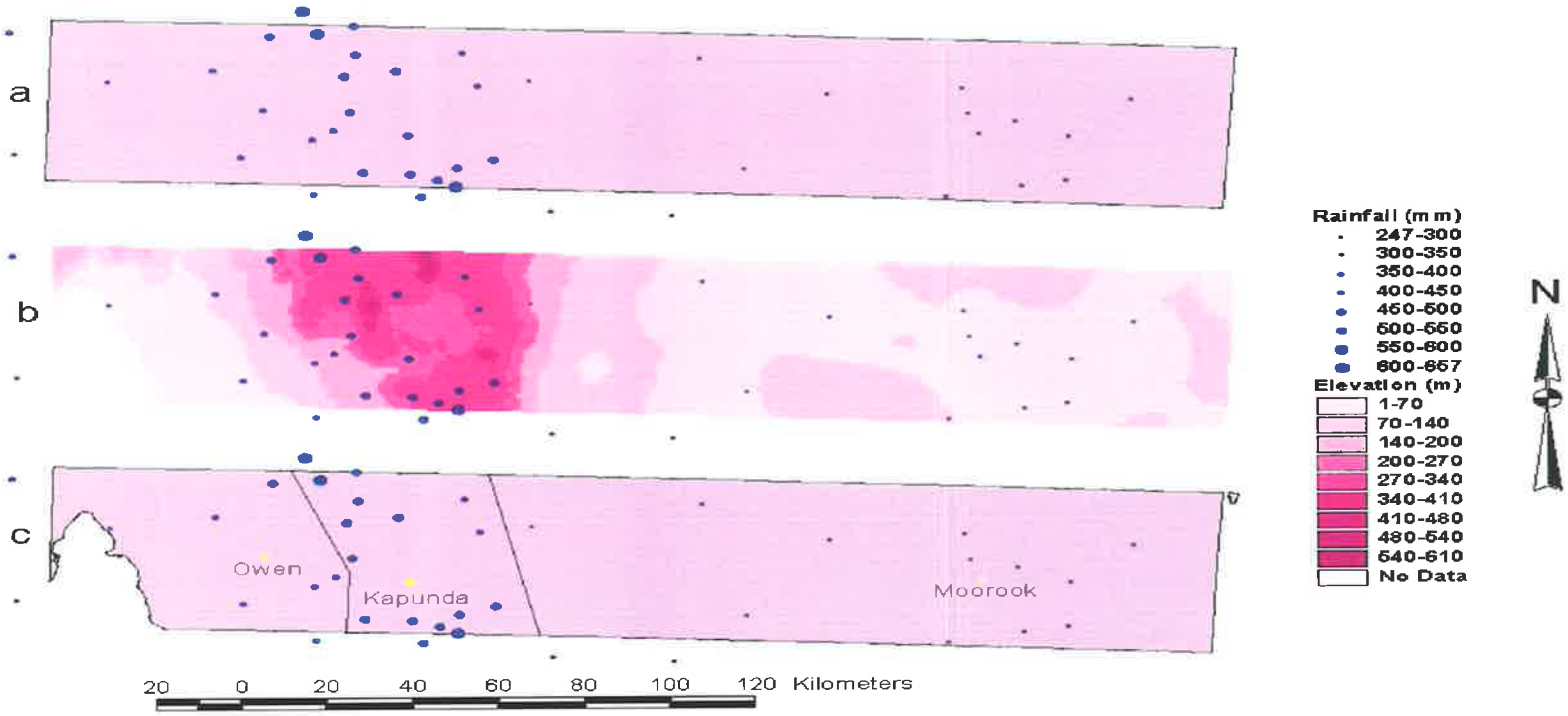


Figure 4.3 Generalisation of climate data. The bigger dots represent higher rainfall stations, the smallest dot represent low rainfall stations. The medium dots represent medium rainfall stations. Three climate divisions with distinctive rainfall patterns: medium rainfall area (left hand polygon), higher rainfall area (middle polygon) and dry rainfall area (right hand polygon) were identified across this region. Long term climate information for stations of Owen, Kapunda and Moorook denoted in yellow colour, representing different division were used to drive APSIM-Wheat module.

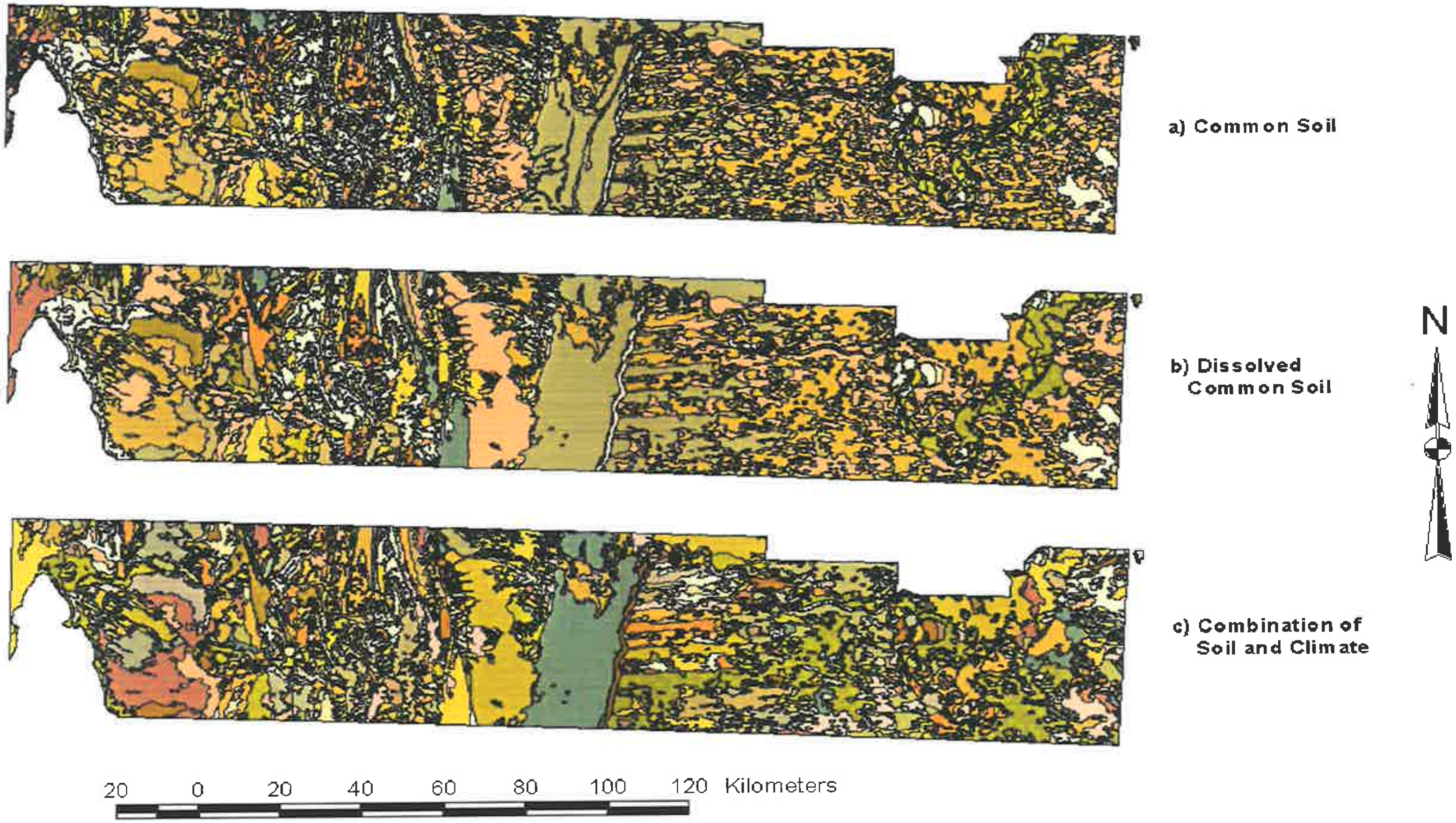


Figure 4.4 Common soils and its union with climate divisions. As a result, 79 unique combinations of climate and soil were formed, which indicate 79 APSIM-Wheat runs will be set up across this region.

4.3 CONCLUSION

Two parallel studies: a site-specific study and a spatial study are involved in this project. These two parallel studies are different from each other in a number of ways such as different study scope and different methodology employed. Special processes are needed by the spatial study before parameterising the APSIM-Wheat model. This chapter has given an overview of the study sites and study area corresponding to these two studies. The number of simulation runs for the spatial study across the study area was determined (79 runs) through analysing spatially climatic and soil data. Three climate divisions with distinctive, relatively homogenous climate features were divided across the spatial study area. The climate divisions were intersected with the generalised soil coverage to form a new coverage, which includes both climate information and soil information. 79 unique combinations of soil and climate were identified indicating 79 simulation runs will be set up across the spatial study area. This is the content of the next chapters: APSIM-Wheat model and its parameterisation.

5. APSIM-WHEAT MODEL AND ITS PARAMETERISATION

Simulation techniques are one of the main methods for studying possible impacts of atmospheric change (climate change and atmospheric pCO_2 change) on ecosystems. The APSIM-Wheat model (Keating et al., 2002) was applied in this study to assess quantitatively and visually South Australian wheat production impacts resulting from atmospheric change. Having determined the number of simulation runs in the last chapter, it is reasonable to move to the APSIM-Wheat model itself. This chapter first describes the APSIM-Wheat Model including its structure, the physiological processes considered, the modifications corresponding to the enhanced atmospheric pCO_2 and its validation. The parameterisation of the APSIM-Wheat model comprising data specification and data integration to the model is then discussed.

5.1 APSIM-WHEAT MODEL

APSIM-Wheat model was released in early 2001 by the Agricultural Production System Research Unit (APSRU), which is a joint research unit of Queensland Departments of Primary Industry (DPI) and Natural Resources (DNR) and CSIRO Tropical Agriculture. The APSIM-Wheat model was developed from two earlier models: NWheat and I-Wheat. While APSIM-Wheat uses many Nwheat/I-Wheat approaches for different crop processes, some entirely new approaches were adopted where it was thought that the existing approaches in either model were not suitable. APSIM-Wheat has an entirely new and highly modular structure. Most of the model constants and parameters are externalised from the code.

5.1.1 Environment for Running APSIM-Wheat Model

APSIM stands for Agricultural Production Systems sIMulator. It is an integration of several interactive modules including Biological Modules (Crop Modules, Grazplan Module etc.), and Environmental Modules (Light, Soil) and other utility and application modules. APSIM has been developed in a way that allows the user to configure a model by choosing a set of submodels from a suite of crop, soil and utility modules. Any logical combination of modules can be simply specified by the user "plugging-in" required modules and "pulling out" any modules no longer required (Anon, 2000b). Figure 5.1 is the overall structure of APSIM.

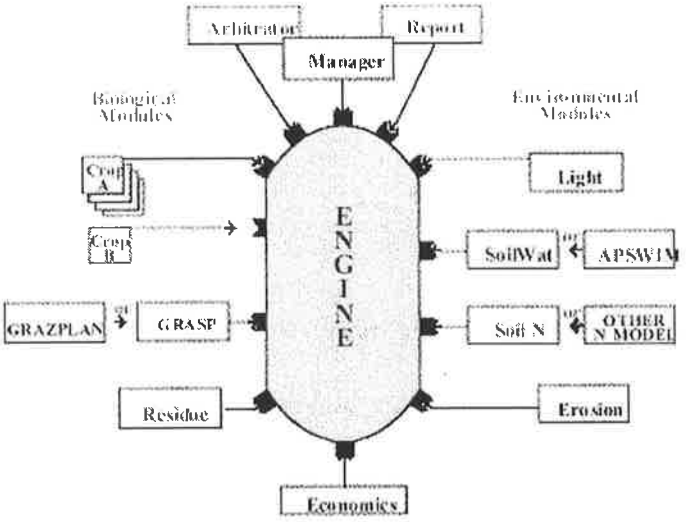


Figure 5.1 Structure of APSIM (Anon, 2000b)

The wheat model is one of the crop models within the APSIM system. It simulates the growth and development of a wheat crop on a daily time-step on an area basis as a function of weather (temperature, rainfall and radiation), soil (soil water and soil nitrogen), crop genetic coefficients and crop management information. The minimum module configuration required to run the APSIM-Wheat module is the inclusion of the Wheat, Manager, Met, Soilwat2, Soiln2, Residue2 and Report Modules. The wheat module is the core of these modules and connects with other modules in a specific way. The Report Module is in charge of the simulated results. Manager, Met, Soilwat2, Soiln2 and Residue2 Modules provide some of information to the wheat module. The Manager Module is a utility module that handles a series of commands relating to wheat cultivation, or management information, and climate change information. The Met Module (within Input Module) provides daily meteorological information to the Wheat Module. The Soilwat2, Soiln2 and Residue2 Modules provide the initial conditions of the soil. In return, the Wheat Module returns information on soil water and nitrogen uptake to the Soilwat2 and Soiln2 Modules on a daily basis for reset of these systems. Figure 5.2 demonstrates the coupling mechanism among these modules.

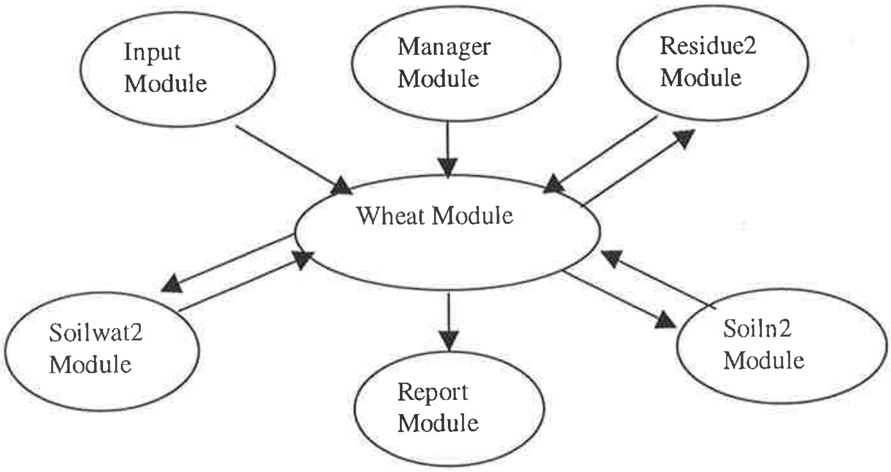


Figure 5.2 Module coupling

5.1.2 Simulated Physiological Processes

Crop physiological processes simulated in the APSIM-Wheat model include phenological development, radiation interception, biomass accumulation and partitioning, canopy, root system, senescence, nitrogen and water balance. The processes are mainly driven by temperature, solar radiation, daylength (photoperiod), soil water and soil nitrogen. The following description is mainly based on The APSIM-Wheat Model (Anon, 2001).

Phenology

APSIM-Wheat uses 12 crop stages and eleven phases as listed in table 5.1. Most of these stages are associated with certain processes.

Table 5.1 Stages of phenological development simulated in APSIM-Wheat*

Stage Code	Stage Name	Starting Processes
1	Sowing	Seed Germination
2	Germination	Emergence, leaf initiation
3	Emergence	Vegetative growth (LAI, DM), water/N uptake
4	End of Juvenile Stage	Photoperiodism
5	Floral Initiation	Spikelet initiation
6	Flag Leaf	Active ear growth
7	Anthesis	Setting grain numbers
8	Start of Grain Filling	Active grain growth
9	End of Grain Filling	Maturity
10	Physiological Maturity	Grain moisture loss
11	Harvest Ripe	
12	End Crop	

*Adapted from APSIM-Wheat Module Documentation

The commencement of each stage is determined by the accumulation of thermal time except for sowing and emergence, which are driven by soil water content.

Germination is assumed to occur as long as the extractable soil water in the seed layer is above a given value. The phase between germination and emergence includes an effect of the depth of sowing on the thermal time target. The phase is comprised of an initial period of the fixed thermal time (40°Cd) during which shoot elongation is slow and a linear period, where the rate of shoot elongation toward the soil surface is linearly related to air temperature (1.5°Cd/mm).

The phase between emergence and end of juvenile stage is composed of a cultivar-specific period of fixed thermal time, known as the basic vegetative or juvenile phase, which is a period when development rate is not affected by photoperiod. The end of the juvenile phase in wheat is currently timed as occurring on the day after emergence because of the sensitivity of the development rate of wheat to photoperiod from emergence.

Between the end of the juvenile phase and floral initiation the crop takes 400 °Cd to reach floral initiation. The rate at which the crop attains this target depends upon photoperiod and vernalisation. The sensitivity to photoperiod and vernalisation is cultivar-specific. The model assumes that wheat, as a long day plant, will have a longer phase between the end of the juvenile phase and floral initiation under short days. Photoperiod is calculated from day of year and latitude using standard astronomical equations accounting for civil twilight which is assumed to be -6°C. Twilight is defined as the interval between sunrise or sunset and the time when the true centre of the sun is 2.2 degrees below the horizon. Vernalisation is simulated from daily average crown temperature and daily maximum and minimum temperature. Devernalisation can occur if daily maximum temperature is above 30°C.

There are fixed thermal time duration for the subsequent phases between floral initiation and flag leaf (3 phyllochrons), from flag leaf to flowering (2 phyllochrons + 80°Cd), and from flowering to the start of grain fill (120°Cd). The duration of grain filling is cultivar specific and usually lies between 500 and 800°Cd.

Leaf Initiation/Appearance and Tillering

Leaves appear at a fixed phyllochron of thermal time (95°Cd). The total number of leaves is equal to the number in the seed at germination (3.5) plus the number initiated during emergence and the number subsequently initiated at a leaf initiation rate of 45°Cd per leaf, until floral initiation is reached. The timing of floral initiation determines the total leaf numbers.

Tillers are produced at a potential rate of one tiller per phyllochron after 2.5 main stem leaves. Actual tillering rate is the potential rate reduced by water and nitrogen stress. Tillering is assumed to stop if the fraction of available soil water in the root zone is below 0.25. The nitrogen stress factor for tillering is calculated as the relative stover N concentration squared. The smaller value of water and nitrogen stress factors is used to reduce the potential tillering rate.

Time course of leaf area production of the main stem and primary tillers is described as a logistic function of thermal time after emergence.

For main stem

$$\mathbf{tiller\_area\ (n) = tiller\_area\_max(n)/(1+exp(\alpha(n)(TT-\beta(n)))} \qquad \textbf{(5.1)}$$

For tillers

$$\mathbf{tiller\_area\ (n) = tiller\_area\_max(n)/(1+exp(\alpha(n)(TT-(1.5+n)*P)-\beta(n)))} \qquad \textbf{(5.2)}$$

where
tiller_area_max(n) = c_max_tiller_area*100/g_plants cm^2
tiller_area(n): leaf area of tiller n
tiller_area_max(n): maximum leaf area of tiller n
TT: thermal time since emergence
P: cultivar specific phyllochron index
α, β: coefficients
g_plants: plant density

Potential LAI growth rate is given by

$$G\_dlt\_LAI\_pot = (TPLA_{today} - TPLA_{yesterday}) * g\_plants * 10^{-4} \qquad (5.3)$$

Water and nitrogen limitations affect leaf area development directly rather than via dry matter production. Water and nitrogen limitations result in either a reduction of leaf expansion or in numbers of tillers produced. It is assumed that leaf expansion growth is reduced when the supply/demand ratio for water is below 1.1 and stops when supply/demand ratio reaches 0.1. The nitrogen stress factor is defined as:

$$G\_nfact\_expansion = N\_fact\_expansion * n\_conc\_ratio\_leaf \qquad (5.4)$$

where
N_conc_ratio_leaf: relative N concentration in leaves
N_fact_expansion: modifying constant

The leaf area growth rate under stress is given by:

$$G\_dlt\_LAI\_stressed = g\_dlt\_LAI\_pot * min\ (g\_swdef\_expansion, g\_nfact\_expansion) \qquad (5.5)$$

Root Growth and Distribution

Root depth is constrained by the soil profile depth. Dry soil can slow roots through a layer if the soil water content is less than 25% of the plant available water content (PAWC). The increase of root depth through a layer can be constrained by known soil constraints through the use of the root exploration parameter "xf " which ranges from 0 to 1.

Growth of root biomass is partitioned with depth using a branching function and converted to root length density using a fixed specific root length of 105,000 mm/g.

Root biomass is grown daily in proportion to the tops production. This proportion is stage dependent and varies from 1.0 at emergence to 0.09 at flowering.

Crop Water Relations

Potential soil water uptake is the sum of root water uptake from each profile layer occupied by roots. A rate constant "kl", which defines the fraction of available water able to be extracted per day, is used to calculate the potential rate of extraction in a layer. Transpiration demand is calculated from the daily crop growth rate limited by radiation use efficiency, the averaged vapor pressure deficit and a transpiration efficiency coefficient. The actual rate of water extraction is the lesser of the potential extraction rate and the transpiration demand.

It is well known that water is a very important factor that affects the whole process of plant growth and development. Three water deficit factors are calculated which correspond to four plant processes (phenology, leaf expansion, tillering and photosynthesis), each having different sensitivity to water stress.

Biomass Accumulation (Photosynthesis)

Three factors, radiation interception, radiation use efficiency and water limitations all influence photosynthesis. Radiation interception is calculated from the leaf area index and a radiation extinction coefficient that varies with leaf area index (LAI) before anthesis. The intercepted radiation is converted to above ground biomass via a radiation use efficiency (RUE), which is 1.34 g MJ^{-1} from emergence to the end of grain filling, and does not vary as a function of daily incident radiation. RUE is reduced by extremes of daily mean temperature and by a nitrogen stress factor.

Under water non-limiting conditions, the biomass growth rate is given by

$$\mathbf{Dlt\_dm\_rue = RUE * radiation\_interception} \qquad \mathbf{(5.6)}$$

Under water limiting conditions, two estimates of daily biomass production are calculated, one limited by available water for transpiration (equation 5.7), and the other limited by radiant energy (equation 5.6). The minimum of the two estimates is the actual biomass production for the day.

$$\mathbf{Dlt\_dm\_water = soil\_water\_supply * transpiration\_efficiency} \tag{5.7}$$

$$\mathbf{Dlt\_dm = min(dlt\_dm\_water, dlt\_dm\_rue)} \tag{5.8}$$

Transpiration efficiency is derived from the transpiration_efficiency_coefficent (=0.006 kPa) and the vapor pressure deficit (vpd) estimated from daily temperatures.

Biomass Partitioning and Retranslocation

On the day of emergence, biomass in plant parts (leaf, root, and stem) is initialised. Daily biomass production is then partitioned between different plant parts in different ratios depending on crop stage. Between emergence and flag leaf stage, the above ground biomass partition only occurs between leaves and stems. From emergence to floral initiation, 65% of the biomass increase is partitioned to leaves. The rest goes to stems. After floral initiation leaf biomass fraction is linearly decreased according to fraction of thermal time to zero at flag leaf. From flag stage to beginning of grain fill all above ground biomass increase is assumed to go to the functional stems.

At the beginning of grain filling, the number of grains/plant is determined by the stem weight accumulated between emergence to start of grain filling. From start to end of grain filling biomass increase is used to meet grain demand first, the rest is put into stems. Grain demand for carbohydrate is calculated by multiplying the grain number by the potential grain growth rate. The potential grain growth rate is temperature determined.

If the supply of assimilate (daily biomass increase) is insufficient to meet grain demand then retranslocation may be used to meet this shortfall. The APSIM-Wheat module allows a total retranslocation of no more than 10 and 30% of leaf and stem biomass present at the start of grain filling, respectively.

Nitrogen Uptake and Re-translocation

Two processes are considered to contribute to nitrogen uptake: passive and active uptake. Passive uptake is the N intake with the transpiration stream, also called mass flow. Active uptake represents a diffusive process, also called diffusion flow. In each rooted soil layer, the N available for uptake from mass flow and diffusion flow is given respectively by

$$\mathbf{NO_3gsm\_mflow = NO_3\_conc * (-dlt\_sw\_dep)} \qquad (5.9)$$

$$\mathbf{NO_3gsm\_diffn \quad = NO_3gsm*sw\_avail\_fract - NO_3gsm\_mflow} \qquad (5.10)$$

where
NO_3_conc: nitrate concentration in the soil solution
NO_3gsm: nitrate content in this layer
dlt_sw_dep: water uptake from the layer
sw_avail_fract: the fraction of available soil water

Demand for N in each part attempts to maintain N at critical level. For each plant part (leaf, stem, root) the N demand is given by

$$\mathbf{N\_demand = dm\_green * (n\_conc\_critic - n\_conc) + dlt\_dm\_green * n\_conc\_critic.} \qquad (5.11)$$

where
dm_green: existing live biomass today
dlt_dm_green: existing live biomass growth rate today
n_conc: actual N concentration
n_conc_critic: critical N concentration

Daily total nitrogen uptake is distributed to the vegetative plant parts (leaf, stem and root) in proportion to their individual demands. Grain N is met only by N re-translocation from other plant parts. N demand of individual grain (rgnfill) is driven by mean daily temperature. The relationship between them is depicted in two equations.

if temperature >10.0°C

$$\mathbf{rgnfill = 4.829666 - 3.2488 * g\_dlt\_tt + 0.2503 * (maxt\text{-}mint) + 4.3067 * temp}$$

else

$$\mathbf{rgnfill = 0.49 * temp} \qquad (5.12)$$

Total grain N demand (grain_n_demand) is calculated by multiplying rgnfill by grain number.

To account for the effects of N deficiency on the processes of plant growth and development, a N concentration ratio is calculated for the stover which is used as a measure of N stress.

$$\mathbf{N\_conc\_ratio} = \frac{\mathbf{N\_conc\_stover - N\_conc\_stover\_min}}{\mathbf{N\_conc\_stover\_crit - N\_conc\_stover\_min}} \qquad \mathbf{(5.13)}$$

Senescence

A rate of 0.5% of root biomass and root length is senesced each day and detached immediately to be sent to the SoilN module and distributed as fresh organic matter in the profile.

Four factors control leaf senescence: age, water stress, nitrogen stress and high temperature stress (>34°C). Stress factors for water, nitrogen and temperature are calculated. The maximum of these is multiplied by the senesced LAI due to age to obtain the day's total senescence.

Between emergence and flag leaf appearance senescence due to age occurs if LAI exceeds 6 so as to maintain 5 green leaves per plant main stem. The fraction of the oldest leaf dying is calculated as the daily thermal time divided by the phyllochron.

Between flag leaf and flowering the daily loss (slan) of LAI is calculated as:

$$\mathbf{Slan = 0.00037 * dlt\_tt * lai\_stage} \qquad \mathbf{(5.14)}$$

Between flowering and start of grain filling,

$$\mathbf{Slan = 0.00075 * dlt\_tt * g\_lai\_stage} \qquad \mathbf{(5.15)}$$

Between the start of grain filling and the end of grain filling, slan is calculated as:

$$\mathbf{Slan = 2. * g\_tt\_tot * g\_dlt\_tt / (g\_phase\_tt(istage) ** 2) * g\_lai\_stage} \qquad \mathbf{(5.16)}$$

where
LAI_stage: LAI at the beginning of the given stage
tt_tot: total thermal time through the phase
phase_tt: thermal time for completion of the phase

5.1.3 Modification of APSIM-Wheat Model to Increased Atmospheric pCO_2

Increased pCO_2 can have a series of direct impacts on wheat production such as stimulating photosynthesis, improving water use efficiency and changing the ratio of carbon and nitrogen. Modifications to the APSIM-Wheat model have been made in three facets by model developer: (1) Radiation Use Efficiency (RUE), (2) Transpiration Efficiency (TE), and (3) Critical Nitrogen Concentration (CNC).

Radiation Use Efficiency

RUE refers to the net aboveground biomass accumulation per unit of intercepted radiation integrated over a specified period. The RUE is used to calculate biomass increments when water is not limiting with the resultant biomass being used to determine Specific Leaf Area (SLA) and nitrogen partitioning.

RUE has been modified according to Reyenga et al. (1999a). The increase in RUE of a wheat crop canopy under enhanced CO_2 could be explained by the simple theoretical increase in light-limited photosynthesis when a small correction for the change in respiratory efficiency was made. The RUE was scaled as the ratio (∅p) of the light-limited photosynthetic response calculated according to Goudriaan et al. (1985) at enhanced CO_2 level compared with the current level (350ppm) in order to include both CO_2 effects and temperature-CO_2 interactions. The temperature-dependent CO_2 compensation point (Z, ppm) is calculated according to Bykov et al. (1981).

$$\mathbf{Z = (163.0\text{-}temp)/(5.0\text{-}0.1{*}temp)} \qquad (5.17)$$

$$\mathbf{\varnothing p = \frac{[(CO_2\text{-}Z){*}(350.0 + 2.0{*}Z)]}{[(CO_2+2.0{*}Z){*}(350.0\text{-}Z)]}} \qquad (5.18)$$

$$\mathbf{RUE = RUEmax * \varnothing p * min\ (g\_nfact\_photo,\ g\_temp\_stress\_photo)} \tag{5.19}$$

where
CO_2: increased CO_2 level
temp: daily average temperature.
g_nfact_photo: N stress factor for photosynthesis
g_temp_stress_photo: temperature modification factor on RUE

Transpiration Efficiency

The reduced stomatal conductance under enhanced pCO_2 is likely to reduce water loss but maintain photosynthesis due to higher water potentials (Nie et al., 1992, Knapp et al., 1993) and higher internal CO_2 levels (Morison 1987, Nie et al., 1992) resulting in an increase in transpiration efficiency. When wheat was grown as a canopy crop in a glasshouse under 340 and 660ppm CO_2, TE increased by 33% under elevated CO_2 (Gifford and Morison, 1993). If this result is translated to a doubling of CO_2 from 350 to 700ppm it represent a 37% increase in TE. The level of enhancement of TE is supported by free-air carbon dioxide experiments with crops with full canopies (Grossman et al., 1995). In the model the transpiration efficiency coefficient (Tanner and Sinclair 1983) was increased by 37% for a doubling of CO_2 with a linear response assumed at intermediate CO_2 concentrations (Eamus and Jarvis 1989).

A series of modifiers are given under different CO_2 levels (Table 5.2). An increase of 37% in TE under doubled CO_2 (700ppm) was adopted in modifying the APSIM-Wheat module. This relation is used to modify TE.

Table 5.2 Modification on transpiration efficiency

CO_2 Levels	0	350	700	1000
CO_2 Modifier	0	1.0	1.37	1.69

Critical Nitrogen Concentration

Elevated atmospheric CO_2 levels tend to reduce the leaf nitrogen concentrations of wheat (Hocking and Meyer 1991; Rogers et al., 1996) due to the change in the balance between the photosynthetic carbon reduction cycle and the photorespiratory cycle (Conroy and Hocking 1993). In particular, there is a consistent reduction in the critical nitrogen concentration (the concentration at which yield drops to 90% of that under optimum nutrition) which has a significant implications for wheat growth and management (Hocking and Meyer 1991, Conroy and Hocking 1993, Rogers et al., 1996). To account for enhanced CO_2 effects, modifier corresponding to typical CO_2 level is given in table 5.3. The relationship between CNC modifier and CO_2 level is shown in Figure 5.3. This relation is used to modify leaf CNC.

Table 5.3 Modification on critical nitrogen concentration

CO_2 Levels	0	350	700	1000
CO_2 Modifier	0	1.0	0.93	0.9

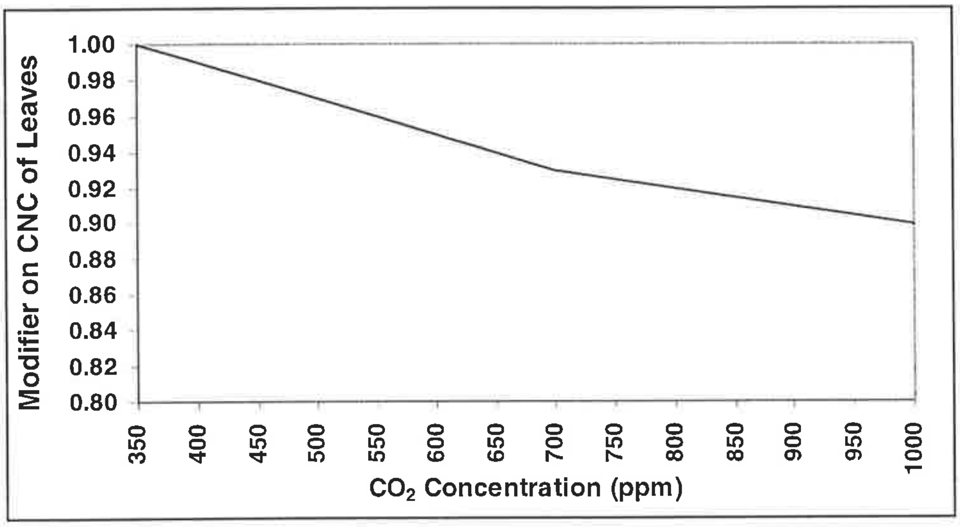
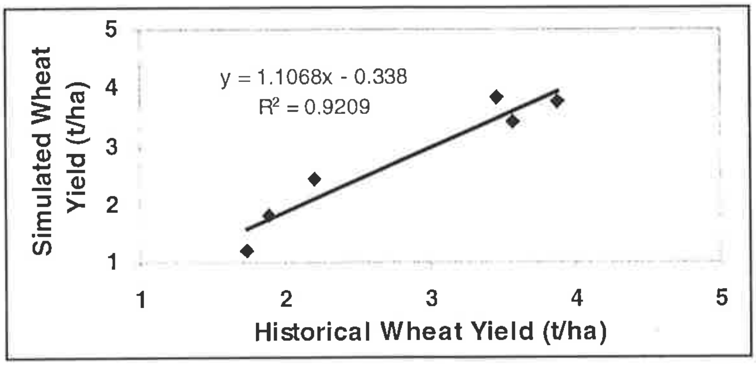


Figure 5.3 Relationship between CNC and pCO_2

5.1.4 Model Validation

APSIM-Wheat has been developed from Nwheat and I-Wheat (Anon, 2001). Nwheat has been validated in Australia (Asseng et al., 1998) and the Netherlands (Asseng et al, 2000). Yunusa et al. (2002) have tested the performance of Nwheat under South Australian conditions. Nwheat satisfactorily simulated wheat growth, development and yield components. APSIM-Wheat has been validated against experimental datasets covering different locations, soil types, water and nitrogen treatments in Queensland, Australia (Anon, 2001). In general, APSIM-Wheat performed quite well. The r-squared value is 0.92 for maximum LAI, 0.83 for grain yield, and around 0.8 for above ground biomass, biomass N and grain nitrogen content. APSIM-Wheat model behaved very well under South Australian environment. Simulated grain yields were compared with observed grain yield (PIRSA, 2001) at several locations



considered in this study (Figure 5.4). The r-squared value is 0.92 for grain yield.

Figure 5.4 Simulated wheat yield versus historical wheat yield

5.2 PARAMETERISATION OF APSIM-WHEAT MODULE

As mentioned in section 5.1.1, several types of information are needed by the APSIM-Wheat model such as climate data, soil profile data and crop genetic coefficients as well as crop cultivation and management information. This section details how the APSIM-Wheat module was specified and parameterised for the research that follows.

5.2.1 Climate Data

Climate plays a very important role in agricultural production. Any changes to climate will bring quite different results to the agricultural system. Maximum temperature, minimum temperature, solar radiation and rainfall are identified as key climatic variables, which are explicitly dealt with in the impact model (APSIM-Wheat) to be used in risk analysis.

Historical Climate Data

Historical daily climate data for maximum temperature, minimum temperature, solar radiation and rainfall covering 1900-1999 were downloaded from the SILO web site (solar radiation data were derived from other variables) (Anon, 2000a) in APSIM format for the site-specific study (8 stations) and the spatial study (3 stations). The coordinates for these stations and their corresponding station ID as well as the annual rainfall for each station are listed in Table 5.4. There are two functions for the historical climate data. First, it was used to drive the wheat model to produce baseline wheat yields and other assessment indicators. Second, the historical weather data was perturbed by climate change to produce climate change scenarios which were then forwarded to the wheat model to explore potential impacts of climate change on wheat production. In this way, the historical variability in climate was preserved in future climate change scenarios.

Table 5.4 Station coordinates

Station	Station_ID	Latitude	Longitude	Annual Rainfall (mm)
Cummins	018023	-34.27	135.73	430.5
Keith	025507	-36.10	140.35	467.9
Lameroo	025509	-35.33	140.52	388.4
Minnipa	018053	-32.86	135.15	362.2
Naracoorte	026023	-36.96	140.74	578.3
Orroroo	019032	-32.74	138.61	341.9
Roseworthy	023020	-34.53	138.69	440.3
Wanbi	025034	-34.78	140.27	303.8
Owen*	023012	-34.27	138.55	420.66
Kapunda*	023307	-34.34	138.92	494.59
Moorook*	024010	-34.29	140.37	258.79

*used in spatial study, the rest are used in site-specific study.

Climate Change Scenarios

The historical climate data for the above locations were perturbed by climate change information through the Manager Module. Part of the atmospheric change information for Roseworthy is listed below. Atmospheric change information set in the manager file of the APSIM model for each location is given in appendix 4. Because a complicated methodology for constructing climate change scenarios was adopted in this study, the detailed procedures for producing probabilistic scenarios are given in a separate chapter (Chapter 6).

```
[R1_T1_C1_ROSEWORTHY.manager.start_of_day]
  if (wheat.stage_code = 2) then
    wheat set co2_switch = 1
    wheat set co2_level  = 527.2
  endif
```

This section shows that the atmospheric pCO_2 was set to 527.2 ppm.

```
maxt=maxt+1.0
mint=mint+1.0
```

The maximum and minimum temperature was set 1°C higher than the current temperature regime.

```
if (date_within('01-May,31-Oct')) then
rain=rain*(1-0.2858)
else
rain=rain*(1-0.2689)
endif
```

This section shows that growing season rainfall was set to 71.42% of current growing season rainfall. The non-growing season rainfall was set to 73.11% of current non-growing season rainfall.

5.2.2 Soil Data

One soil profile data for each site in the site-specific study and 43 representative soil profile data for spatial study were collected from David Maschmedt at Primary Industries and Resources, South Australia (PIRSA).

A large number of soil parameters are needed by the APSIM-Wheat model as listed in Table 5.5. Table 5.6 gives specifications for some of soil parameters and intermediate variables on which to estimate other soil parameters (i.e. sat).

Most of the soil parameters listed in table 5.5 have to be derived from original soil profile data, using relevant formulae, as shown below.

$$\mathbf{sat\ (\%\ volumetric) = (po - e) * 100} \quad \mathbf{(5.20)}$$

where
$po = (1 - bd / 2.65) * 100$
e = air filled porosity at q_g,
q_g is the gravimetric water content of wet soil (Dalgliesh and Foale, 1998)

$$\mathbf{sw = air\text{-}dry} \quad \text{if soil depth} < 250\text{-}300\text{mm} \quad \mathbf{(5.21)}$$

$$\mathbf{sw = ll15 + 3\%} \quad \text{if soil depth} > 300\text{mm}$$

$$\mathbf{ll = ll15} \quad \text{if soil depth} < 1\text{m} \quad \mathbf{(5.22)}$$

$$\mathbf{ll = ll15 + 0.05} \quad \text{if soil depth} > 1\text{m}$$

Table 5.5 Soil and crop parameters required by the APSIM-Wheat model

Categories	Code	Definition
Soil Water Parameters	Insoil	Initial soil water
	Cona	Stage 2 evaporation coefficient
	U	Stage 1 evaporation coefficient
	diffuse_const	Constant term in diffusivity calculation
	diffuse_slope	Slope term in diffusivity calculation
	cn2_bare	Bare soil runoff curve number
	cn_red	Maximum reduction in curve number due to cover
	cn_cov	Cover effecting a maximum reduction in curve number
	salb	Bare soil albedo
	dlayer*	Soil depth-layered
	air_dry*	Volumetric air dry-layered
	dul*	Volumetric drained upper limit-layered
	ll15*	Volumetric 15 bar lower limit-layered
	sat*	Volumetric saturation-layered
	sw*	Soil water
	swcon*	Soil water profile drainage coefficient
	bd*	Bulk density
Soil Nitrogen Parameters	amp*	Difference between highest and lowest mean monthly air temperature
	tav*	Mean annual air temperature
	root_cn	C:N ratio of initial root residues
	root_wt	Initial weight of root fresh organic matter in soil profile
	soil_cn	C:N ratio of the soil
	enr_a_coeff	Enrichment equation coefficient
	enr_b_coeff	Enrichment equation coefficient
	profile_reduction	Whether to re-map N+ C if soil loss occur
	oc*	Organic carbon
	ph*	Soil pH
	fbiom	Initial biom as proportion of non_inert C
	finert	Proportion of initial organic C assumed to be inert
	ureappm	Soil urea concentration
	NO_3ppm	Soil nitrate concentration
	NH4ppm	Soil ammonium concentration
Initial Residue	pot_decomp_rate	Potential decomposition rate
	residue_wt	Initial surface residue
	residue_cnr	C:N ratio of initial residue
	residue_type	Type if initial residue
Wheat Parameters	ll*	Crop lower limit mm water/mm soil
	kl	Water extraction parameter (0-1)
	xf	Root exploration factor (0-1)

"*"denotes that these parameters are set differently according to specific soil profile, others are set the constant among localities.

Table 5.6 Specification for swcon, air-dry and e

Soil type	Abbreviation	air-dry	swcon	e
Coarse Sand, Sand	CS, S	0.05	0.8	0.07
Light Sand	LS		0.7	
Fine Sandy Loam, Sandy Loam	FSL, SL, KSL	0.05	0.6	0.06
Sandy Clay Loam, Clay Loam, Loam, Fine Sandy Clay Loam, Fine Sandy Medium Clay, Sandy Light Clay, Sandy Medium Clay, Fine Sandy Clay	SCL, CL, L, FSCL, FSMC, SLC, SMC, FSC	0.06	0.5	0.05
Light Clay, Medium Clay and Light Medium Clay	LC, MC, LMC	0.07	0.3	0.04
Heavy Clay	HC, MHC	0.08	0.1	0.03

Here is an example of the initial soil condition for Roseworthy. Readers are directed to Appendix 5 for the initial soil condition of other locations (soil types).

```
[roseworthy.wheat.parameters]
   ll = 0.12    0.20    0.26    0.30    0.31
   kl = 0.034   0.034   0.032   0.034   0.041
   xf = 1.0     1.0     1.0     1.0     1.0
```

This section describes the characteristics of wheat root for accessing soil water

```
[roseworthy.soilwat2.parameters]
insoil= 2 ()
cona= 2.0 ()
u=4.2 ()
diffus_const= 44 ()
diffus_slope= 16 ()
cn2_bare= 76 ()
cn_red= 20 ()
cn_cov= 0.8 ()
salb= 0.14 ()
!layer      1       2        3       4       5
!           130     350      600     900     1800
-----------------------------------------------------
-----------------------------------------------------
dlayer=    130.   220.   250.   300.   900.(mm)
air_dry=   0.06   0.06   0.07   0.08   0.08  (mm/mm)
dul=       0.27   0.30   0.33   0.36   0.36  (mm/mm)
ll15=      0.12   0.15   0.21   0.25   0.26  (mm/mm)
sat=       0.422  0.384  0.394  0.366  0.366(mm/mm)
```

```
sw=        0.06   0.18   0.24   0.28   0.29 (mm/mm)
swcon=     0.6    0.5    0.3    0.1    0.1
bd=        1.4    1.5    1.5    1.6    1.6 (g/cc)
```

This section presents soil water parameters used by soilwat2 module

```
[roseworthy.soilN2.parameters]
amp= 12.71
tav= 16.63
root_cn= 45.0 ()
root_wt= 400.0 (kg/ha)
soil_cn= 14.2 ()
enr_a_coeff= 7.4 ()
enr_b_coeff= 0.2 ()
profile_reduction= off

!layer     1      2       3       4       5
oc      =  1.31   0.72    0.30    0.048   0.046
pH      =  8.6    8.7     9.2     9.4     9.2
ureappm=   0.000  0.000   0.000   0.000   0.000
fbiom   =  0.05   0.05    0.02    0.015   0.01
finert  =  0.1    0.1     0.4     0.9     0.95
NO3ppm  = 11.97   8.45    3.85    3.36    2.57
NH4ppm  =  0.50   0.50    0.50    0.40    0.10
```

This section shows soil nitrogen parameters used by soiln2 module

5.2.3 Model Setting

Two types of wheat cultivar were used in this study. One is Janz: Australian Hard Wheat (AH) with grain protein content greater than 12%. The other is Excalibur: Australian Soft Wheat (ASW) with grain protein content within 8%-12%. Janz, is a mid-late maturity variety, and was used in the mid-high rainfall area. Excalibur was used in the low rainfall areas due to its early maturity characteristics. Their genetic coefficients are listed in Table 5.7. Soil nitrogen, soil water, and residues were reset on the first of March for each year of simulation run. Different sowing rules were applied to the site-specific study and the spatial study. For the site-specific study, the sowing rule was specified as follows: if cumulative rainfall within 3 days >= 20 mm between 15 of April and 15 of June, then sow Janz; if cumulative rainfall within three days >=15 mm between 15 of June and 15 of August, then sow Excalibur. For the spatial study, the sowing rule was set differently from the site-specific study only in the amount of 10 mm rather than 15 mm for Excalibur planting (low rainfall areas), because of the extremely low annual rainfall for Excalibur's growth and development. In order to have comparable simulation runs out of 100 years, the amount of rain required over continuous three days to initiate sowing was set to 10mm for Excalibur in the spatial study.

Sowing density was 200 plants/m^2, at a depth of 3 cm. Two fertiliser levels were applied at planting date: 40kg/ha NO_3-N at medium-high rainfall locations and 20kg/ha NO_3-N at lower rainfall locations at a depth of 5 cm. In addition to fertiliser nitrogen, initial soil nitrate-N was set at 60 kg NO3/ha in the top 35cm of the soil profile at Roseworthy. These levels were chosen to represent a non-limiting nitrogen environment.

As indicated in Chapter 2, consideration of the physiological effects of increased atmospheric CO_2 on wheat production is a purpose of this study. Atmospheric pCO_2 is one of the environmental variables, which drive the APSIM-wheat module. CO_2 levels were set to 330ppm(current), 527.2ppm, 634.8ppm, 687.1ppm, and 785.8ppm respectively, to explore the direct effects of CO_2 on grain yield and grain quality (grain protein content).

Table 5.7 Genetic coefficients for Janz and Excalibur*

Coefficient	**Janz**	**Excalibur**
p1v: sensitivity to vernalisation	1.0	1.5
p1d: sensitivity to daylength	2.0	2.0
p5: grain filling duration, °Cd	640	703
grno: grain number per head	34.0	27.0
fillrate: rate of grain filling, mg d^{-1}	2.5	3.5
stem weight (mg)	1.65	2.4
phyllo: phyllochron interval, °Cd	95	95
sla: specific leaf area (mg cm^{-2})	185	180

* Data Source: Department of Agronomy and Farming Systems, Adelaide University

5.3 CONCLUSION

APSIM-Wheat is a process based, daily time step wheat module that simulates the processes described above as a function of climate data, soil data, wheat genetic coefficients as well as cultivation information. It has special features that make it well suited to the study of the impact of climate change on wheat production. These include sensitivity to soil water stress, inclusion of temperature as a driving variable of key growth and development processes, and the capability of evaluating the impact from elevated CO_2 on key physiological processes. APSIM-Wheat has been specified and parameterised for the site-specific study and the spatial study. Site specific historical climate data and representative soil profiles were assembled for each simulation run. Example Manager files and soil profile descriptions are described for Roseworthy, and a complete set of management information and soil conditions are given in the CD. The next chapter focuses on the construction of probabilistic environment change scenarios, which is part of the content of APSIM-Wheat module parameterisation.

6. CONSTRUCTION OF PROBABILISTIC ATMOSPHERIC CHANGE SCENARIOS

The aim of risk analysis is to quantify the relationship between impact thresholds and the uncertainty space created from the combination of key environmental variables under atmospheric change. To do this, scenarios or projected ranges for key environmental variables need to be constructed (Jones, 2000c), which is part of the content of APSIM-Wheat parameterisation. As mentioned in chapter 2, there are disadvantages in using direct output of GCMs, single scenarios and the high and low end of projected atmospheric change scenarios in agricultural impact and adaptation studies. This study overcomes those limitations associated with previous studies and improves assessment of atmospheric change impacts on wheat production by applying statistical techniques such as the Monte Carlo Random Sampling. Downscaled outputs of nine climate models and information from IPCC SRES were used to construct atmospheric change ranges, which contain an upper and lower limit with probability attached to the atmospheric change scenarios. The uncertainties from greenhouse gas emissions, climate sensitivity and differences between climate models for global warming and local climate change were identified, quantified and treated. By applying this approach it is possible to attach probability to wheat impact outcomes and to conduct risk analysis which is a new area of atmospheric change impact assessment. Adaptations based on such a method should be more practical and applicable. Figure 6.1 gives the fundamental structure of procedures employed in the construction of probabilistic atmospheric change scenarios.

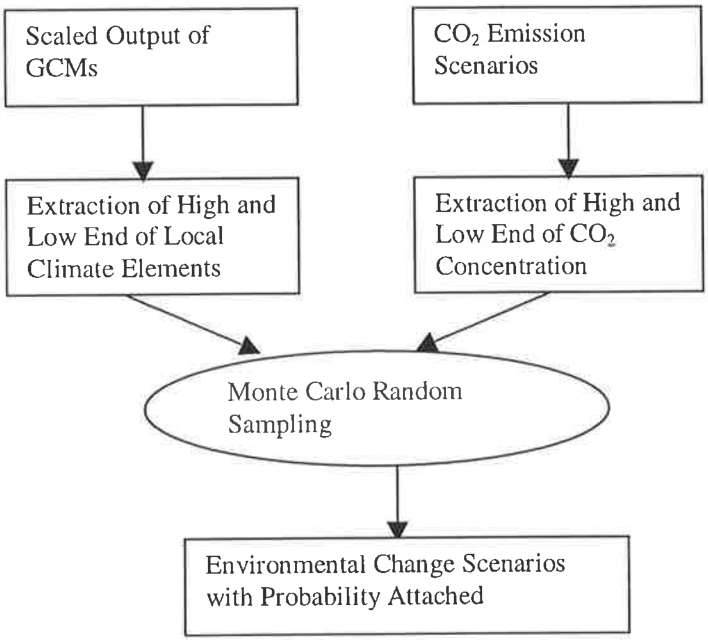


Figure 6.1 Systematic structure for the construction of probabilistic atmospheric change scenarios.

6.1 KEY CONCEPTS

Projections and scenarios are often used in climate change and climate impact studies, but sometimes these two terms are confused and misunderstood. A *scenario* is a description of a plausible future used without reference to its likelihood such as the IPCC individual IS92a-f emission scenarios, IPCC Special Report on Emission Scenarios (SRES) marker scenarios, and the climate change scenarios (projections) generated by GCMs where a single emission path is used. Scenarios may contain several sources of uncertainties but generally do not acknowledge them explicitly.

Climate change *projection* is the term the IPCC Second Assessment Report (SAR) uses for a model estimate of future climate. It is presented in two senses:

(1) A single trajectory over time produced from one or more emission scenarios, for example, projected global temperature (1.58°C) for the year 2080 using the IS92a emission scenario with a climate sensitivity of 2.5°C. In the IPCC SAR, both projection and scenario are used to describe possible future states, with projection used mainly in terms of climate change and sea-level rise. This usage defines climate projections expressed as a single trajectory,

as a subset of scenarios. When used as input into impact assessment, the same climate projections are commonly referred to as climate scenarios.

(2) A range of projections expressed at a particular time in the future incorporating one or more sources of uncertainty. Examples include projected global warming ranges based on the SRES marker scenarios (1.081-3.82°C) with a climate sensitivity of 1.5-4.5°C under 2*CO_2 for 2080; and regional temperature/rainfall change ranges per degree of global warming. Projected ranges of uncertainty can have probabilities attached to the range and within the range, so are more likely to occur than individual scenarios. From this sense, a projected range of climate can no longer be defined as a climate scenario. However, as there is significant remaining uncertainty beyond the projected range, such projections can not be regarded as forecasts (Jones, 2000a; IPCC, 2001a).

The relationship between scenarios, projected ranges and forecasts is shown in Figure 6.2.

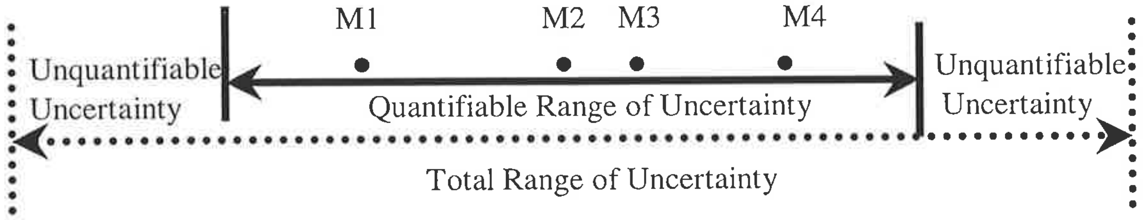


Figure 6.2 Schematic depiction of the relationship between scenarios, projected range and total uncertainty range. M1 to M4 represent 4 scenarios produced by 4 models. The projected range consists of a quantifiable range of uncertainty that encompasses the 4 scenarios. This lies within a total range of uncertainty that can not be fully quantified at this stage (Jones, 2000a.).

6.2 IDENTIFICATION OF UNCERTAINTIES

"Uncertainty" implies anything from confidence just short of certainty to informed guesses or speculation. Lack of information obviously results in uncertainty, but often disagreement about what is known or even knowable is a source of uncertainty. There are quite a few sources of uncertainty associated with CO_2 emission projections and climate change projections. Some categories of uncertainty are amenable to quantification, while other kinds cannot be expressed sensibly in terms of probabilities. Because of this, uncertainties are classified into two groups: quantifiable and unquantifiable. Uncertainties from greenhouse gas emissions, aerosol emissions, climate sensitivity and regional climate response are quantifiable as summarised in Table 6.1. Greenhouse gas emissions are subject to uncertainties concerning population growth, technological change and social and political behaviour. Climate model responses are most uncertain in how they represent feedback effects, particularly those dealing with changes to cloud regimes, biological effects and ocean-atmosphere interactions. The coarse spatial resolution of climate models also remains a limitation on their ability to simulate the details of regional climate change (CSIRO, 2001). It should be noted that in some cases owing to topographic and other effects regional climate model results may change the sign of rainfall changes derived from coarse resolution GCMs (Whetton et al., 2000). In Table 6.1, the first three sources contribute to uncertainties in estimating the degree of global climate change, measured as degrees of global warming. The last one contributes to the calculation of the local climate change, which is derived from a number of GCMs, and measured as local climate change per degree of global warming.

Table 6.1 Quantifiable uncertainties (Jones, 2001)

Type of uncertainty	**Source of uncertainty**	**Expression**	**Reference**
Greenhouse Gas Emissions	social, economic, and physical (accounting)	Mass/volume per year	IPCC IS92a-f (Pepper at al., 1992), SRES (Nakicenovic et al., 2000)
Aerosol Emission	scientific, physical (accounting), economic	Mass/volume per year	IPCC (1996)
Climate Sensitivity	scientific, emergent chaotic behaviour	global warming for $2XCO_2$ atmosphere, or per unit of radiative forcing	IPCC (1996), Hansen et al. (1998)
Regional Climate Response	scientific, emergent chaotic behaviour	local change per degree of global warming	CSIRO (1996) (Jones, 2001)

The unquantifiable uncertainties include uncertainties from greenhouse gas mixing (how emissions lead to atmospheric concentration), and radiative forcing (how atmospheric concentrations of greenhouse gases contribute to changes in absorbed radiation). They are ignored in estimating the range of uncertainties due to their unquantifible characteristics. Fortunately, they have much less effect on the projection of climate change than quantifiable uncertainties (Jones, 2001).

When the climate change information is applied to impact assessment, additional impact-related uncertainties arise. If the vertical integration of physical through to social –economic impacts is sought, the incorporation of these broad ranges of uncertainty into the impact analysis can produce a very large range of impacts, sometimes termed the cascade of uncertainties or uncertainty explosion (Figure 6.3).

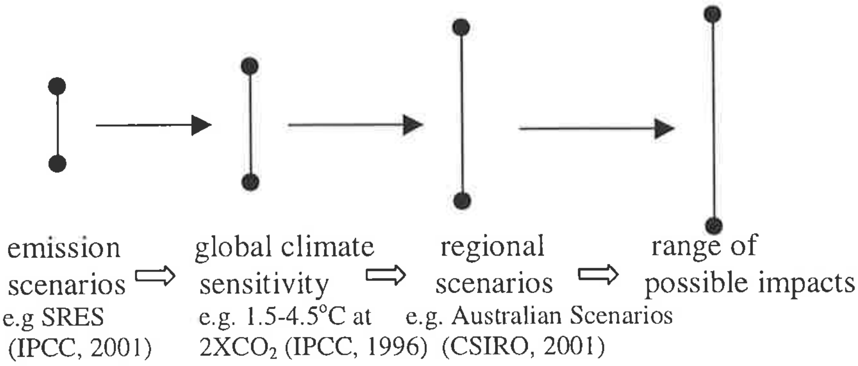


Figure 6.3 Range of uncertainties involved in impact modelling at a particular time, showing the uncertainty explosion caused when these range are multiplied to encompass the full range of future possibilities. (Modified after Jones, 2000a).

6.3 QUANTIFICATION OF UNCERTAINTIES

Uncertainties about future human behaviour and shortcomings in climate modelling limit the climate projections to ranges of change for some variables, and qualified statements on possible changes for others. Uncertainties have been quantified where possible, accounting for future greenhouse gas emissions, climate sensitivity, and between model differences in simulating both global and regional climate responses. Projections of global warming from IPCC (2001b) and projections of local climate change per degree of global warming for temperature and rainfall were incorporated into the construction of future climate change scenarios. Their use satisfies the requirement that the fullest possible range of uncertainty should be used.

6.3.1 Quantification of Uncertainties from Projections of CO_2 Emission Scenarios, Climate Sensitivity and Global Warming

The projection of global warming range used the same simple climate model (upwelling diffusion-energy climate model) that was used in the construction of the IPCC (1996) projections of global warming. But the Special Report on Emission Scenarios (SRES) scenarios were used rather than IS92a-f scenarios. The SERS scenarios are based on a range of assumptions about population, energy sources and regional or global approaches to development and socio-economic arrangements. The scenarios do not include any specific greenhouse gas mitigation activities (CSIRO, 2001). However they are more realistic than IS92a-f scenarios, particularly in their representation of sulphate aerosol emissions that cause a relative cooling effect (Jones, 2001). The simple climate model account for the first three uncertainties as listed in Table 6.1.

The projection of global warming is based on greenhouse gas emission scenarios and the sensitivity of the climate system to these emission scenarios. Four different narrative storylines /families (B1, B2, A1 and A2) or 3 families and 3 groups of scenario within family A1 (A1, A1T, A1F) were developed to describe consistently the relationship between emission driving forces and their evolution in the IPCC Special Report on Emissions Scenarios (SRES) (Anon, 1). Each storyline represents different demographic, social, economic, technological, and environmental developments. No judgement is offered as to the preference for any of the scenarios and they are not assigned probabilities of occurrence. For details of these scenarios, please refer to Appendix 1. Eighteen global warming scenarios (emission scenarios multiplied by three levels of climate sensitivity) correspond to these 6 greenhouse gas emission scenarios. Table 6.2 gives quantified uncertainties related to global warming and atmospheric pCO_2 for year 2080 among these 6 emission scenarios. The bold figures in this table are upper end and lower end for pCO2 and global warming, which were used in Monte Carlo Random Sampling procedures (section 6.4.3).

Table 6.2 Global warming and atmospheric CO_2 concentrations in year 2080*

		B1	**B2**	**A1**	**A2**	**A1F**	**A1T**
CO_2 Concentration (ppmv)		527.2	549.2	634.8	687.1	785.8	545.5
CO_2 Concentration Change (%)		**50.63**	56.91	81.37	96.31	**124.51**	55.86
Global	Lower limit	**1.081**	1.14	1.41	1.54	1.86	1.21
Warming	Middle	1.60	1.69	2.07	2.24	2.70	1.80
(°C)	Upper Limit	2.33	2.46	2.99	3.18	**3.82**	2.63

*Data Source: IPCC SRES

6.3.2 Quantification of Uncertainties from Projections of Local Climate Change

There are significant differences between models with regard to climate changes simulated at the regional scale, particularly for precipitation. Thus to represent this uncertainty a range of model results should be used in preparing regional projections. OZCLIM, CSIRO's climate scenario generator, developed at CSIRO Atmospheric Research by the Climate Impact Group in collaboration with the International Atmospheric change Institute (IGCI), New Zealand, was used to extract local monthly climate change information such as temperature and rainfall change for the site-specific and the spatial studies. Local monthly climate change projection is based on 9 scaled GCM-derived patterns of climate change and is in per degree of global warming format. Projected ranges preserve local patterns of change while being scaled for different assumptions of climate sensitivity and greenhouse gas emissions. The details of these 9 GCMs are shown in table 6.3. Table 6.4 and 6.5 give the monthly temperature and rainfall change respectively in the format of per degree of global warming at Roseworthy as an example.

Table 6.3 GCMs/RCMs details and their projection features for study sites considered

GCMs/RCMs	Laboratories	Features
MK2	CSIRO	rainfall decrease
CGCM1	Canadian Climate Centre	rainfall decrease
HADCM2	Hadley Centre, UK	rainfall decrease
ECHAM4 / OPYC3	Max Planck	rainfall decrease
ECHAM3 /LSG	Max Planck	winter rainfall decrease, summer rainfall increase
DARLAM 125km	CSIRO	winter rainfall decrease, summer rainfall increase
DOE-PCM	NCAR	rainfall decrease
HADCM3	Hadley Centre, UK	rainfall decrease
R15-a	GFDL	winter rainfall increase, summer rainfall decrease

Table 6.4 Monthly temperature change (°C) per degree of global warming for Roseworthy in 2080

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Mk2	1.10	0.96	1.00	0.80	0.82	0.80	0.86	0.89	0.90	1.06	1.06	1.14	0.95
CGCM1	0.69	0.62	0.63	0.69	0.71	0.78	0.87	0.88	0.85	0.89	0.83	0.75	0.77
R15-a	1.20	1.26	1.15	1.23	0.86	1.04	1.02	1.06	1.05	0.74	0.96	1.38	1.08
HADCM2	0.65	0.78	0.96	1.02	0.90	0.87	1.02	0.98	0.99	0.85	0.85	0.70	0.88
HADCM3	0.96	0.84	1.21	0.96	1.02	0.91	0.87	0.89	0.92	1.02	1.18	1.05	0.99
OPYC3	0.95	1.00	0.96	0.83	0.68	0.63	0.56	0.61	0.71	0.82	0.96	1.09	0.82
LSG	0.95	0.84	0.93	1.07	1.01	1.09	1.04	1.06	1.13	1.12	1.01	1.14	1.03
DARLAM	0.88	0.79	0.95	0.71	0.83	0.71	0.75	0.77	0.79	0.94	0.89	0.89	0.83
DOE-PCM	0.79	0.88	0.93	1.00	0.92	1.06	0.74	0.80	1.02	1.12	0.95	0.95	0.93
Model Average	0.91	0.89	0.97	0.92	0.86	0.88	0.86	0.88	0.93	0.95	0.97	1.01	
Standard Deviation*	0.18	0.18	0.16	0.18	0.12	0.16	0.16	0.14	0.13	0.14	0.11	0.21	

*Standard deviation among models

Table 6.5 Monthly rainfall change (%) per degree of global warming for Roseworthy in 2080

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Mk2	-0.38	-0.06	3.72	-1.12	-2.93	-2.50	-6.16	-10.20	-9.56	-13.57	-12.64	-10.17	-5.46
GCM1	3.82	-1.17	2.51	-0.53	-3.29	-1.87	-1.68	-5.77	-7.16	-5.91	-4.68	-5.52	-2.60
R15-a	-6.41	-4.48	4.55	-5.40	3.54	7.18	-4.17	0.52	3.33	6.69	-2.36	-7.81	-0.40
HADCM2	-8.36	-5.14	-16.01	-6.87	-2.82	2.06	-4.03	-7.80	-8.64	-0.25	1.15	-7.71	-5.37
HADCM3	0.55	-0.92	-10.13	-0.70	-1.34	0.41	-4.43	-3.11	-15.03	-17.33	-9.20	-13.60	-6.24
OPYC3	0.52	0.66	-4.52	-4.85	-1.26	-7.17	-8.06	-6.31	-6.45	-9.47	-8.03	0.43	-4.54
LSG	38.18	15.16	11.69	9.71	-7.98	-5.83	-5.36	-5.97	-6.66	-4.37	-3.19	1.45	3.07
DARLAM	6.24	6.78	5.21	3.86	-3.63	-3.12	-1.42	0.13	-5.69	-3.17	-2.51	2.00	0.39
DOE-PCM	-6.16	0.82	-3.08	-9.05	0.17	5.86	-3.25	1.02	-9.20	-11.01	-6.75	9.27	-2.61
Model Average	3.11	1.29	-0.67	-1.66	-2.17	-0.55	-4.28	-4.17	-7.23	-6.49	-5.36	-3.52	
Standard Deviation	14.03	6.23	8.58	5.79	3.12	4.90	2.09	4.01	4.83	7.29	4.21	7.25	

6.4 TREATMENT OF UNCERTAINTIES

The quantifiable uncertainties mentioned above can be treated by applying statistical techniques such as the Monte Carlo Random Sampling technique and can be incorporated into atmospheric change scenarios and atmospheric change impact studies.

6.4.1 Theory and Assumptions for Monte Carlo Random Sampling

Following Jones (2000a.b; 2001), if the steps within the uncertainty explosion are each assumed to have a uniform distribution and are multiplied together, the resultant distribution will not be uniform but will peak around an average value. Under atmospheric change, projections of atmospheric pCO_2 and climate change derived from physical models are used in lieu of a statistically represented history. This implies that uncertainties existing in every step of impact assessment can be reduced and probability can be attached to certain outcomes through statistical techniques.

The Monte Carlo Random Sampling technique is used here to calculate the cumulative probability for atmospheric pCO_2, regional temperature and rainfall, which are then used in the APSIM-Wheat model. Calculated probabilities are conditional on the assumptions used to construct sampling strategies and component ranges. The probabilities are also conditional in the sense that unquantifiable uncertainties are also known to affect the magnitude of global warming.

Several assumptions (prerequisites) are embedded in random sampling and impact assessment. First, a random sample is taken within a range defined by an upper limit and lower limit such as a projected range for global warming and local climate change as listed in Table 6.7. Second, the range (i.e. global warming range, atmospheric pCO_2 range, local temperature change range, seasonal rainfall change range) has a uniform distribution, which means that the sample could fall anywhere along the range with an equal probability (Figure 6.4, 6.5). Because the probability distribution function of these ranges of uncertainty is unknown, the use of lower and upper limits leads to the default assumption of uniform probability, which persists through all the steps of impact analysis. This assumption of uniform probability is likely to be conservative except where the true probability distribution function is L- or M-shaped. Third, the components (temperature, rainfall and CO_2 change) randomly sampled must be independent of each other. If factors show dependence, this must be correctly applied to the sampling method. Fourth, the major factors affecting impact under analysis should be incorporated into the methodology wherever possible. Finally, the full range of quantifiable uncertainty, or a comprehensive range with adequate justification, must be applied within each step of the process to avoid the underestimation of risk through the use of truncated ranges.

6.4.2 Construction of Ranges for Atmospheric pCO_2 Change, Global Warming and Local Climate Change

Three variables: temperature, rainfall and atmospheric CO_2 concentration, which will have significant impacts on wheat production, are considered in this study. As a result, ranges for temperature, rainfall and atmospheric pCO_2 were constructed for random sampling. Ranges were derived that incorporate quantifiable uncertainties associated with the projection of local climate change. For Roseworthy, the monthly temperature change in Table 6.4 was averaged annually model by model. The monthly rainfall change in Table 6.5 was averaged according to growing season (May-October) and non-growing season (November-April) model by model. The averaged results are shown in Table 6.6 and were used to extract ranges for growing season and non-growing season rainfall change and local temperature change. The same procedures apply to other localities. The ranges for local rainfall and temperature change for all locations considered in this study are listed in columns 2, 3, 4, 5, 6 and 7 of Table 6.7. Ranges that incorporate quantifiable uncertainties associated with the projection of future emission scenarios and the projection of global warming were extracted based on Table 6.2 and listed in columns 8, 9, 10 and 11 of Table 6.7.

Table 6.6 Averaged climate change information among GCMs for 2080 at Roseworthy

	Local Temperature Change (°C)	Growing Season Rainfall Change (%)	Non-Growing Season Rainfall Change (%)
MK2	0.95	**-7.49**	-3.44
CGCM1	**0.77**	-4.28	-0.93
R15-a	**1.08**	**2.85**	-3.65
HADCM2	0.88	-3.58	**-7.16**
HADCM3	0.99	-6.81	-5.67
OPYC3	0.82	-6.45	-2.63
LSG	1.03	-6.03	**12.17**
DARLAM	0.83	-2.82	3.60
DOE-PCM	0.93	-2.74	-2.49

Table 6.7 Ranges for global warming, atmospheric pCO_2 and local climate change projection for 2080

Localities	Local Rainfall Change (%)				Local Temperature Change (°C)		Global Warming (°C)		Atmospheric pCO_2 Change (%)	
	Growing Season		Non-Growing Season							
	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
Cummins	-8.03	3.48	-7.29	11.22	0.69	1.03	1.081	3.82	50.63	124.51
Keith	-7.21	1.61	-7.57	10.12	0.77	1.10				
Lameroo	-7.00	2.15	-7.35	11.73	0.83	1.11				
Minnipa	-8.56	4.55	-6.86	15.36	0.85	1.03				
Naracoorte	-6.49	1.01	-8.04	7.75	0.66	1.11				
Orroroo	-7.94	3.80	-7.42	16.00	0.92	1.08				
Roseworthy	-7.49	2.85	-7.16	12.17	0.77	1.08				
Wanbi	-7.24	2.52	-7.27	12.52	0.85	1.11				
Owen*	-7.69	3.11	-7.21	12.60	0.79	1.08				
Kapunda*	-7.63	3.05	-7.22	12.85	0.81	1.09				
Moorook*	-7.48	2.88	-7.34	13.47	0.90	1.11				

*denotes these three locations are for spatial study, others are for site-specific study

Data presented in this table demonstrate that the growing season is biased towards rainfall decrease whereas the non-growing season is biased towards rainfall increase.

6.4.3 Procedures for Monte Carlo Random Sampling

Once those ranges for atmospheric pCO_2, global warming, local temperature, growing season and non-growing season rainfall are obtained, the next step is to proceed to Monte Carlo Random Sampling. Two ranges of uncertainty: global warming uncertainty (Column 8 and 9 of Table 6.7) and local temperature uncertainty (column 6,7 of Table 6.7) were incorporated into regional temperature change derivation. Global warming range and local temperature change range are assumed to have a uniform distribution as shown in Figure 6.4 and Figure

6.5 respectively. Global warming range and local temperature change range were randomly sampled 100,000 times and then multiplied repeatedly, to obtain a non-uniform distribution of regional temperature change, peaking around an average value (Jones, 2000b)(Figure 6.6).

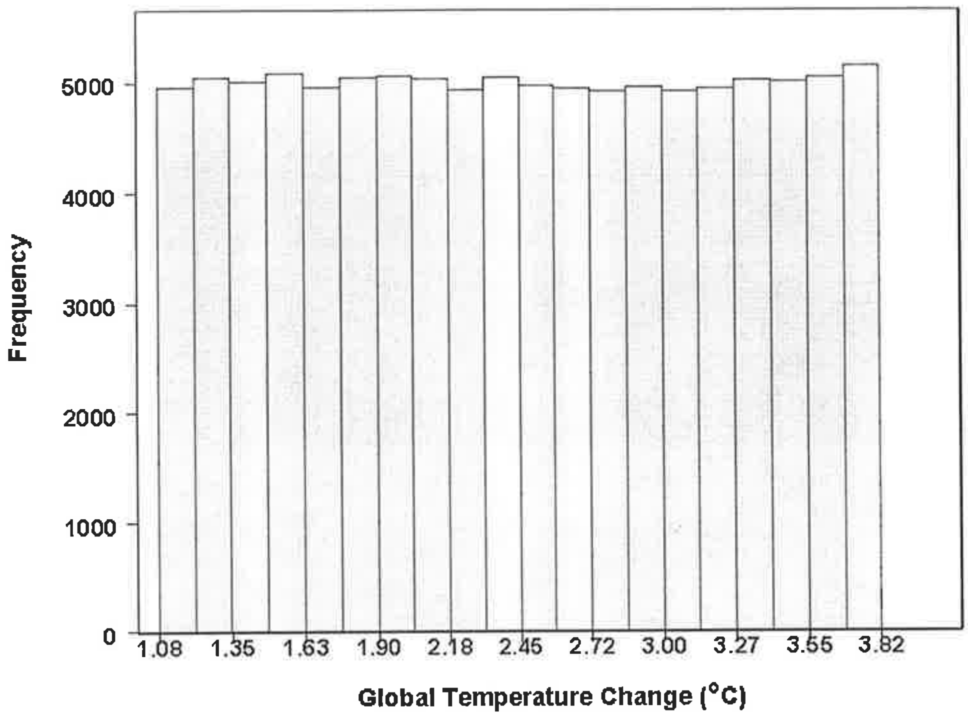


Figure 6.4 Probability distribution of a projected range (1.081-3.82°C) for global warming in 2080. The ordinate value is the frequency for any specific temperature to occur.

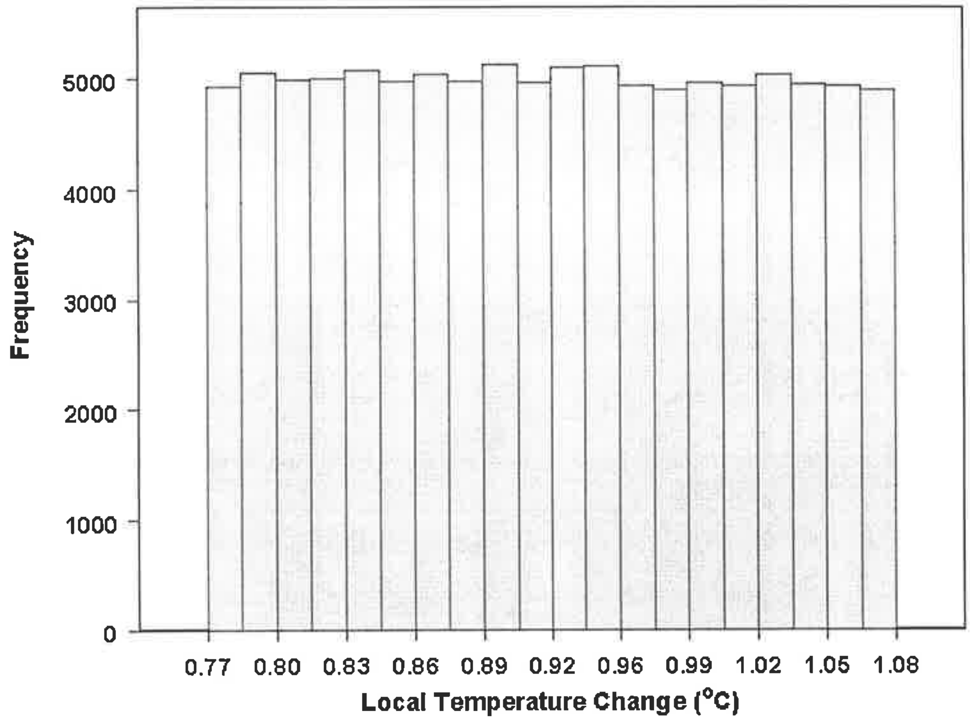


Figure 6.5 Probability distribution of a projected range (0.77-1.08°C) for local temperature change at Roseworthy. The ordinate value is the frequency for any specific temperature to occur.

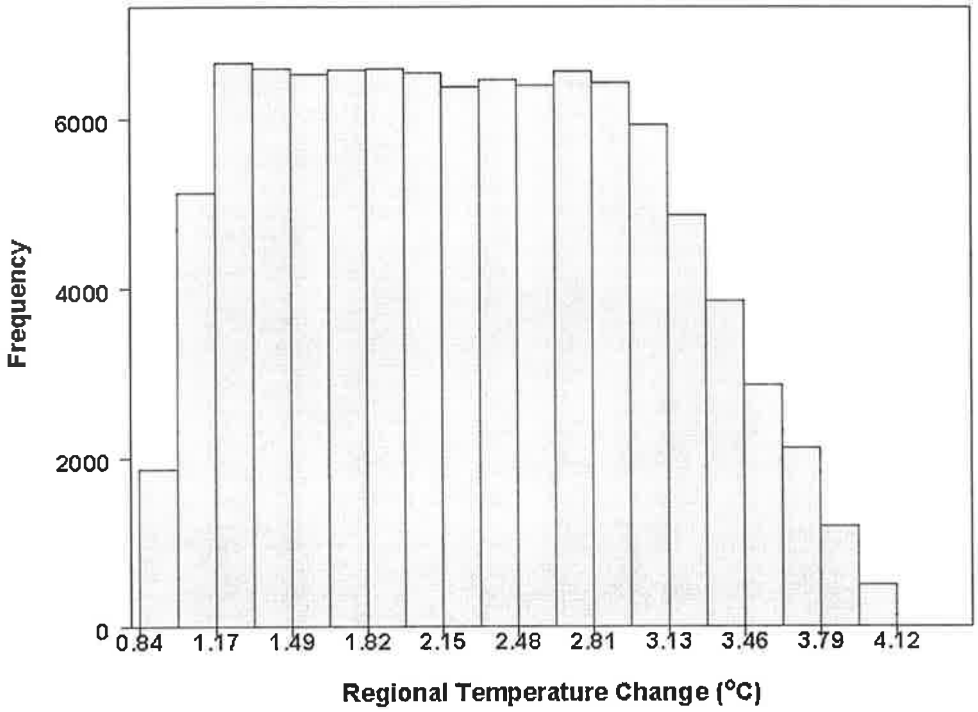


Figure 6.6 Probability distribution of a projected range (0.84-4.12°C) for regional temperature change at Roseworthy based on Monte Carlo Random Sampling. Samples from global warming range and local temperature change range were multiplied and non-uniform probability distribution for regional temperature change was obtained.

Local rainfall change was divided into separate ranges for growing season and non-growing season, expressed as a percentage change per degree of global warming (Column 2, 3, 4 and 5 of Table 6.7). Global warming was used to scale the possible ranges for growing season and non-growing season rainfall change. The lower limit and upper limit for growing season and non-growing season rainfall change were multiplied by the upper bound of global warming (i.e. 3.82) to ensure that values anomalous to that degree of warming were not sampled. The altered two ranges were then separately sampled and repeated 100,000 times. Samples from these two ranges were then averaged to get regional rainfall change based on weight with 2/3 given to growing season rainfall change and 1/3 given to non-growing season rainfall change. The magnitude of weight is based on the distribution of rainfall during the growing season and the non-growing season from the current climate condition.

In order to consider the combined effects of climate change and increased pCO_2 on South Australian wheat production, range for atmospheric pCO_2 change was also randomly sampled based on columns 10, and 11 of table 6.7. There is no obvious relationship between CO_2 concentration and temperature. Theoretically, there should be some relationship, but that relationship was covered by climate sensitivity.

6.4.4 Generation of Probabilistic Scenarios

The random samples for regional temperature, regional rainfall and CO_2 change ranges were rounded, tabulated and binned. The percentage frequency of outcomes for rounded regional temperature, regional rainfall and atmospheric pCO_2 were calculated and summed from the most frequent to the least frequent. The co-pair plots between rainfall and temperature, between rainfall and pCO_2, and between temperature and pCO_2 for Roseworthy in 2080 were shown in Figure 6.7, Figure 6.8 and Figure 6.9 respectively. Each contour contains a level of cumulative probability of particular atmospheric change being reached. Five contour levels represented by different levels of grey were set based on the cumulative probability information. The darkest grey represents the most likely atmospheric change scenarios with cumulative probability ranging from 0-20%. The white stands for the least likely atmospheric change scenario with cumulative probability between 80-100%. The cumulative probabilities represented by other levels of grey are between the most likely and the least likely.

The cumulative probability plots in Figure 6.7 and Figure 6.8 show that, rather than being a large rectangle of uniform probability described by projected ranges of rainfall and temperature as in CSIRO (1996) and projected rainfall and pCO_2, some outcomes are more likely than others. For instance, combinations of extreme changes in both rainfall and temperature are unlikely. These figures also show that the projected range with a low probability of occurrence (<20) occupy a larger portion of space. This means that a large uncertainty created by combining results from different GCMs and SRES scenarios can potentially be treated through simple statistical techniques (Jones, 2000b).

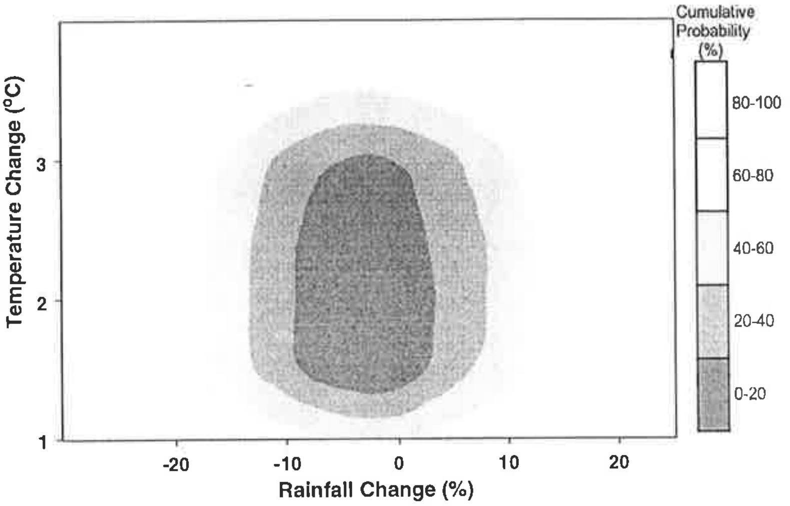


Figure 6.7 Regional rainfall and regional temperature change range and the cumulative probability for these two climatic variables to occur at Roseworthy. The darkest contour shows the most likely climate change scenario. The white area shows the least likely climate change scenario.

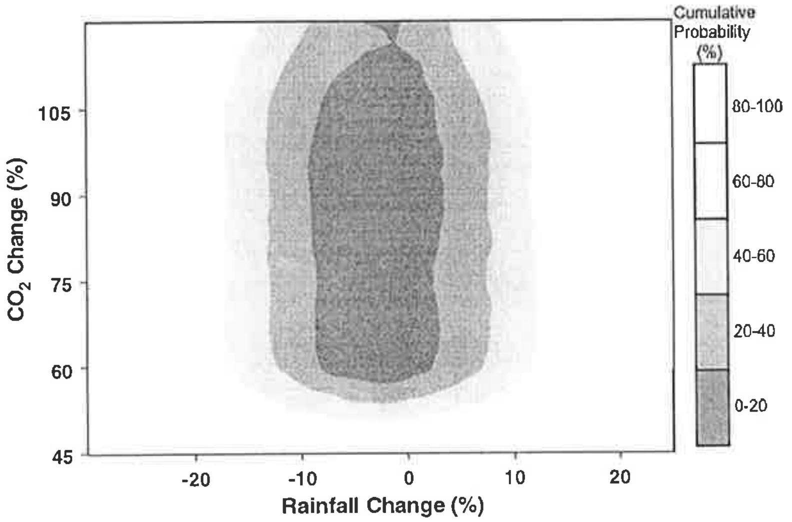


Figure 6.8 Regional rainfall and atmospheric CO_2 change range and the cumulative probability for these two environmental elements to occur at Roseworthy. The darkest contour shows the most likely rainfall and atmospheric CO_2 change scenario. The white area shows the least likely rainfall and atmospheric CO_2 change scenario.

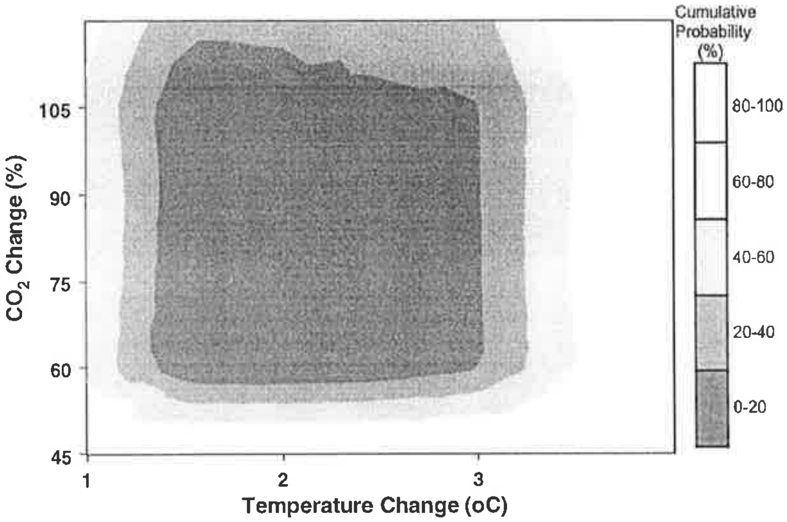


Figure 6.9 Regional temperature and atmospheric CO_2 change range and the cumulative probability for these two environmental elements to occur at Roseworthy. The darkest contour shows the most likely temperature and atmospheric CO_2 change scenario. The white area shows the least likely temperature and atmospheric CO_2 change scenario.

These three two dimensional plots were then welded to a three-dimensional plot to have an overall impression of atmospheric change range and the cumulative probability for particular atmospheric changes to occur which laid a sound basis for impact analysis and risk analysis presented in the following chapter.

6.5 DESCRIPTION OF INDIVIDUAL PROBABILISTIC SCENARIOS

The change range of pCO_2 (50%~120%) and the most probable pCO_2 scenario (60% ~120%) is universal to all locations. As a result, the climate change ranges and the most likely climate change scenarios are given more details site by site in this section. The probabilistic scenarios for each location are listed in Figure 6.10-6.20, which were derived from quantitative information summarised in Table 6.7.

Cummins

In Cummins, rainfall changes from -30% to 22.5%. Temperature changes from 0.5°C to 4°C. The most likely climate change occurs within the window of rainfall changing from –7.5% to 0% and temperature changing from 1.5°C to 2.5°C.

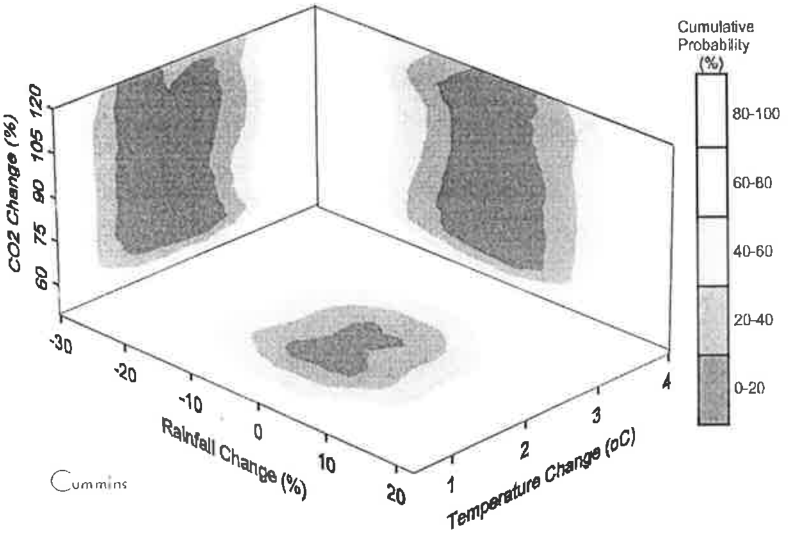


Figure 6.10 Probabilistic atmospheric change scenarios for Cummins. Rainfall Change denotes annual rainfall percentage change (%). Temperature Change denotes average annual temperature change (°C). CO_2 Change denotes atmospheric pCO_2 change (%).

Keith

In Keith, rainfall changes from -30% to 15%, temperature increase from 1°C to 4°C. The most likely climate change window is with rainfall changing from -10% to -0% and temperature increasing from 1.5°C to 3°C.

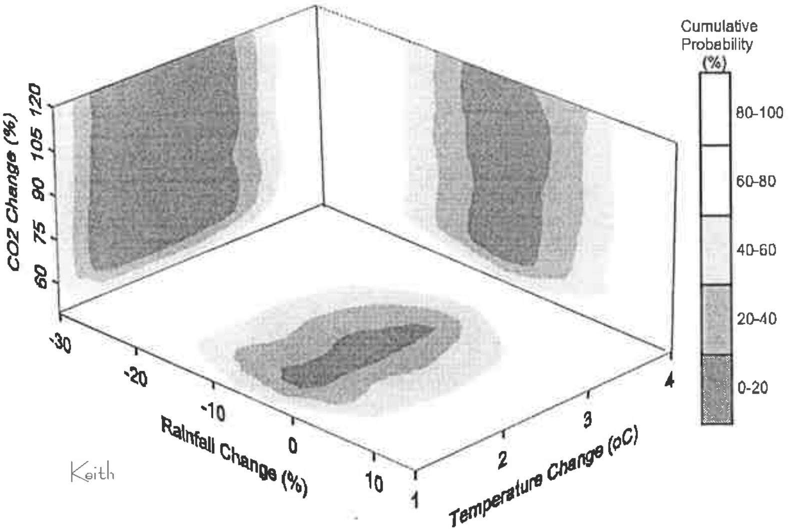


Figure 6.11 Probabilistic atmospheric change scenarios for Keith

Lameroo

In Lameroo, rainfall change ranges from -25% to 20%; temperature increases from 1°C to 4°C. The most likely climate change scenario is within the window of rainfall changing from -5% to 0% and temperature changing from 1.5°C to 3°C, very similar to Keith.

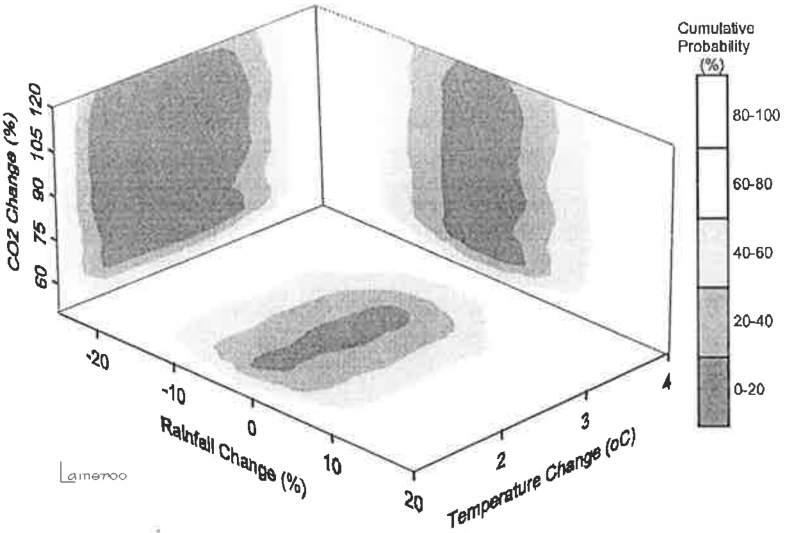


Figure 6.12 Probabilistic atmospheric change scenarios for Lameroo

Minnipa

Climate change window in Minnipa is within rainfall changing from -30% to 30% and temperature changing from 1°C to 4°C. Rainfall changing from -5% to 5% and temperature changing from 1.5°C to 3°C are the most likely climate change window.

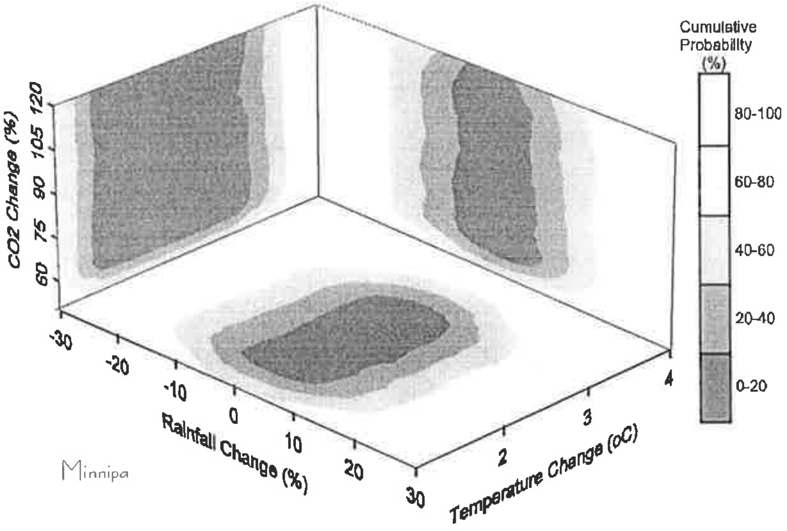


Figure 6.13 Probabilistic atmospheric change scenarios for Minnipa

Naracoorte

Projected rainfall change for Naracoorte ranges from -25% to 10%. Temperature increases from 0.5°C to 4°C. The most likely climate change window occurs within rainfall decreasing from 5% to 10% and temperature increasing from 1°C to 4°C.

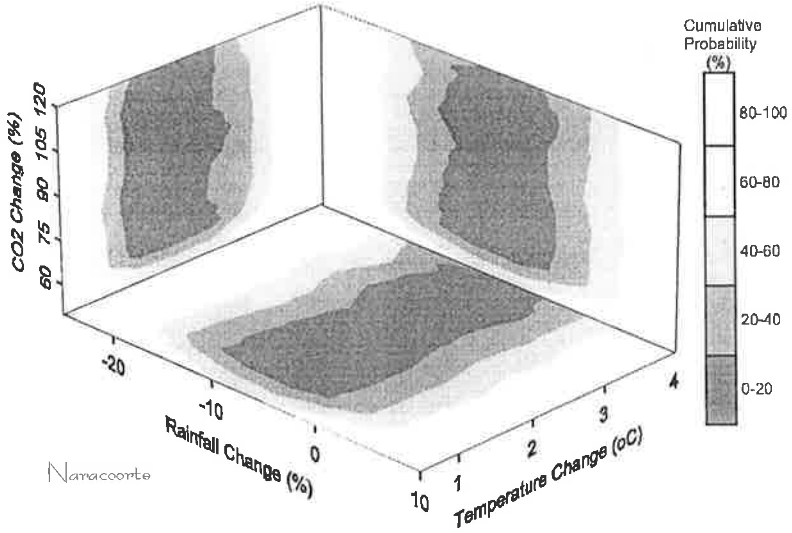


Figure 6.14 Probabilistic atmospheric change scenarios for Naracoorte

Orroroo

In Orroroo, rainfall change symmetrically ranges from -30% to 30%, temperature increases from 1°C to 4°C. Climate change window is the same as in Minnipa. The most likely climate change scenarios in Orroroo is within the window of rainfall changing from -5% to 5% and temperature changing from 1.5°C to 3.5°C.

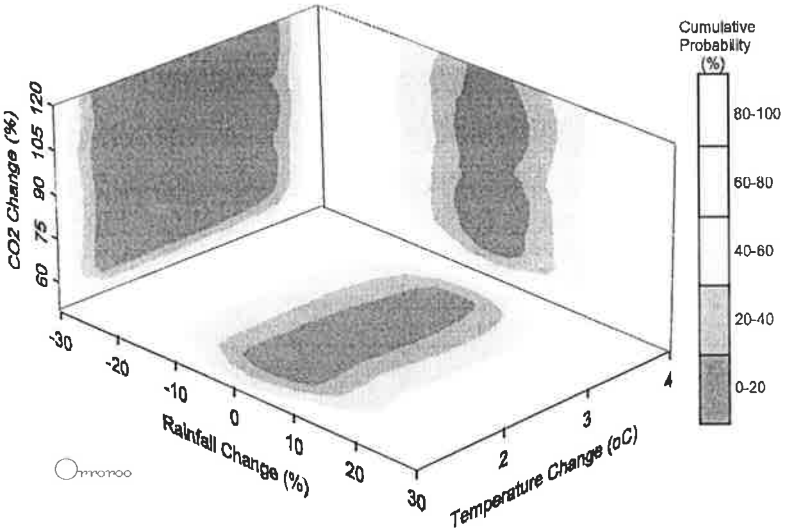


Figure 6.15 Probabilistic atmospheric change scenarios for Orroroo

Roseworthy

Projected rainfall changes from -30% to 25%; temperature increases from 1°C to 4°C in Roseworthy. Temperature increasing from 1.5°C to 3°C and rainfall changing from -5% to 0% are the most probable climate change window.

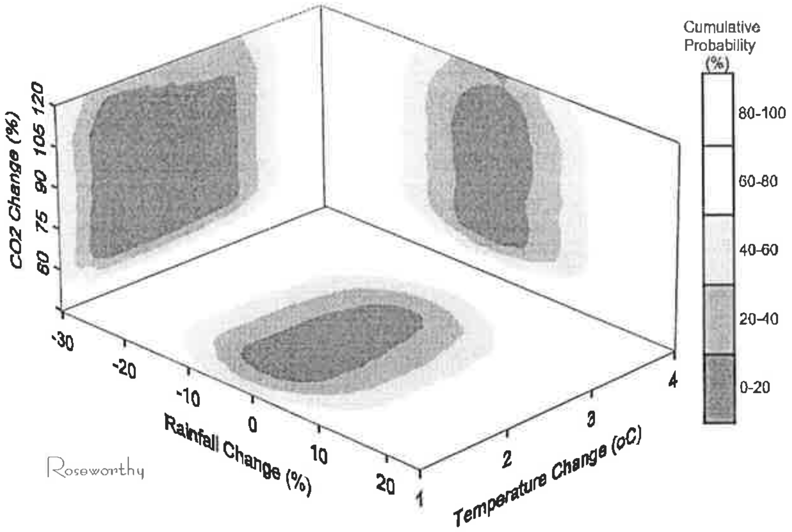


Figure 6.16 Probabilistic atmospheric change scenarios for Roseworthy

Wanbi

Projected rainfall changes from -30% to 20%, temperature increases form 1°C to 4°C in Wanbi. Rainfall changing from -5% to 0% and temperature increasing from 1.5°C to 3°C are the most likely climate change window.

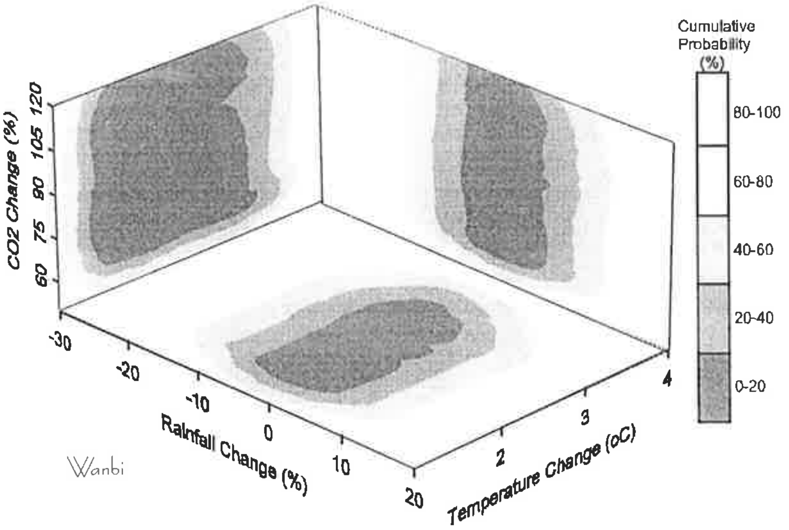


Figure 6.17 Probabilistic atmospheric change scenarios for Wanbi

Owen

Projected rainfall changes from -30% to 25%; temperature increases from 1°C to 4°C in Owen. Temperature increasing from 1.5°C to 3°C and rainfall changing from -5% to 0% are the most probable climate change window.

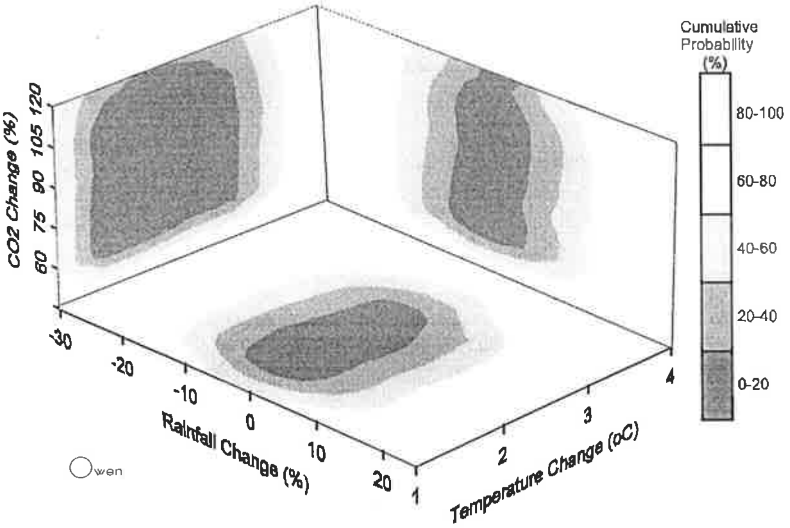


Figure 6.18 Probabilistic atmospheric change scenarios for Owen

Kapunda

Projected rainfall changes from -30% to 25%; temperature increases from 1°C to 4°C in Kapunda. Temperature increasing from 1.5°C to 3°C and rainfall changing from -5% to 0% are the most probable climate change window.

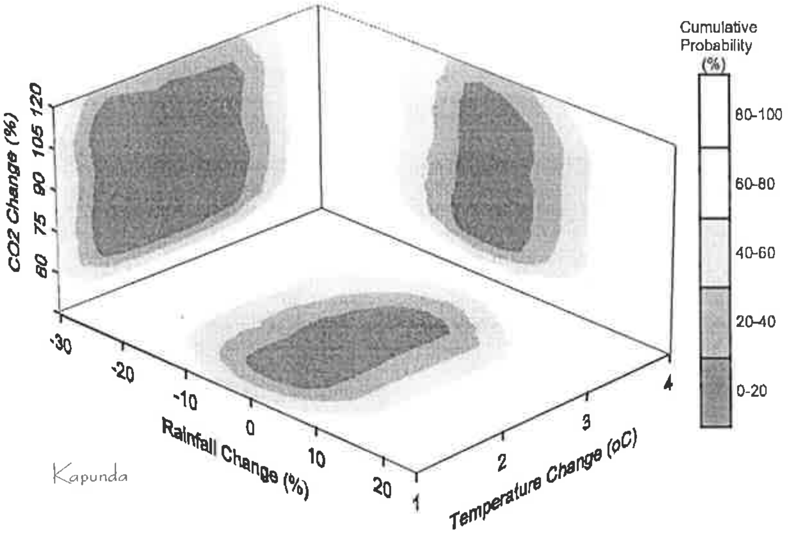


Figure 6.19 Probabilistic atmospheric change scenarios for Kapunda

Moorook

Projected rainfall changes from -30% to 25%; temperature increases from 1°C to 4°C in Moorook. Temperature increasing from 1.5°C to 3.5°C and rainfall changing from -5% to 0% are the most probable climate change window.

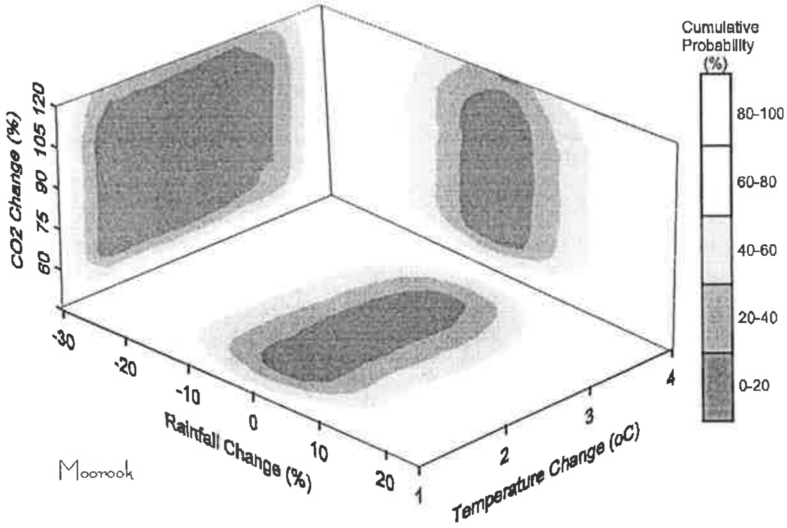


Figure 6.20 Probabilistic atmospheric change scenarios for Moorook

Generally, annual rainfall changes from -30% to 30% among these 11 localities (8 for site-specific study, 3 for spatial study), some variations exist though from site to site. Temperature increases from 1°C to 4°C with the except of Cummins and Naracoorte where temperature increases from 0.5°C to 4°C, a little bit lower than that of others. The atmospheric change window (shape) with the same probability level varies among these 11 sites.

9 GCMs and RCMs consistently projected seasonal rainfall change trend crossing the 11 stations. Projected winter rainfall decreased except for model R-15a, though the change magnitude is different among climate models and among locations. Projected summer rainfall also decrease across all locations except for model LSG and DARLAM and except for model LSG, DARLAM and OPYC3 in Orroroo and Moorook (Tables 6.3 and 6.6).

6.6 INTEGRATION OF PROBABILISTIC SCENARIOS INTO APSIM-WHEAT MODULE

After obtaining the probabilistic scenarios for regional temperature, regional rainfall and atmospheric pCO_2, the next step is to integrate atmospheric change information to the APSIM-Wheat module. There are some differences in the number of atmospheric change scenarios used between site-specific study and spatial study.

For the site-specific study, 5 rainfall levels, 4 temperature levels and 4 CO_2 concentration levels were chosen for running the APSIM-Wheat module according to the probabilistic scenarios. Thus, there is a total of 81 runs (80 atmospheric change scenarios (5*4*4) and 1 baseline scenario: historical climate and current pCO_2) per location for the site-specific study. Table 6.8a gives the specific value for regional rainfall, regional temperature and pCO_2 extracted on a station by station basis from figures 6.10-6.17. Selection of these values is based on the following three conditions:

- Values should cover the whole atmospheric change range.
- The upper end and lower end of atmospheric change range were chosen as two levels of the inputs.
- Intermediate values should be as evenly distributed within the range as possible except that there are special reasons for not doing so. Annual regional rainfall levels (weighted average of

growing season rainfall change and of non-growing season rainfall change) are evenly distributed. Temperature levels are evenly distributed except for Cummins and Naracoorte where lower temperature change occurred. Levels of pCO_2 are from the four emission scenarios (B1, A1, A2, and A1F).

For the spatial study, 4 runs for each unique combination of soil polygon and climate polygon were conducted. These 4 runs specifically are one baseline plus three atmospheric change scenarios (worst case, most likely and best case). For the worst case, rainfall decreasing most, temperature increasing most, and pCO_2 increasing least were chosen, and vice versa for the best case. For the most likely case, rainfall, temperature and pCO_2 with the highest probability were chosen. Changes for temperature, rainfall and pCO_2 used by APSIM-Wheat module are extracted on a station by station basis from figures 6.18-6.20 and given in Table 6.8b.

Table 6.8a Change levels for rainfall, temperature and atmospheric pCO_2 used by APSIM-Wheat module[*]

Locations	Rainfall Change (%)		Temperature Change (°C)	CO_2 Change (ppm)
	Growing Season	Non-Growing Season		
Cummins	-30.60, -17.34, -16.49, 10.52, 12.80	-27.77, -8.70, 25.39, 17.96, 42.48	0.5, 2, 3, 4	527.2
Keith	-27.42, -24.00, -21.46, -6.34, 3.00	-28.50, -3.92, 25.37, 25.25, 36.39	1, 2, 3, 4	634.8
Lameroo	-23.40, -16.82, -13.96, -2.55, 7.10	-27.38, -12.40, 12.48, 15.79, 44.66		687.4
Minnipa	-32.11, -18.24, -16.70, -7.12, 16.36	-24.33, -8.36, 27.73, 57.90, 56.45		785.8
Naracoorte	-24.77, -14.46, -15.87, -0.13, -0.15	-22.45, -9.96, 16.89, 7.15, 24.90	0.5, 2, 3, 4	
Orroroo	-29.01, -20.89, -28.01, -6.46, 13.56	-26.66, -5.56, 57.50, 49.31, 59.71	1, 2, 3, 4	
Roseworthy	-28.58, -28.36, -12.32, -3.50, 10.83	-26.89, 9.97, 16.23, 32.31, 46.28		
Wanbi	-27.53, -22.78, -18.82, -7.75, 8.09	-27.75, 2.83, 31.79, 37.50, 41.50		

[*] Values were extracted on a station by station basis from figures 6.10-6.17.

Table 6.8b Change levels for rainfall, temperature and atmospheric pCO_2 needed by APSIM-Wheat module[*]

Locations	Scenarios	Rainfall Change (%)		Temperature Change (°C)	CO_2 Change (ppm)
		Growing Season	Non-Growing Season		
Owen	Worst Case	-29.16	-27.21	4.11	527.2
	Most Likely	-10.88	15.19	2.38	650
	Best Case	11.85	47.95	0.86	785.8
Kapunda	Worst Case	-29.05	-27.53	4.15	527.2
	Most Likely	-20.34	37.07	2.31	650
	Best Case	11.61	48.93	0.88	785.8
Moorook	Worst Case	-28.54	-27.90	4.23	527.2
	Most Likely	-12.10	16.94	1.99	650
	Best Case	10.96	51.04	0.98	785.8

[*] Values were extracted on a station by station basis from figures 6.18-6.20.

6.7 CONCLUSION

This chapter focused on the construction of probabilistic atmospheric change scenarios through the identification, quantification and treatment of uncertainties surrounding atmospheric change impact assessment by applying statistical techniques, which is the second step of environmental impact risk assessment. The construction of probabilistic atmospheric change scenarios will lay a sound basis for assigning probability to projected impact outcomes and for putting forward appropriate adaptation strategies to cope with atmospheric change impacts. Through this approach, decision maker and scientist will be more confident with the projected impact outcome and with actions taken to counteract those impacts. After the databases including the historical weather database, soil database, wheat genetic database, crop management database described in the last chapter and atmospheric change database depicted in this chapter are coupled with the APSIM-Wheat module, the impact information under atmospheric change scenarios can be obtained by running the APSIM-Wheat model. The next chapter thoroughly and specifically explored the individual impact and combined effects of regional rainfall, temperature and atmospheric pCO_2 change on South Australian wheat production including median grain yield, median grain nitrogen content, risk and failed sowing year through impact analysis, risk analysis and spatial analysis.

7. ANALYSES OF ATMOSPHERIC CHANGE IMPACTS ON SOUTH AUSTRALIAN WHEAT PRODUCTION

Information about the individual effects and combined effects of regional rainfall, temperature and atmospheric pCO_2 on median grain yield, median grain nitrogen content, on risk of wheat production and on frequency of crop failure was obtained through running the APSIM-Wheat model and through three analyses: impact analysis, risk analysis and spatial analysis. Impact assessment involved two progressive analyses: impact analysis and risk analysis. Impact analysis explores the responses of median grain yield and median grain nitrogen content to future atmospheric changes. Risk analysis emphasises the consequences of those responses in the form of conditional probability of not exceeding the critical threshold. Impact analysis is linked to risk analysis through the application of critical impact threshold. These three facets are included in this chapter.

7.1 RESPONSES OF GRAIN YIELD AND GRAIN NITROGEN CONTENT

Impact analysis is used to survey the broad changes and trends that an impact may be subject to under atmospheric change. This is complementary to the task of constructing ranges for key environmental variables, which has been done in Chapter 6 and can be used to scope the likely risks as analysed in section 7.3 of this Chapter. Impact analysis was conducted to explore the possible effects of atmospheric changes on median grain yield and median grain nitrogen content for the site-specific study and the spatial study. For the site-specific study, two aspects of impact analysis were carried out: the individual effect of atmospheric changes in regional rainfall, regional temperature, and pCO_2 on wheat yield; and the combined effects of atmospheric changes on grain yield and grain nitrogen content. The combined effects of atmospheric change on grain yield and grain nitrogen content were investigated in the spatial study. The reasoning behind using “median” rather than “mean” yield/grain nitrogen content in the impact study is given in the first section.

7.1.1 Indicators Used in Impact Assessment

Mean yield is widely used in agricultural impact studies. It is calculated by adding yield totals over a long time sequence (100 years) divided by the number of years. However, in view of statistics, mean value is most meaningful when the samples of yield have a normal distribution. In the case of highly skewed distribution as found in this study, other indicators such as median and percentile/or quartile give a better indication of central tendency.

In this study, the distribution of yield and grain nitrogen content from the 100- year-run (historical climate from 1900 to 1999 and current CO_2 forcing) was tested as shown in Figures 7.1 and 7.2. Obviously, yield and grain nitrogen content distribution is non-normal. As a result, median value is used as the indicators for yield change and change in grain nitrogen content. The median is the middle value of yield/grain nitrogen content when they are ranked from lowest to highest.

There are some differences in calculating median yield and median grain nitrogen content. For yield, zeros were added to the yield database when crops fail to grow in that year. Thus the median grain yield is based on 100 yield samples. However this does not apply to grain nitrogen content. The median value for grain nitrogen content is based on the actual number of years that a crop was predicted to grow rather than 100 samples.

7.1.2 Site-Specific Study

The potential impacts of atmospheric change on median grain yield and on grain nitrogen content for site-specific study were analysed in this section. Two aspects of impact analysis were involved in the site-specific study: the individual effect of atmospheric change on grain yield and the interactive effects of atmospheric change on grain yield as well as on grain nitrogen content.

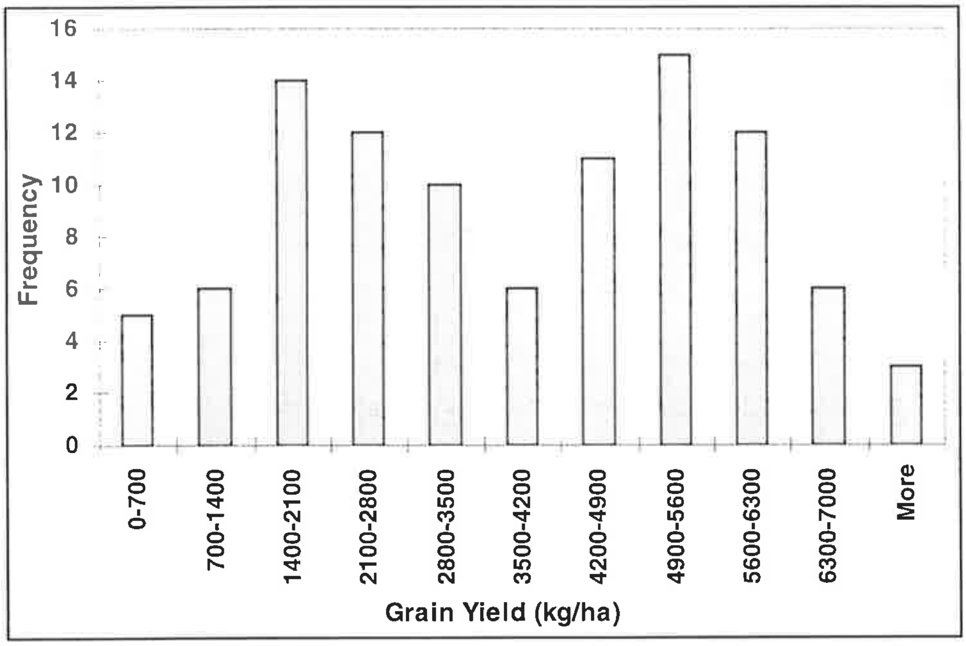


Figure 7.1 Non-normal yield distribution of 100-year-run in Cummins

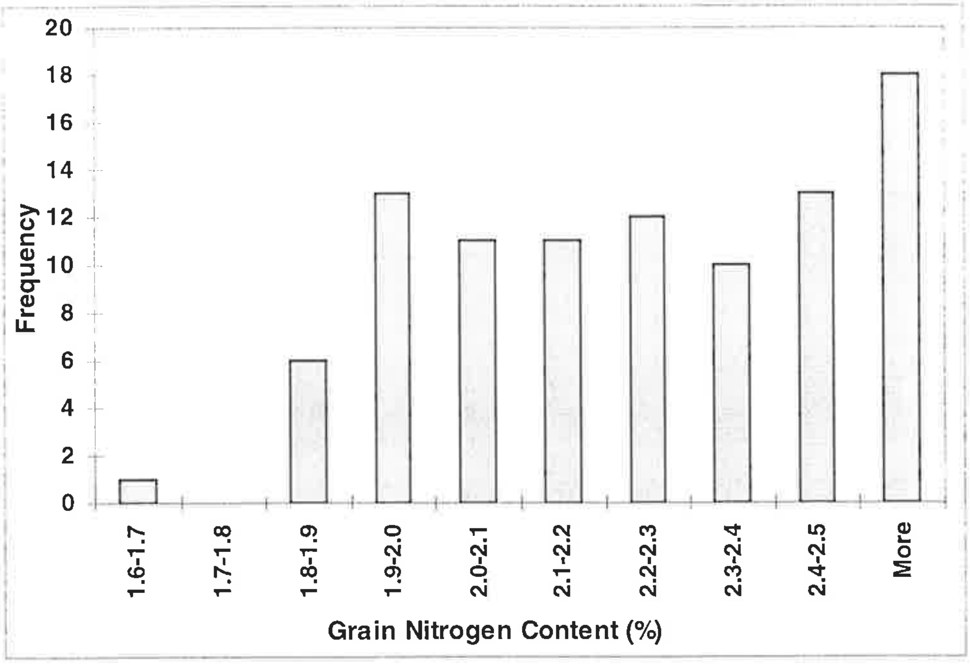


Figure 7.2 Non-normal grain nitrogen content distribution of 100-year-run in Cummins

Individual Effects of Environmental Factors on Median Grain Yield and on Frequency of Crop Failure

The individual effect of environmental factors on median grain yield and on frequency of crop failure (number of years in which wheat can not be grown within the 100-year-run due to the unsatisfaction of sowing rules. section 5.2.3) was explored at two locations. Two sites (Keith and Minnipa), representing a wet site and a drier site respectively, were selected to look at the individual impact of rainfall, temperature and pCO_2 on grain yield, based on a subset of those 80 atmospheric change scenarios (section 6.6). While looking at the individual effect of a certain environmental component, other elements were kept constant, i.e., set to the most likely scenario. Table 7.1 gives specific values for rainfall, temperature and pCO_2 at Keith and Minnipa. The individual effects of rainfall, temperature and pCO_2 on grain yield on frequency of crop failure and on risks of wheat production at these two locations were presented in Figures 7.3, 7.4 and 7.5. Median grain yield was plotted versus conditional probability of not exceeding the critical yield threshold (below which, the wheat industry is not sustainable. pp163-168) under rainfall, temperature and pCO_2 change scenarios. These figures can be used to analyse the potential impacts of rainfall, temperature and pCO_2 change on median grain yield, on frequency of crop failure and on risks of wheat production in each location. The individual impact of rainfall, temperature and pCO_2 on median grain yield and frequency of crop failure are discussed here. The individual impact of these three factors on risks of wheat production was discussed in section 7.3.1 for the reasonability.

Table 7.1 Specific values for rainfall, temperature and pCO_2 at Keith and Minnipa

Scenario		Keith	Minnipa
Annual Rainfall Change (%)	R1	-27.78	-29.52
	R2	-17.31	-14.94
	R3	-5.85	-1.89
	R4	4.19	14.55
	R5	14.13	29.72
PCO_2 Change (ppm)	C1	527.2	
	C2	634.8	
	C3	687.1	
	C4	785.8	
Annual Average Temperature Change (°C)	T1	1	
	T2	2	
	T3	3	
	T4	4	

Potential Impact of Rainfall on Median Grain Yield and on Frequency of Crop Failure

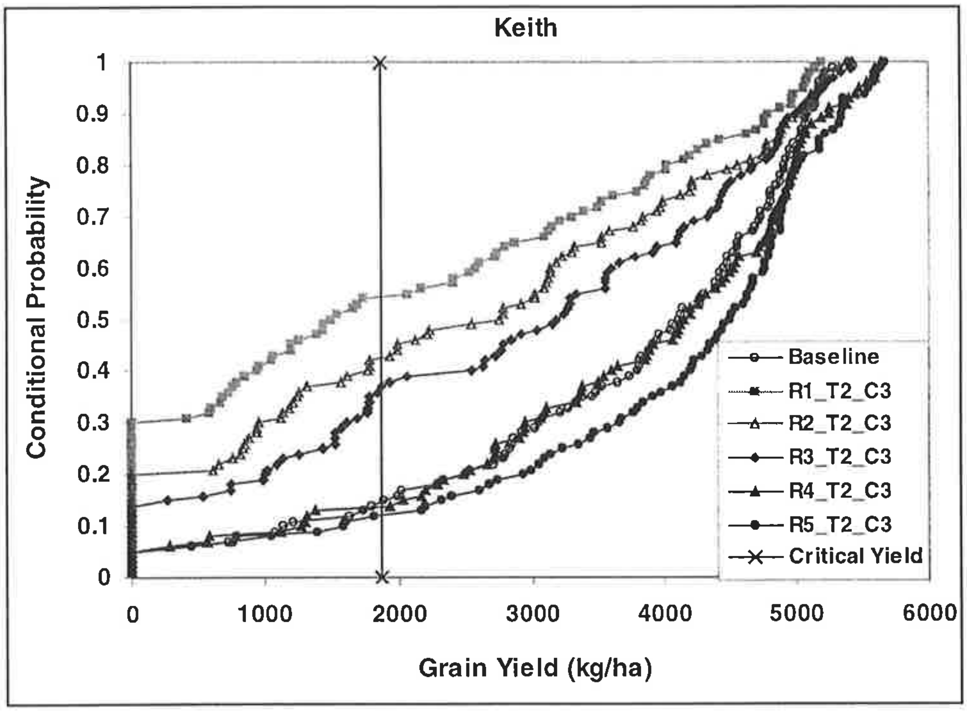
To look at the potential impacts of rainfall change on median grain yield, five atmospheric change scenarios were chosen. Specifically rainfall changes from R1 to R5 while keeping temperature and pCO_2 in most likely situation (section 6.5). The potential impacts of rainfall scenarios on grain yield are shown in Figure 7.3. Readers are directed to see section 6.6 for the definition of baseline scenario.

Rainfall scenarios have a dramatic effect on predicted median grain yield in Keith (-63% to +14%). Median grain yield for R1 (28% reduction in average annual rainfall) is just 1497 kg/ha (63% reduction in median grain yield) compared to the baseline historical median of 4099 kg/ha. Even under the most probable rainfall scenario (R3, 6% reduction in average annual rainfall), predicted median grain yield is only 3186 kg/ha (22% reduction in median grain yield). Predicted grain yield is virtually unchanged under R4 (4% increase in average annual rainfall), and increases slightly under R5 (14% increase in average annual rainfall).

Frequency of crop failure in Keith increased under R1 (30), R2 (20) and R3 (14) compared with that of baseline (5). Frequency of crop failure under R4 and R5 maintains the same as under baseline.

Rainfall scenarios have a large impact on grain yield (-77% to +64%) in Minnipa. Under the worst rainfall case (R1, rainfall decrease 30%), median yield is very low, only 304kg/ha, a 77% reduction compared with the baseline median yield (1294kg/ha). There is still a 40% yield reduction under the most probable rainfall scenario R3 (2% rainfall decrease). Median yield declines 11% even under R4 (15% rainfall increase). There is a large increase of yield (64%) under R5 due to the 30% rainfall increase.

Frequency of crop failure in Minnipa increased under R1 (25), R2 (13), R3 (12) and R4 (6) compared with that of baseline (2). Frequency of crop failure declined to 1 under R5.



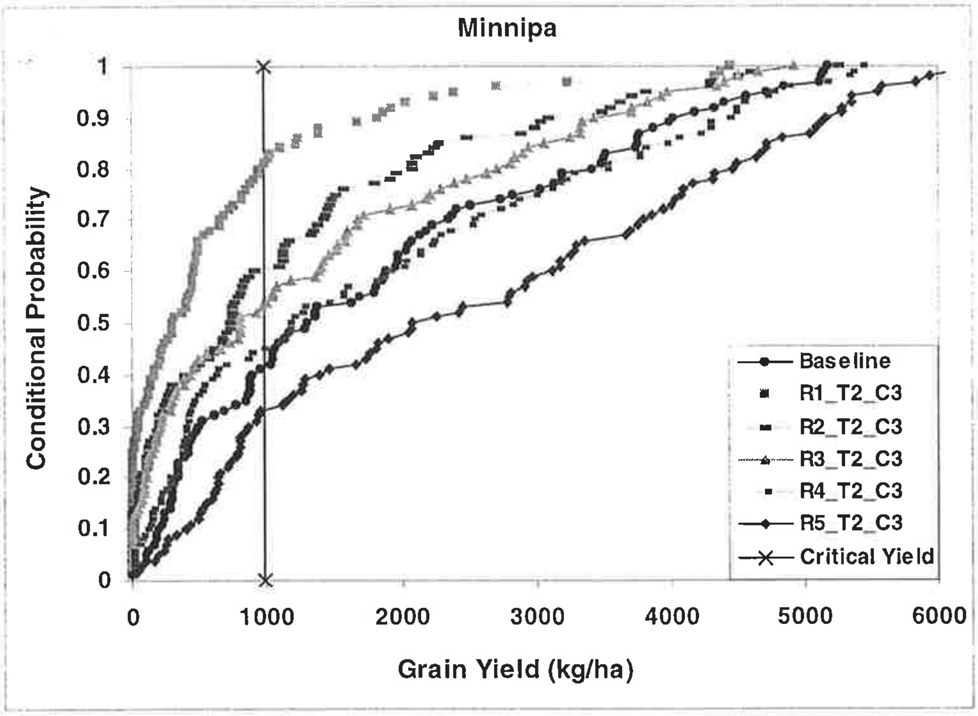


Figure 7.3 Effects of *rainfall* scenarios on wheat grain yield, frequency of crop failure and risks of wheat production at Keith and Minnipa with the most probable temperature and CO_2 scenarios

Potential Impact of Temperature on Grain Yield and on Frequency of Crop Failure

To look at the potential impacts of temperature change on grain yield, four atmospheric change scenarios were chosen. Specifically temperature changes from T1 to T4 while keeping rainfall (section 6.5) and pCO_2 in the most likely situation. Detailed information is presented in Table 7.1.The possible effects of temperature scenarios on grain yield are shown in Figure 7.4.

Temperature also has a large effect on grain yield in Keith (-45% to -12%) but not quite as large as the extreme rainfall scenarios (Figure 7.4). Under the worst temperature scenario (T4, 4°C increase in average annual temperature), median grain yield declines to 2229 kg/ha (45% reduction). Under the most probable temperature scenario (T2, 2°C increase in average annual temperature), median grain yield declines to 3186 kg/ha, a decline of 22%. Even a small increase in temperature (T1, 1°C increase in average annual temperature), results in a large decrease (12%) in median grain yield.

The same frequency of crop failure (14) has been found under the four temperature scenarios. Frequency of crop failure under temperature scenarios in Keith increased compared with that of the baseline (5).

Temperature increase has certain effects on grain yield (-46% to -25%) under the most likely rainfall and pCO_2 change scenarios at Minnipa. Median yield reduces to 705kg/ha (46% decrease) under the worst temperature increase scenario (4°C). Median yield reduces to 805kg/ha (39% decline) under the most likely temperature increase scenario (2°C). Median yield decreases 25% even with the smallest temperature increase (1°C). Unlike the situation in Keith, there is not much difference in median yield under different temperature scenarios (T1, T2, T3 and T4). This indicates that rainfall played a larger part in final grain yield formation than temperature in a drier environment.

Frequency of crop failure in Minnipa increased from 2 under baseline to 10 under T4 and to 12 under T1, T2 and T3. Small variation has been found among temperature change scenarios in Minnipa.

Potential Impact of pCO_2 on Grain Yield and on Frequency of Crop Failure

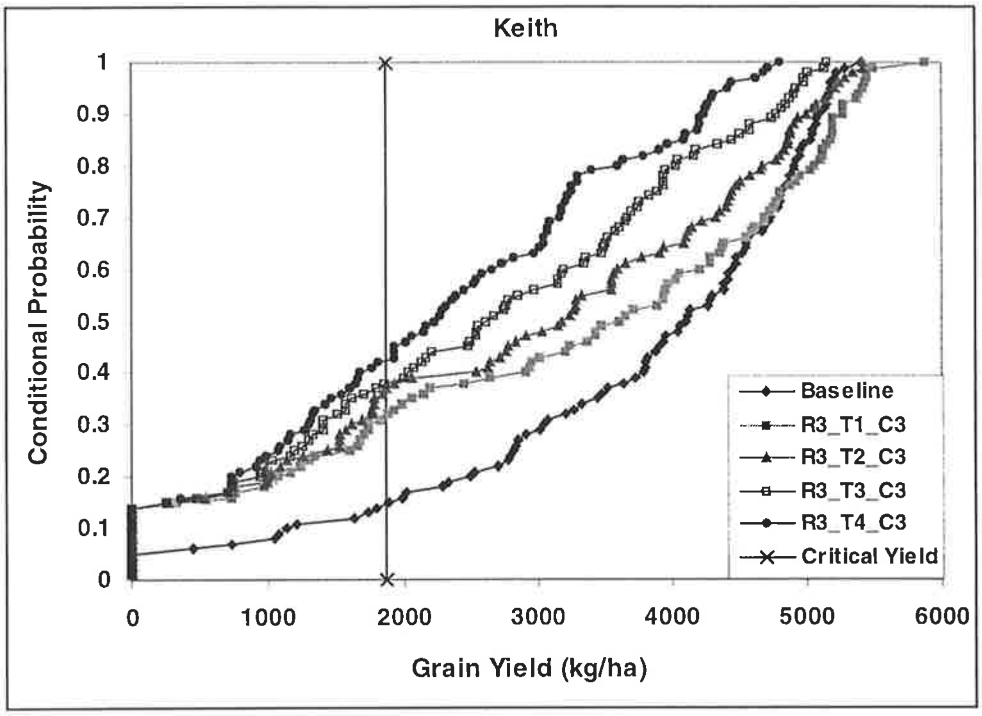
To look at the potential impacts of pCO_2 change on grain yield, four atmospheric change scenarios were chosen. Specifically pCO_2 changes from C1 to C4 while keeping rainfall and temperature in the most likely situation (R3 and T2). For specific value of pCO_2 changes and fixed rainfall and temperature change setting see Table 7.1. Figure 7.5 shows the possible impacts of increased atmospheric CO_2 concentration on grain yield.

There is a slight yield improvement with elevated CO_2 in Keith. Median grain yield increases from 2,800 kg/ha under C1 (527.2 ppm) to 3,379 kg/ha under C4 (785.8 ppm) (Figure 7.5). Frequency of crop failure in Keith increased from 5 under baseline to 14 under the four CO_2 scenarios. The frequency of crop failure under these four CO_2 scenarios is the same as that of under the four temperature change scenarios.

The slight amelioration effect of CO_2 was also found in Minnipa. Median grain yield increases from 757kg/ha to 872kg/ha with the increase of pCO_2 from C1 (527.2 ppm) to C4 (785.8 ppm) under the most likely rainfall (-1.89%) and temperature change ($2^{o}C$) scenario. Frequency of crop failure in Minnipa increased from 2 under baseline to 12 under the four CO_2 scenarios.

In conclusion, rainfall exerts the strongest influence on grain yield at Keith and Minnipa. Detrimental impacts of temperature increase on grain yield were projected at these two locations. But this detrimental effect is smaller in Minnipa indicating that rainfall is a key factor in determining the grain yield in the drier environment. There is a slight beneficial effect of increased atmospheric CO_2 concentration on grain yield in both sites. Among these three environmental variables, rainfall has the biggest impact on yield, followed by temperature and then by pCO_2. Rainfall and pCO_2 have positive relationship with median grain yield. However, temperature has an inverse relationship with median grain yield.

Rainfall also has considerable effects on frequency of crop failure. Large variation of frequency of crop failure among rainfall scenarios existed at these two locations. Rainfall has an inverse relationship with frequency of crop failure. On the contrary, temperature and pCO_2 nearly have no effect on frequency of crop failure.



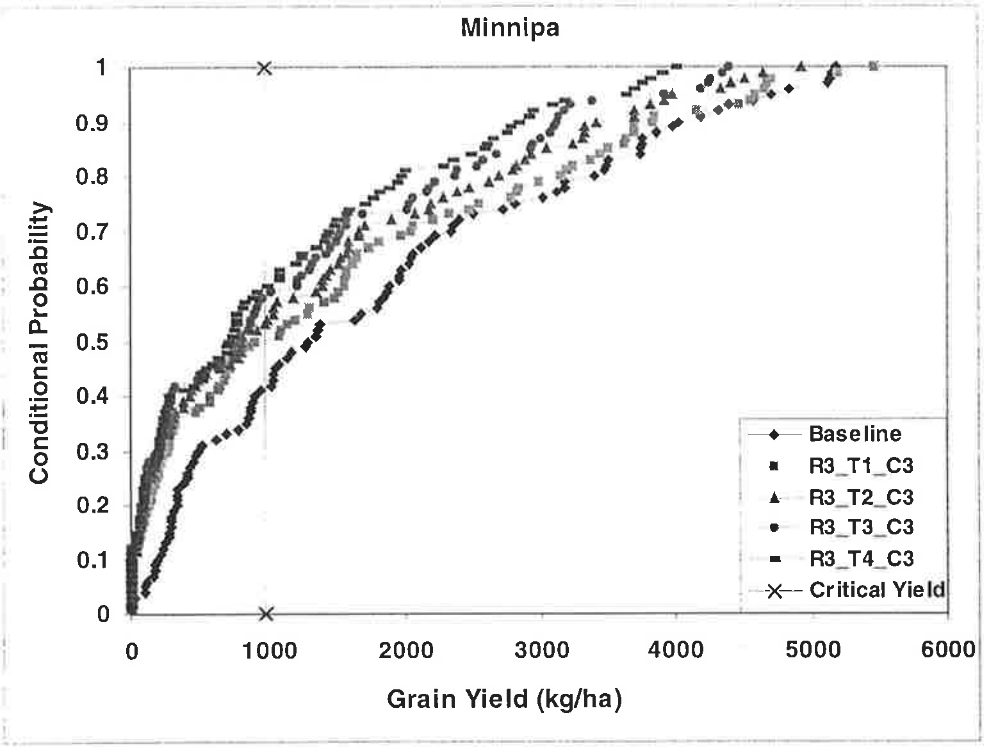
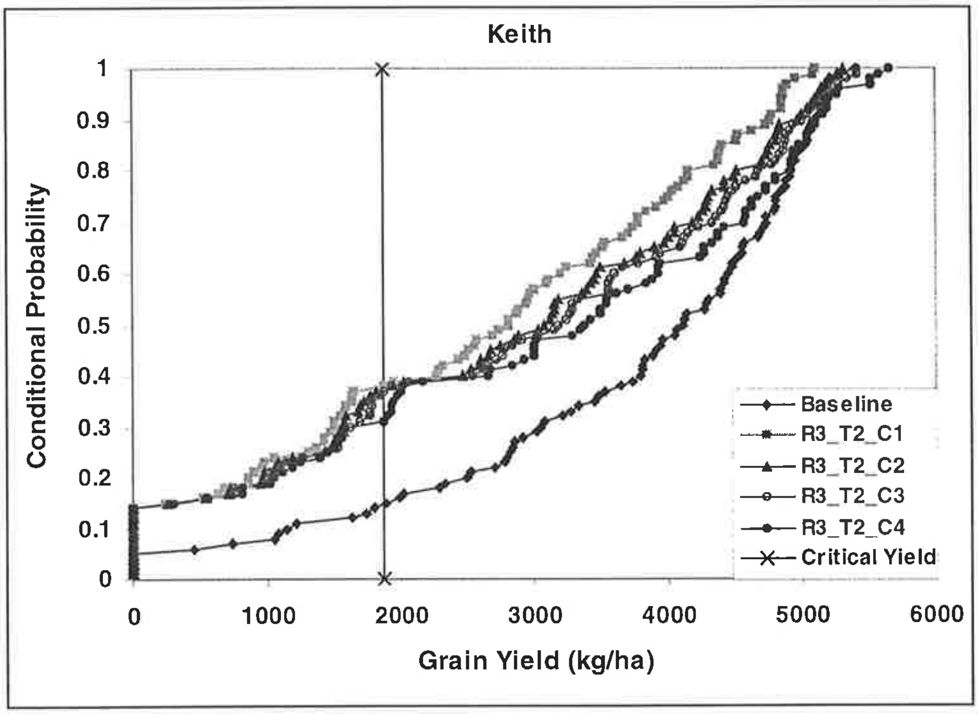


Figure 7.4 Effect of *temperature* scenarios on wheat grain yield, frequency of crop failure and risks of wheat production at Keith and Minnipa with the most probable rainfall and CO_2 scenarios.



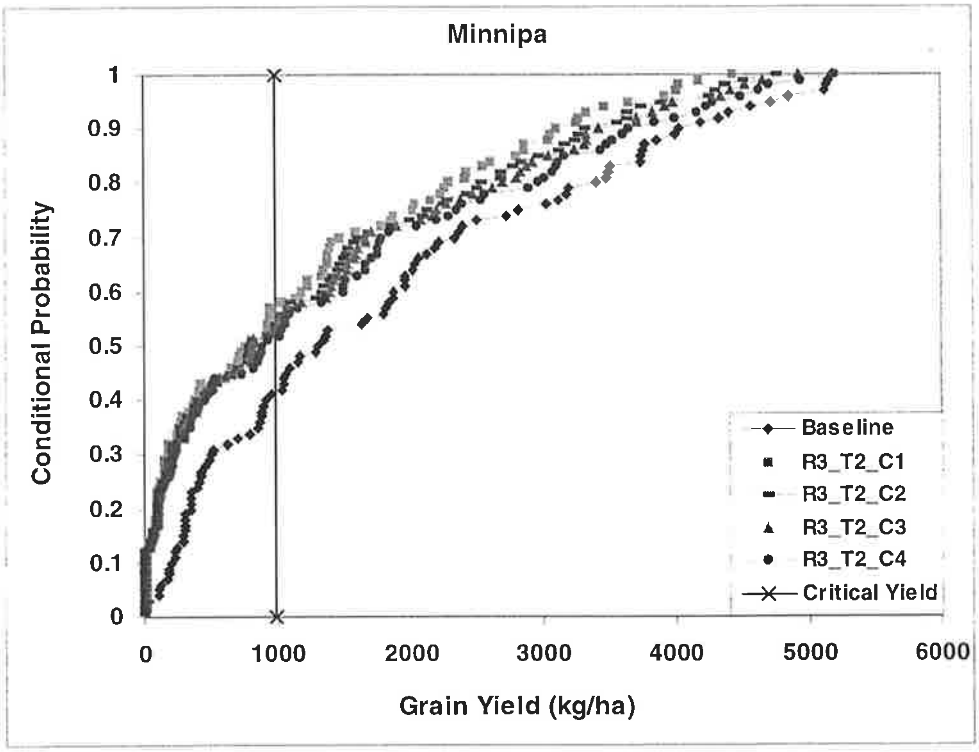


Figure 7.5 Effect of pCO_2 scenarios on wheat grain yield, frequency of crop failure and risks of wheat production at Keith and Minnipa with the most probable rainfall and temperature scenarios

Combined Effects of Rainfall, Temperature and pCO_2 on Wheat Production

Response of grain yield and grain nitrogen content to atmospheric change was based on 80 atmospheric change scenarios for each location (section 6.6). The same kind of information was analysed across the eight study sites.

Yield/grain nitrogen content responses under changed environment were overlaid with the probabilistic scenario to give detailed information on the degree of probability that a certain amount of median yield /grain nitrogen content will change. The overlaid plot is a five-dimensional plot, also known as a response surface, which captures a large quantity of information including atmospheric change ranges (3 axes), cumulative probability of atmospheric change scenarios (shaded areas), and yield/grain nitrogen content response magnitude represented by lines traversing those three planes/windows. Information on grain yield/grain nitrogen content change range or change trend/pattern can be obtained form this plot, as well as the information on probability to achieve a certain level of yield/grain nitrogen content. The 50% probability and the most likely yield/grain nitrogen content change are derived corresponding to the 50% and the most likely atmospheric change scenarios in this study.

Yield Response

The yield response surface was constructed across the full range of uncertainties of regional rainfall, regional temperature and pCO_2 concentration and overlaid with probabilistic atmospheric change scenarios. The procedures of synthesising the five dimensional plot are illustrated in Figures 7.6 by using information at Roseworthy as an example. The design of Figure 7.6a is the same as used in Figures 6.7 and 6.8. Yield response was added to Figure 7.6a: isopleths in Figure 7.6b. The same procedures apply to other planes (between rainfall and pCO_2, and between temperature and pCO_2). Once yield response was overlaid with its corresponding plane, the five dimensional plot then can be obtained (Figure 7.6c). Figures 7.6c-7.34 (except for 7.24-2.26) are patterned after figures 6.10-6.20. The planes are projections of a volume density onto a single axis. When yield changes, for example, in the plane between rainfall and pCO_2, temperature maintains to 4°C.

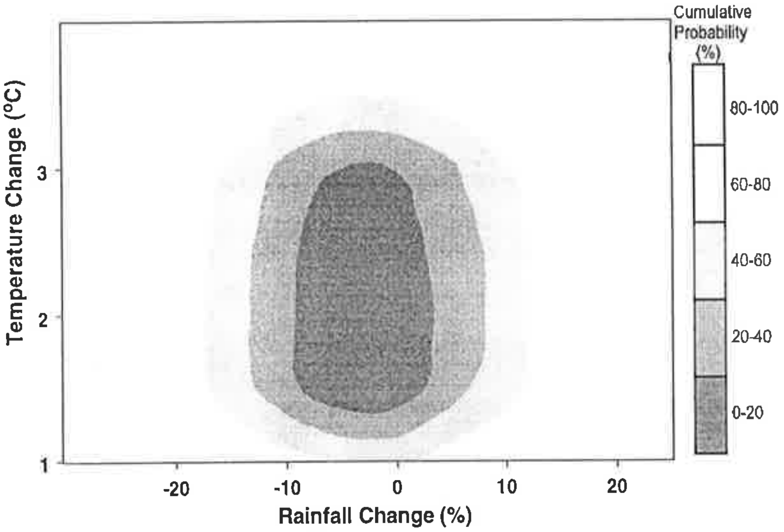


Figure 7.6a Annual average rainfall change (%), annual average temperature change (°C) and cumulative probability (shaded area) for certain atmospheric change to occur (%). The darkest area is the most likely atmospheric change scenario with cumulative probability 0f 0-20%, while the white area is the least likely atmospheric change scenario with cumulative probability of 80% -100%.

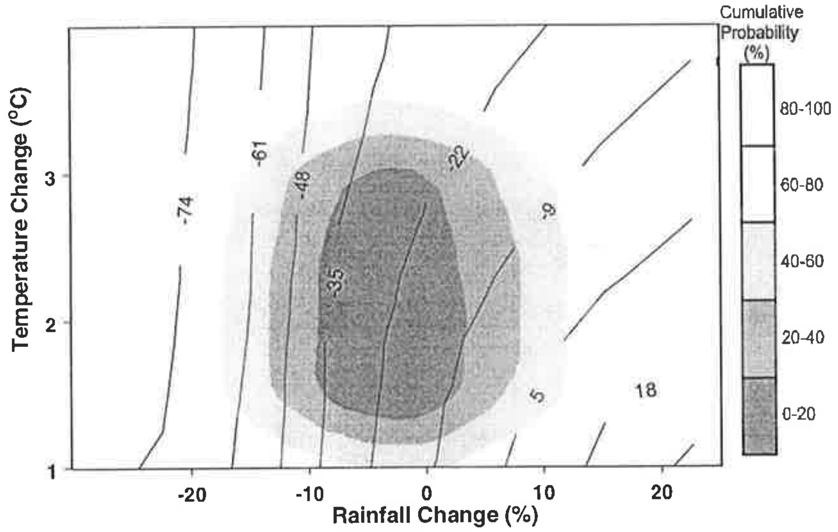


Figure 7.6b Yield response (percentage change of median grain yield compared to baseline) (contour lines) was overlaid with probabilistic scenarios.

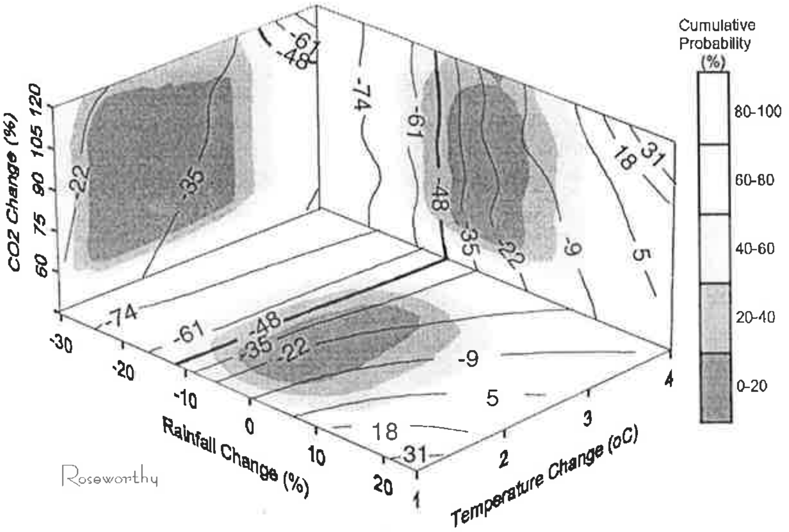


Figure 7.6c Yield responses surface in three planes. The bold line is critical yield threshold corresponding to that of baseline. The planes are projections of a volume density onto a single axis. When yield changes, for example, in the plane between rainfall and pCO_2, temperature maintains to 4°C.

Cummins

Grain yield decreases are expected over most part of the climate change window (between rainfall and temperature). Yield increase was found in the lower right hand corner of this window where rainfall increase is more and temperature increase is less. Maximum yield response (56%) was achieved at the 10% rainfall and 0.6°C temperature change while the lowest yield response (-69%) occurred at the -26% rainfall and the whole temperature change range scenarios. Based on CSIRO (2001) climate change scenarios (the generation of probabilistic climate change scenario is based on the information of CSIRO (2001), section 6.3.2), there is a 50% probability that the yield response will be in the range of about -48% ~ +25% with the most likely yield response -45% ~ -17%.

Yield decrease occupies most of the window between rainfall and atmospheric pCO_2 change. Yield increase is found in the right hand part of this plane where rainfall increase is more. Maximum yield response was achieved (66%) at 21% rainfall and 119% pCO_2 while the lowest yield response (-69%) occurred at about -26% rainfall and the whole pCO_2 change range scenarios. Based on CSIRO (2001) climate change scenarios and IPCC (2001) emission scenarios there is a 50% probability that the yield response will be in the range of about -48%

~ +12% with the most likely yield response -48% ~ -17%. Rainfall is the dominant factor driving these results.

In the plane of temperature and pCO_2 change, yield mainly shows a decrease trend except in the upper left hand corner where temperature increase less and pCO_2 increase more. Maximum yield response was achieved (4%) with pCO_2 increasing about 99% and temperature increasing around 0.8°C while the lowest yield response (-69%) occurred at temperature around 4°C. Based on CSIRO (2001) climate change scenarios and IPCC (2001) emission scenarios, there is a 50% probability that the yield response will be in the range of about -38% ~ -1% with the most likely yield response -35%~-4%.

The most likely yield change comprising three atmospheric change planes will be in the range of -33% ~ -7%. The extent of most likely yield change is extracted when regional rainfall, regional temperature and pCO_2 are under most likely scenarios based on table information rather than the three dimensional plot.

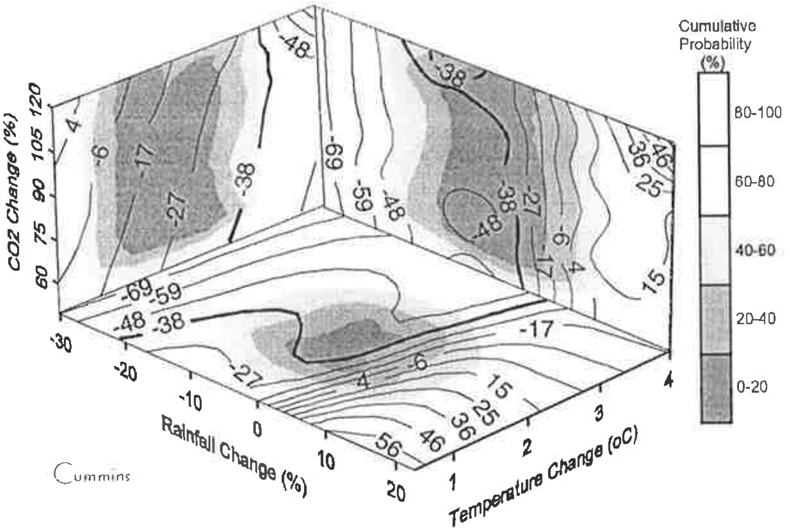


Figure 7.7 Median yield response (%) under future atmospheric change scenarios in Cummins

Keith

The yield presents a decrease trend in the climate change window with the exception in the lower right hand corner where the rainfall increase is more and the temperature increase is less. Maximum yield response was achieved (9%) with rainfall increase 3% and temperature increase 2°C while the lowest yield response (-65%) occurred at 24% rainfall and 2.3°C temperature. There is a 50% probability that the yield response will be in the range of about -44% ~ +2% with the most likely yield response -35% ~ -10%.

Yield also exhibits a decrease trend in the window between rainfall and pCO_2 composed of regional rainfall change and pCO_2 change except in the upper right hand corner where rainfall and pCO_2 increase more. Maximum yield response was achieved (9%) at 9% rainfall and 108% pCO_2 while the lowest yield response (-65%) occurred at -28% rainfall and 106% pCO_2. There is a 50% probability that the yield response will be in the range of about -44% ~ +2% with the most likely yield response -40% ~ -14%.

Yield shows a decrease trend in the window between temperature and pCO_2. The least yield decrease was achieved (-19%) at 70% pCO_2 and 2.2°C temperature while the lowest yield response (-65%) occurred at around 3.8°C temperature and 115% pCO_2. There is a 50% probability that the yield response will be in the range of about -41% ~ -8% with the most likely yield response -38% ~ -14%.

The most likely yield change comprising three atmospheric change planes will be in the range of -38% ~ -14%.

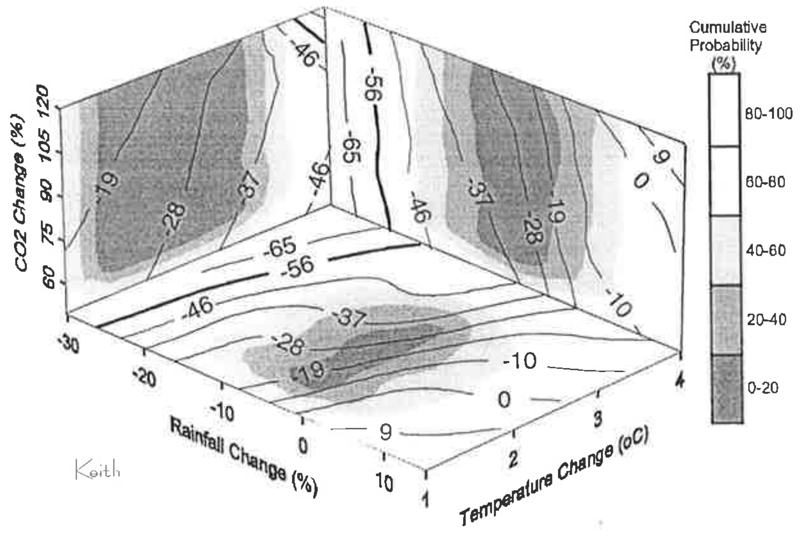


Figure 7.8 Median yield response (%) under future atmospheric change scenarios in Keith

Lameroo

A large range of yield variation occurred (-60% ~ +89%) under the climate change window. Yield exhibits a decrease trend in the left hand part of this window. Yield presents an increase trend in the right hand part of this window. Maximum yield response was achieved (89%) at rainfall close to 20% and temperature close to 1°C while the lowest yield response (-60%) occurred at 24% rainfall decrease and the whole temperature change range. There is a 50% probability that the yield response will be in the range of about -51% ~ +24% with the most likely yield response -36% ~ -8%.

Some increases and decreases happened within the plane composed of pCO_2 and regional rainfall. Yield presents a decrease trend in the left hand part of this window. Maximum yield response was achieved (89%) at 16% rainfall and 113% pCO_2 while the lowest yield response (-60%) occurred at -18% rainfall and the whole pCO_2 change range. There is a 50% probability that the yield response will be in the range of about -54% ~ +30% with the most likely yield response -42% ~ +1%. Rainfall is the dominant factor in determining these yield responses.

Yield decreases are projected in the plane of pCO_2 and regional temperature (4% to 60%). Least yield decrease was achieved (-4%) at 69% pCO_2 and 1.8°C temperature while the lowest yield response (-60%) occurred at 3.8°C temperature increase and 115% pCO_2 increase. There is a 50% probability that the yield response will be in the range of about -42% ~ +2% with the most likely yield response -29% ~ -2%.

The most likely yield change comprising three atmospheric change planes will be in the range of -31% ~ -1%.

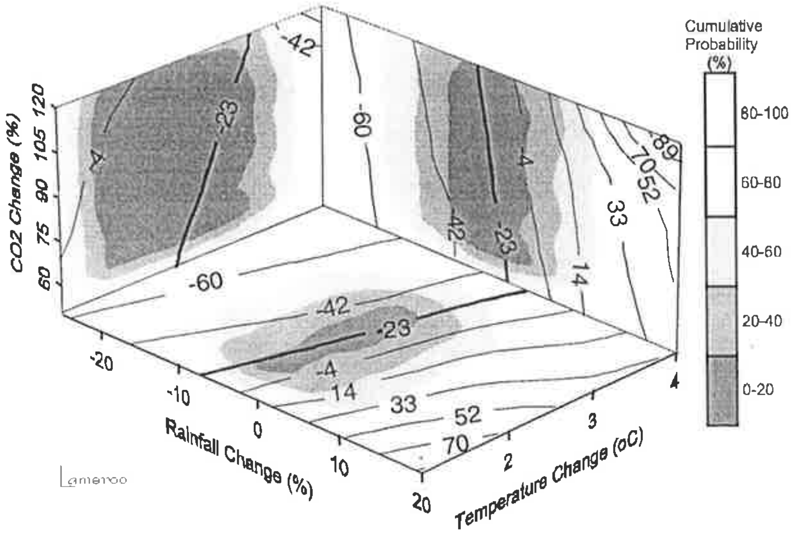


Figure 7.9 Median yield response (%) under future atmospheric change scenarios in Lameroo

Minnipa

Yield change is from -67% to 70% under the climate change window. Yield decreases takes up most of this plane. Maximum yield response was achieved (70%) at 27% rainfall and 2°C temperature while the lowest yield response (-67%) occurred at -29% rainfall and the whole temperature change range. There is a 50% probability that the yield response will be in the range of about -50% ~ -4% with the most likely yield response -45% ~ -28%. Rainfall played an important role in yield response in this plane.

A large yield response (-67% ~ 90%) occurred in the window between rainfall and pCO_2 composed of regional rainfall and pCO_2. Maximum yield response was achieved (90%) at 27% rainfall and 113% pCO_2 while the lowest yield response (-67%) occurred at -23% rainfall and the whole pCO_2 change range. There is a 50% probability that the yield response will be in the range of about -48%~-8% with the most likely yield response -41% ~ -28%. Rainfall played an important part in yield response in this plane.

Yield exhibits a decrease trend (-67%~-8%) within the window between temperature and pCO_2 composed of regional temperature and pCO_2 change. Least yield decrease was projected (-8%) at 76% pCO_2 and 1.6°C temperature while the lowest yield response (-67%) occurred at 3.75°C temperature and 115% pCO_2. There is a 50% probability that the yield response will be in the range of about -48% ~ -3% with the most likely yield response -38% ~ -6%.

The most likely yield change comprising three atmospheric change planes will be in the range of -35% ~ -5%.

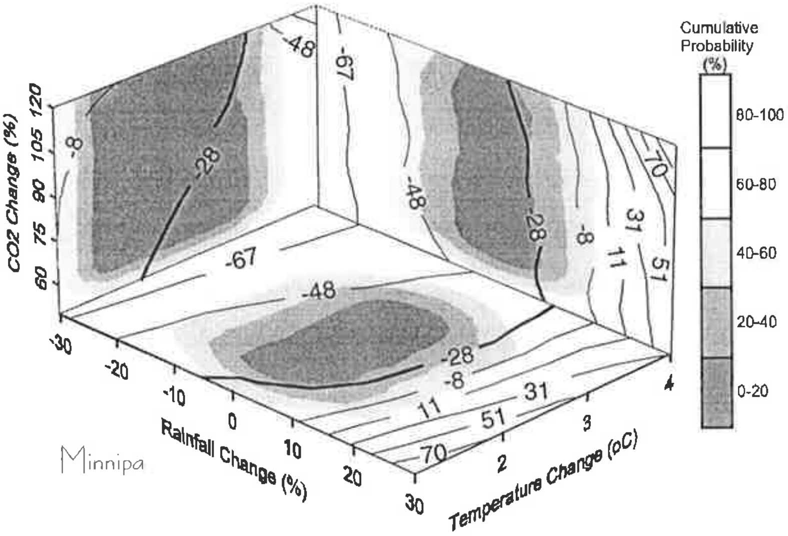


Figure 7.10 Median yield response (%) under future atmospheric change scenarios in Minnipa

Naracoorte

Yield changes from -41% to 11% in the climate change window. Maximum yield response was achieved (11%) with -2% rainfall and 1.8°C temperature while the lowest yield response (-41%) occurred with a temperature increase around 3.8°C and the whole rainfall change range. The pattern of the effects of rainfall on wheat yield in Naracoorte is not the same as in other locations where rainfall played an important role on final yield. However, in Naracoorte, temperature had a strong effect on final yield. This is because Naracoorte receives higher rainfall than the other locations. A certain amount of rainfall decrease or increase tends not to change grain yield dramatically. Therefore, yield is mainly sensitive to temperature. There is a 50% probability that the yield response will be in the range of about -41% ~ +11% with the most likely yield response –41 ~ +3%.

Yield changes from -33% to 18% in the window between rainfall and pCO_2. Maximum yield response was achieved (18%) at 9% rainfall and 118% pCO_2 while the lowest yield response (-33%) occurred at 53% pCO_2 and -24% rainfall. There is a 50% probability that the yield response will be in the range of about -26% ~ -6% with the most likely yield response -26% to -11%. PCO_2 is the controlling factor in yield response in this plane.

Yield change range in the window between temperature and pCO_2 is the same as in the climate change window (-41% ~ +11%). Maximum yield response was achieved (11%) at 99% pCO_2 and 0.75°C temperature while the lowest yield response (-41%) occurred 69% pCO_2 and 3.8°C temperature. There is a 50% probability that the yield response will be in the range of about -33% ~ +6% with the most likely yield response -27% ~ -1%.

The most likely yield change comprising three atmospheric change planes will be in the range of -26% ~ -1%.

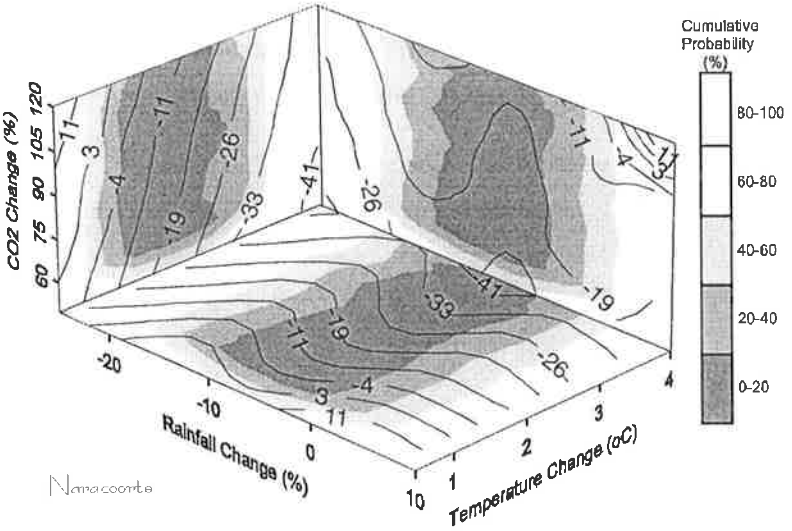


Figure 7.11 Median yield response (%) under future atmospheric change scenarios in Naracoorte

Orroroo

There are large variations of yield change (-67%~102%) due to climate change. Maximum yield response was achieved (102%) at 27% rainfall and 1.6°C temperature while the lowest yield response (-67%) occurred at -29% rainfall and crossing the whole temperature change range. There is a 50% probability that the yield response will be in the range of about -67% ~ +18% with the most likely yield response -67% ~ -11%.

An even wider change range of yield (-67% ~ 116%) occurred in the window between rainfall and pCO_2. Maximum yield response was achieved (116%) at 28% rainfall and 115% pCO_2 while the lowest yield response (-67%) occurred at -23% rainfall and crossing the whole pCO_2 change range. There is a 50% probability that the yield response will be in the range of about -

53%~+18% with the most likely yield response -53% ~ -25%. Rainfall is the controlling factor in yield response in the above two windows.

Within the window of temperature and pCO_2, yield changes from -67% to 3%. Maximum yield response was achieved (3%) at 107% pCO_2 and 1.2°C temperature while the lowest yield response (-67%) occurred at 3.9°C temperature and 118% pCO_2. There is a 50% probability that the yield response will be in the range of about -60% ~ +3% with the most likely yield response -46% ~ -1%.

The most likely yield change comprising three atmospheric change planes will be in the range of -33% ~ 0%.

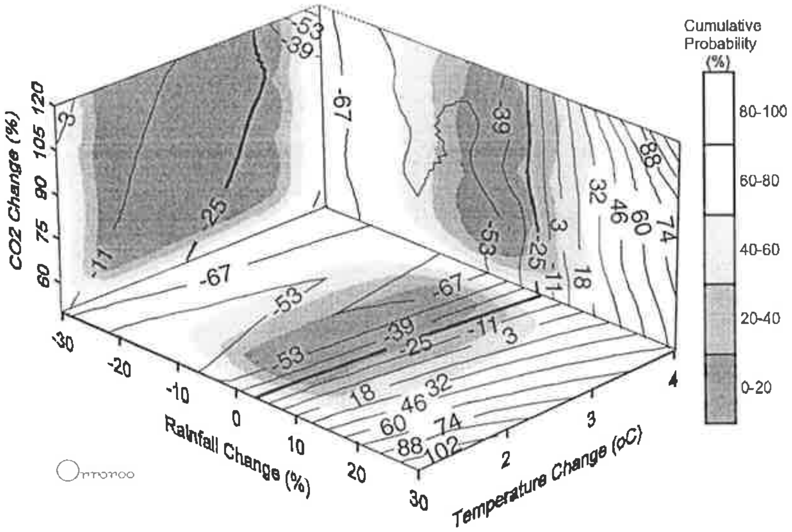


Figure 7.12 Median yield response (%) under future atmospheric change scenarios in Orroroo

Roseworthy

Yield changes from -74% to 31% in the climate change window. Yield exhibits a decrease trend in most of this window except in the lower right hand corner of this window where rainfall increase is more and temperature increase less. Maximum yield response was achieved (4755kg/ha, an increase of 31%) at 21% rainfall and 1.1°C temperature while the lowest yield response (944kg/ha, a decrease of 74%) occurred at -23% rainfall and crossing the whole temperature change range. There is a 50% probability that the yield response will be in the range of about -61% ~ +5% (1416kg/ha~3811kg/ha) with the most likely yield response -40% ~ -8% (2178kg/ha~3339 kg/ha).

Yield response range within the window of rainfall and pCO_2 is the same as in the climate change window. Maximum yield response was achieved (31%) at rainfall 18% and 109% pCO_2 while the lowest yield response (-74%) occurred at -22% rainfall and crossing the whole pCO_2 change range. There is a 50% probability that the yield response will be in the range of about -61% ~ -2% (1416kg/ha~3557kg/ha) with the most likely yield response -42% ~ -9% (2105kg/ha~3303kg/ha). Rainfall is the controlling factor in yield response in the above two windows.

Yield shows a decrease (22% ~ 74%) trend in the window between temperature and pCO_2. Least yield decrease (2831kg/ha, a 22% reduction) occurred at 82% pCO_2 and 1.5°C temperature while the lowest yield response (944kg/ha, a reduction of 74%) occurred at 3.8°C temperature and 115% pCO_2. There is a 50% probability that the yield response will be in the range of about -42% ~ -20% (2105kg/ha~2904kg/ha) with the most likely yield response -39% ~ -23% (2214kg/ha~2795kg/ha).

The most likely yield change comprising three atmospheric change planes will be in the range of -41% ~ -23%.

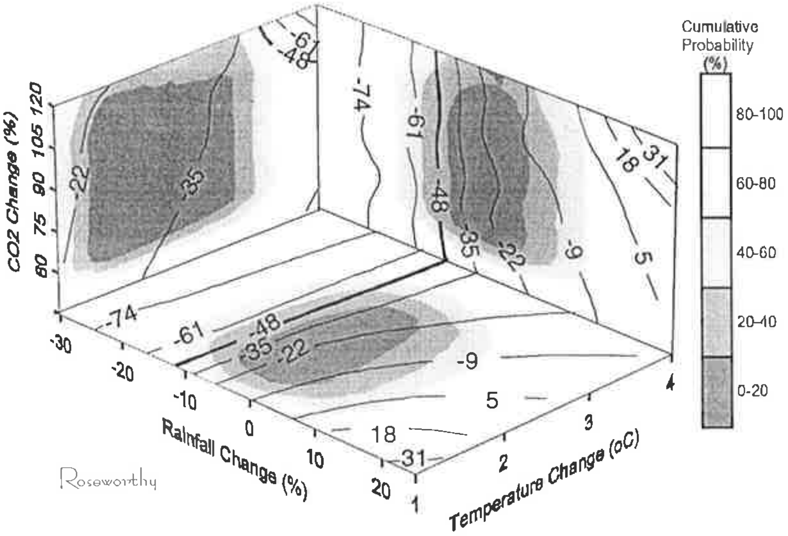


Figure 7.13 Median yield response (%) under future atmospheric change scenarios in Roseworthy

Wanbi

Yield changes from -59% to 59% in the climate change window. Maximum yield response was achieved (59%) at 18% rainfall and 1.5°C temperature while the lowest yield response (-59%) occurred at -29% rainfall and the whole temperature change range. There is a 50% probability that the yield response will be in the range of about -55% ~ +15% with the most likely yield response -49% ~ -7%.

Yield response in the plane of rainfall and pCO_2 shares the same change range (-59% ~ 59%) as in the climate change window. Maximum yield response was achieved (59%) at 17% rainfall and 108% pCO_2 while the lowest yield response (-59%) occurred at -28% rainfall and the whole pCO_2 change range. There is a 50% probability that the yield response will be in the range of about -56% ~ +12% with the most likely yield response -48% to -15%.

Yield exhibits decrease trend (-59% to -15%) in the window of temperature and pCO_2 change. Least yield decrease occurred (-15%) at 2.3°C temperature and the whole pCO_2 change range while the lowest yield response (-59%) occurred at 3.9°C temperature and 117% pCO_2. There is a 50% probability that the yield response will be in the range of about -44% ~ -5% with the most likely yield response -33% ~ -8%.

The most likely yield change comprising three atmospheric change planes will be in the range of -34% ~ -7%.

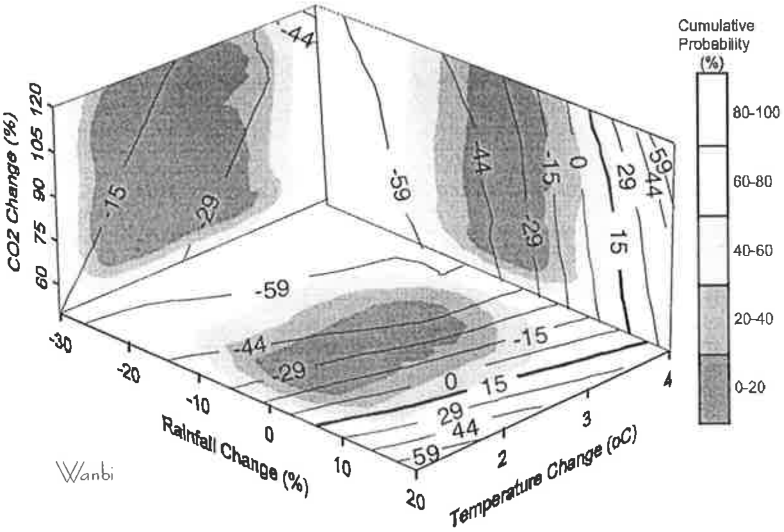


Figure 7.14 Median yield response (%) under future atmospheric change scenarios in Wanbi

Summary

The yield change range or change trend in the bottom panel and the top panel are quite similar. Rainfall dominated yield response in these two windows in the lower rainfall areas. Yield response in medium rainfall area is the result of interactive effects between rainfall and temperature and between pCO_2 and rainfall. Yield was dominated by temperature in the climate change window and by pCO_2 in the window between rainfall and pCO_2 at the higher rainfall site, such as at Naracoorte.

Yield mainly presents a decrease trend in the window between temperature and pCO_2 composed of temperature and pCO_2 change, because this plane is projected at the maximum rainfall decrease. Temperature and pCO_2 interactively exerted effects on grain yield response crossing all localities.

Yield is positively correlated with rainfall change and pCO_2 change, and negatively correlated with temperature change across all locations. This conclusion can be demonstrated by Figure 7.15a, b, c, which show the relationship of grain yield to rainfall, grain yield to atmospheric pCO_2 and grain yield to temperature respectively. This finding is in line with the conclusions of previous studies in which temperature increase is likely to decrease wheat yields through speeding the processes of wheat growth and development, especially during the grain filling period (Mckeon et al., 1988; Aggarwal and Sinha, 1993; Bayasgalan et al., 1996; Pilifosova et al., 1996). The direct effects of CO_2 may compensate for the reduced yields to some extent through the stimulation of photosynthesis and through improved water use efficiency. Therefore, yield decreases most in the upper left hand corner of the climate change window, in the lower left hand corner of the rainfall and pCO_2 change window and in the lower right hand corner of the temperature and pCO_2 change window. Yield decreases least or even shows some increases opposite to the above mentioned positions.

Overall, there are significant changes to median grain yield in each location due to environment change. Yield change range is from to -74% to +116% with the most likely yield decreases (-41% ~ 0%) (Table 7.2) across all locations. The most likely yield change (-41% ~ 0%) indicates that adverse effects from future environment change were projected for wheat production in South Australia implicating adaptation strategies should be taken to cope with the adverse effects resulting from atmospheric changes to maintain the sustainable development of wheat production in this state.

Table 7.2 The most likely median yield change

Locations	Yield Change (%)
Cummins	-33 ~ -7
Keith	-38 ~ -14
Lameroo	-31 ~ -1
Minnipa	-35 ~ -5
Naracoorte	-26 ~ -1
Orroroo	-33 ~ 0
Roseworthy	-41 ~ -23
Wanbi	-34 ~ -7

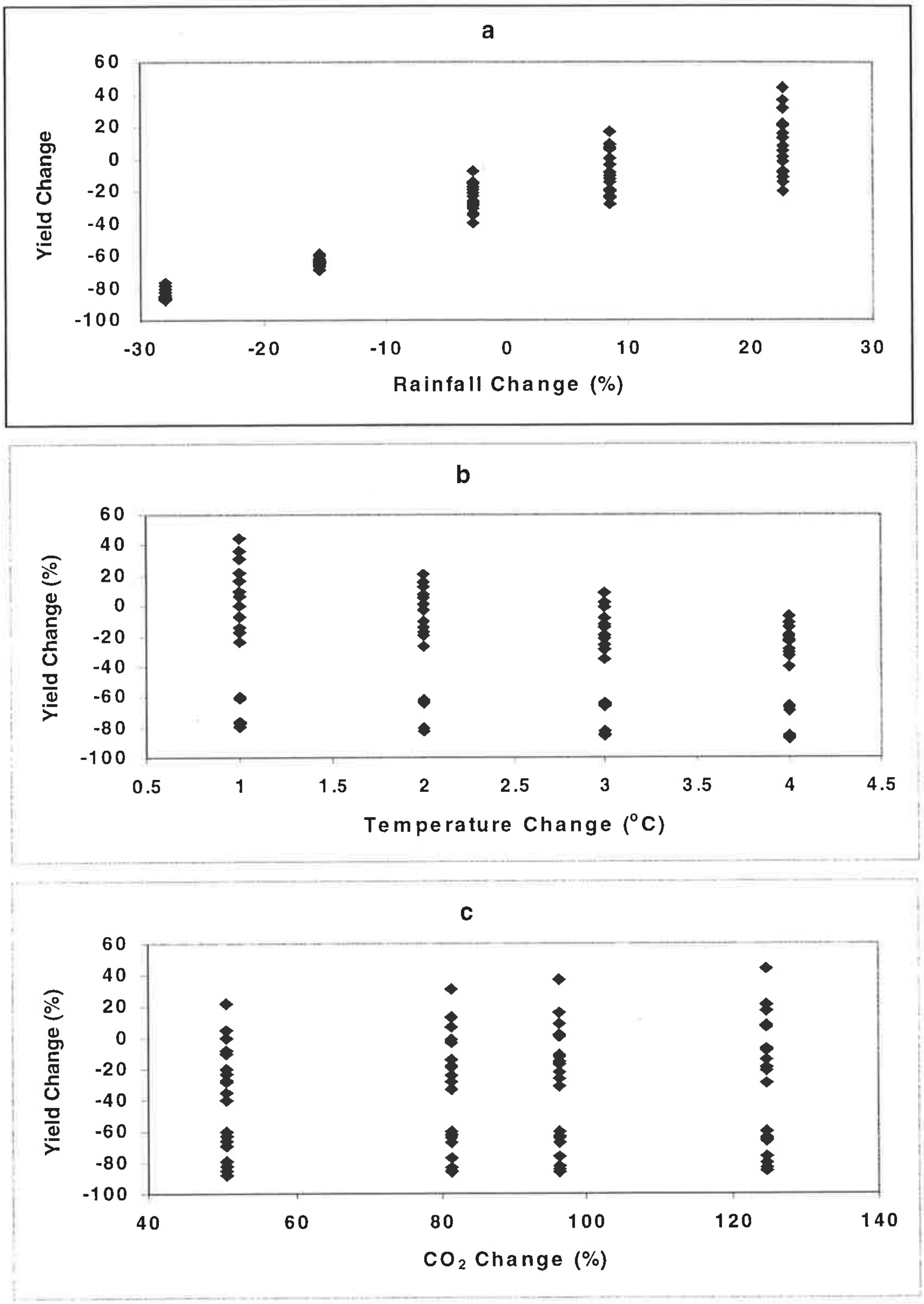


Figure 7.15 Relationship between grain yield and environmental factors: a) relationship between grain yield and rainfall; b) relationship between grain yield and temperature; c) relationship between grain yield and pCO_2. Each point is for each simulation run.

Grain Nitrogen Content (GNC) Response

The same procedures as the construction of yield response surface apply to the construction of GNC response surface.

Cummins

GNC changes from -6% to 8% under the climate change window. GNC exhibits an increase trend in the climate change window when temperature increase is greater than 2°C. GNC shows a decrease trend in the lower part of this window. Temperature played an important role in GNC response in the climate change window. There is a 50% probability that GNC response will be in the range of about -3% ~ +7% with the most likely response +4% ~ +7%.

GNC presents an increase trend in most parts of the window between rainfall and pCO_2. GNC decreases in the upper right hand corner of this window due to the higher increase of rainfall and pCO_2. In this plane, pCO_2 is the main control factor to the response of GNC. There is a 50% probability that GNC response will be in the range of about -1% to +6% with the most likely response about +1% ~ +6%.

The same range of GNC change (-6% ~ 8%) as in the climate change window was found in the window between temperature and pCO_2. The change pattern of GNC in this window is the result of the interaction between temperature and pCO_2. There is a 50% probability that GNC response will be in the range of -5% ~ +6% with the most likely response -3% ~ +5%.

The most likely GNC change comprising the three environmental planes will be in the range of -3% ~ 5%.

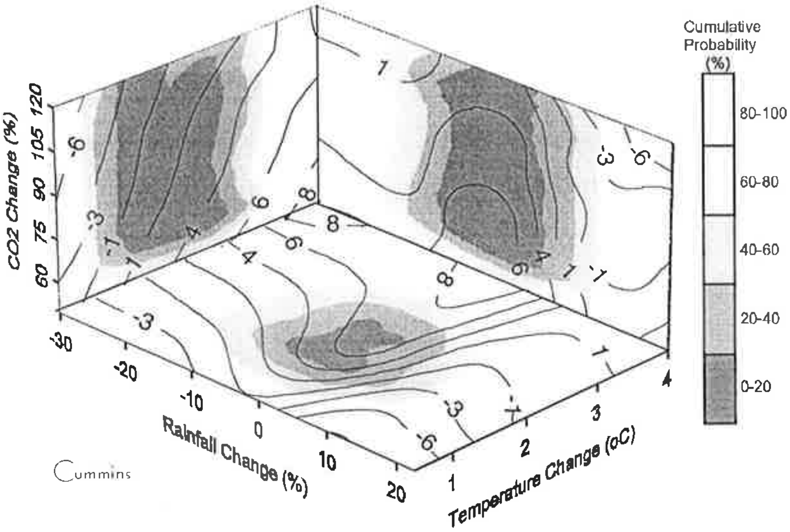


Figure 7.16 Median grain nitrogen content response (%) under future atmospheric change scenarios in Cummins

Keith

GNC mainly presents an increase trend in the climate change window except in the lower right hand corner of this window where temperature increases less and rainfall increases. Temperature played a greater part in GNC response. There is a 50% probability that GNC response will be in the range of about -1% ~ +15% with the most likely response about +2% ~ +14%.

GNC changes from -7% to 15% in the window between rainfall and pCO_2. GNC increase takes up the most part of this window with the exception of the upper right hand corner where rainfall and pCO_2 increase more. There is an obvious impact of pCO_2 on the response of GNC. There is a 50% probability that GNC response will be in the range of about +1% ~ +12% with the most likely response +7% ~ +12%.

GNC changes from –4% ~ +18% in the window between temperature and pCO_2. GNC increase occupies a large part of this window except in the upper left hand corner where pCO_2 increase is more and temperature increase is less. The response of GNC in this window is the result of the interactive effects between temperature and pCO_2. There is a 50% probability that GNC response will be in the range of about -4% ~ +16% with the most likely response -1% ~ +15%.

The most likely GNC change comprising the three environmental planes will be in the range of -1% ~ 16%.

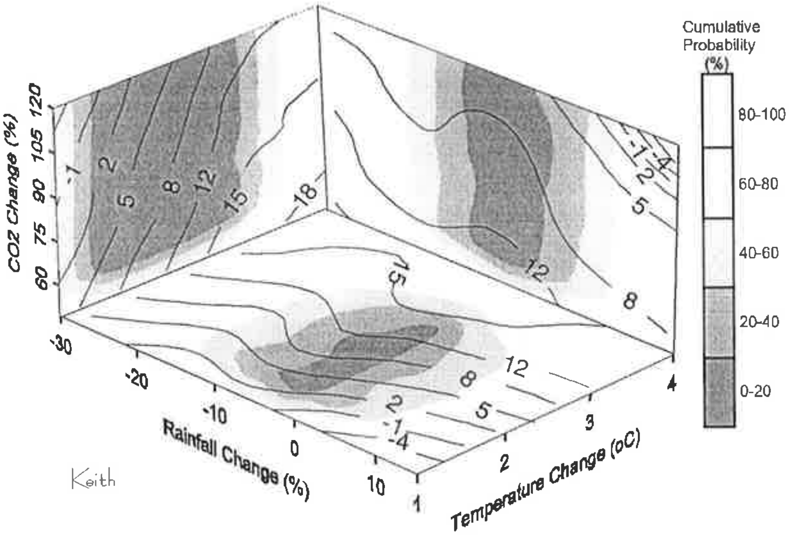


Figure 7.17 Median grain nitrogen content response (%) under future atmospheric change scenarios in Keith

Lameroo

GNC changes from -4% to 4% in the climate change window. Temperature played an important role in GNC change. It is positively correlated with GNC. GNC change shows an increase trend when temperature increase is greater than 3.25°C. There is a 50% probability that GNC response will be in the range of about -3% ~ +2% with the most likely response -3% ~ 0%.

There is a negative correlation between GNC and pCO_2. GNC change presents an increase tendency in the lower left hand part of the window between rainfall and pCO_2. Otherwise GNC increases. This change pattern is the result of the interactive effect of rainfall and pCO_2. There is a 50% probability that GNC response will be in the range of about -3% ~ +3% with the most likely response -1% ~ +1%.

GNC change exhibits an increase trend in the lower right hand part of the window between temperature and pCO_2. GNC decreases in the rest of this plane. Temperature and pCO_2 interactively exerted effects on GNC change. There is a 50% probability that GNC response will be in the range of -4% ~ +4% with the most likely response -2% ~ +1%.

The most likely GNC change comprising the three environmental planes will be in the range of -3% ~ 3%.

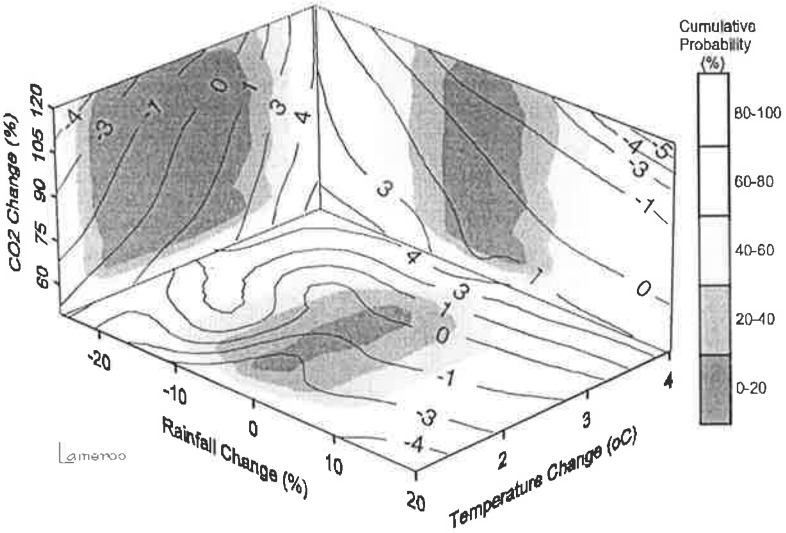


Figure 7.18 Median grain nitrogen content response (%) under future atmospheric change scenarios in Lameroo

Minnipa

GNC changes from -8% to 2% in the climate change window. GNC decrease takes up most of this plane. There is a 50% probability that GNC response will be in the range of about -7% ~ +1% with the most likely response-7% ~ -1%.

GNC change exhibits a decrease trend in the upper right hand part of the window between rainfall and pCO_2 due to the higher increase of rainfall and pCO_2. There is a 50% probability that GNC response will be in the range of -6% ~ +1% with the most likely response -5% ~ 0%.

GNC change presents a decrease trend in the upper left hand part of the window between temperature and pCO_2 due to a higher increase of pCO_2 and lower temperature increase. There is a 50% probability that GNC response will be in the range of about -7% ~ +2% with the most likely response -7% ~ +1%.

The responses of GNC in these three windows are the synergistic effects of temperature, rainfall and pCO_2. The most likely GNC change comprising the three environmental planes will be in the range of -6% ~ 1%.

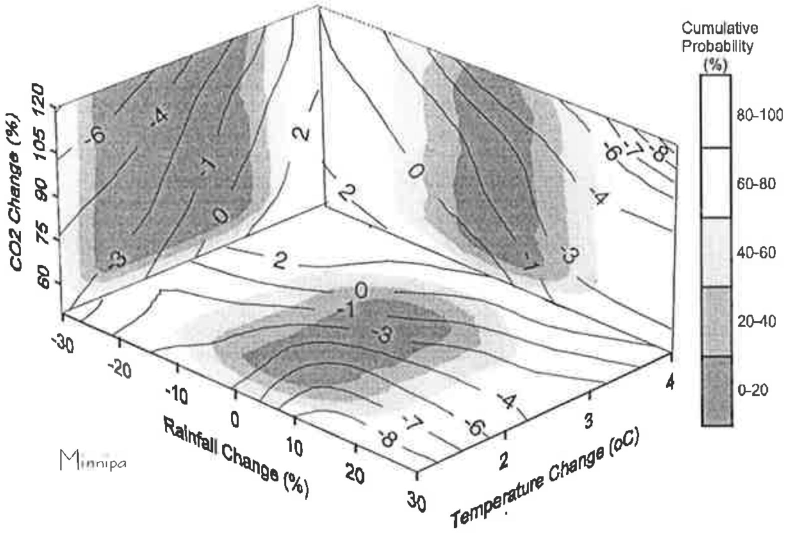


Figure 7.19 Median grain nitrogen content response (%) under future atmospheric change scenarios in Minnipa

Naracoorte

GNC changes from -5% to 4% in the climate change window. GNC shows an increase tendency in the upper part of this window due to the higher increase of temperature. Temperature plays an important role in GNC response. There is a 50% probability that GNC response will be in the range of about -4% ~ +4% with the most likely response about -3% ~ +4%.

GNC changes from -4% to 4% in the window between rainfall and pCO_2. An increase of GNC occurred in most parts of this window. PCO_2 exerted a significant effect on GNC response. There is a 50% probability that GNC response will be in the range of about -2% ~ +3% with the most likely response 0% ~ +3%.

GNC presents an increase trend in the right hand part of the window between temperature and pCO_2. Otherwise, GNC decreases. This response is the result of the interactive effects of pCO_2 and temperature. There is a 50% probability that GNC response will be in the range of -4% ~ +5% with the most likely response about -2% ~ +4%.

The most likely GNC change comprising the three environmental planes will be in the range of -1% ~ 4%.

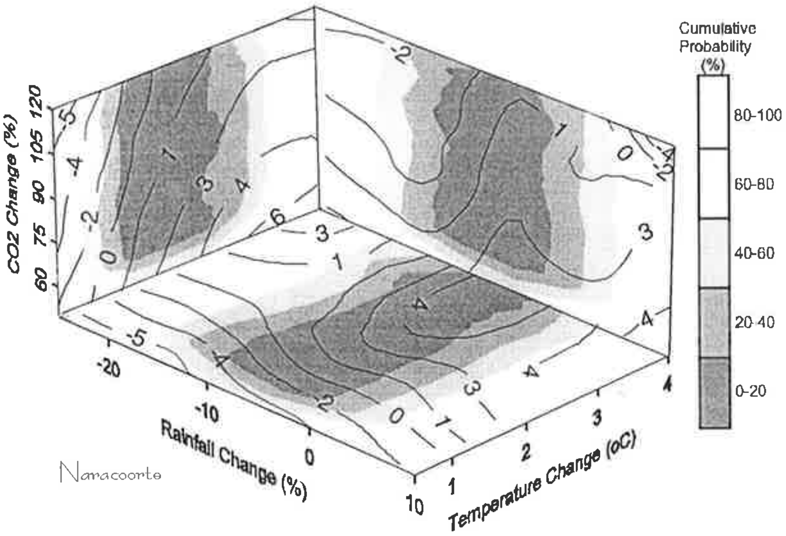


Figure 7.20 Median grain nitrogen content response (%) under future atmospheric change scenarios in Naracoorte

Orroroo

GNC changes from -17% to 11% in the climate change window. GNC decreases in the right hand part of this window. Conversely, GNC increases in the rest of this window. There is a 50% probability that GNC response will be in the range of about -7% ~ +9% with the most likely response about -3% ~ +9%.

A relative larger change range of GNC (-21%~11%) was found in the window of rainfall and pCO_2. GNC decreases in the right hand part of this plane due to a higher increase of rainfall and pCO_2. There is a 50% probability that GNC response will be in the range of -11% ~ +9% with the most likely response around -2% ~ +8%.

GNC decreases in the upper left hand part of this window between temperature and pCO_2 where a higher increase of pCO_2 and lower increase of temperature occurred. There is a 50% probability that GNC response will be in the range of about -7% ~ +8% with the most likely response -6% ~ +7%.

Rainfall, temperature and pCO_2 made nearly the same amount of contribution to the GNC response in Orroroo. The most likely GNC change comprising the three environmental planes will be in the range of -7% ~ 8%.

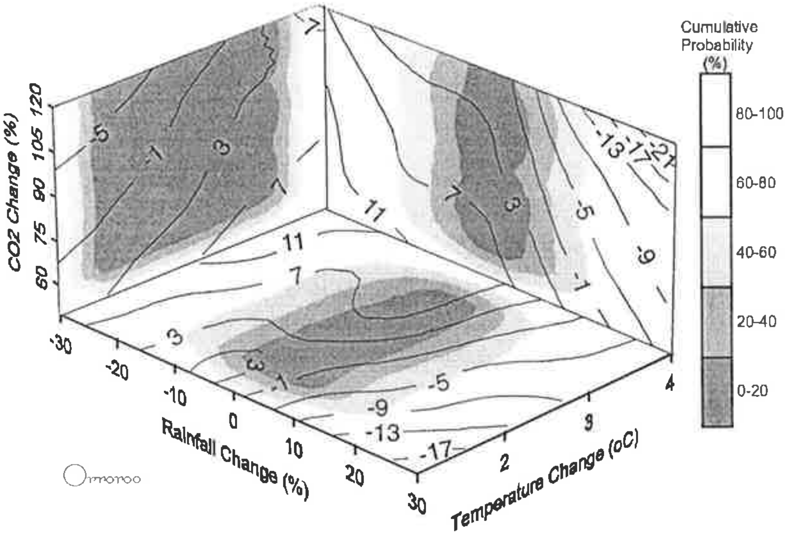


Figure 7.21 Median grain nitrogen content response (%) under future atmospheric change scenarios in Orroroo

Roseworthy

GNC changes from -3% to 9% in the climate change window. GNC increases in the upper part of this window due to the higher temperature increase. There is a 50% probability that GNC will be in the range of about 2.2% ~ 2.43%, a change of GNC of -3% ~ +7% with the most likely GNC around 2.2% ~ 2.31%, a change of GNC of -3% ~ +2%.

GNC increases or decreases in the window between rainfall and pCO_2 depending on the combination of rainfall and pCO_2. Decrease of GNC occurred in the upper right hand corner of this window where rainfall and pCO_2 increase more. There is a 50% probability that GNC change will be in the range of about -3% ~ +7% with the most likely GNC change -3% ~ +3%.

GNC changes from -5% to 7% in the window between temperature and pCO_2. GNC decreases in the upper left hand corner of this plane where the pCO_2 increase is more and the temperature increase is less. GNC increases in the rest of this window. There is a 50% probability that GNC will be in the range of about 2.18% ~ 2.4%, a change of GNC of -4% ~ +6% with the most likely GNC about 2.2% ~ 2.36%, a change of GNC of -3 % ~ +4%.

The most likely GNC change comprising the three environmental planes will be in the range of -3% ~ 5%.

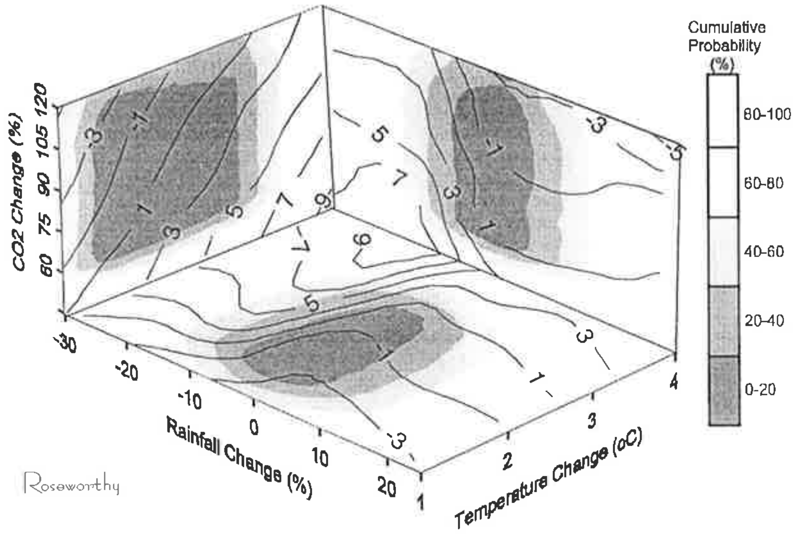


Figure 7.22 Median grain nitrogen content response (%) under future atmospheric change scenarios in Roseworthy

Wanbi

GNC shows a decrease trend under the three atmospheric change windows. The most likely GNC change comprising the three environmental planes will be in the range of -5% ~ 0%.

GNC changes from -10% to 0% in the climate change window. There is a 50% probability that GNC response will be in the range of about -4% ~ 0% with the most likely response -2% ~ 0%.

GNC change ranges from -12% to 0% in the window between rainfall and pCO_2. There is a 50% probability that GNC response will be in the range of about -4% ~ 0% with the most likely response -1% to 0%.

GNC changes from -5% to 0% in the window between temperature and pCO_2. There is a 50% probability that GNC response will be in the range of about -4% ~ 0% with the most likely response -4% ~ -1%.

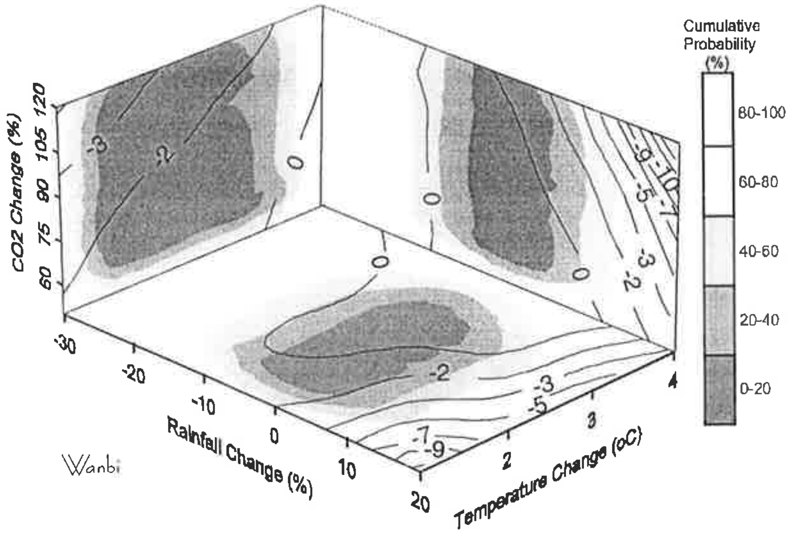


Figure 7.23 Median grain nitrogen content response (%) under future atmospheric change scenarios in Wanbi

Summary

Atmospheric change has direct and indirect effects on grain nitrogen change. The direct effect of atmospheric change on GNC is through the change of soil nitrogen mineralisation rates due to enhanced temperature and through the change of soil C: N ratio due to increased atmospheric pCO_2. But the direct effect is very small in this study as nitrogen supply was set to non-limiting to allow for environmental (climatic) change study and that soil initial nitrogen and residue were reset at early for each simulation run. The indirect effect of atmospheric change on GNC is through the change of grain yield, also known as the dilution effect, which exerted a major effect on GNC. With similar plant N uptake level, when grain yield increase in a certain year, GNC has to decline proportionally in that year. GNC has an inverse relationship with grain yield (Figure 7.24).

Grain nitrogen content is dominated by temperature in the climate change window and by pCO_2 in the window between rainfall and pCO_2 in medium to higher rainfall areas. GNC is insensitive to rainfall in this condition. However, rainfall and temperature, rainfall and pCO_2 interactively have an effect on GNC in the climate change window and in the window between rainfall and pCO_2, respectively, in drier conditions. GNC response in the window between temperature and pCO_2 is the result of the interactive effect of temperature and pCO_2 crossing all localities.

GNC change increase is greatest or the decrease is least in the upper left hand corner of the climate change window, in the lower left hand corner of rainfall and pCO_2 change window, and in the lower right hand corner of temperature and pCO_2 change window. GNC decrease is greatest opposite to the above position mentioned.

GNC change range is much smaller (-21%~+18%) than yield change range under the three atmospheric change windows across all locations indicating GNC is less sensitive to atmospheric change. The most likely GNC change range for each location is summarised in Table 7.3. The most likely GNC change across all locations is the range of -7% ~ 16% with Keith and Naracoorte showing mainly an increase, Minnipa and Wanbi mainly a decrease, and other locations in the intermediate values. The greatest decrease of most likely GNC (7%) will not downgrade grain quality very much. This is the reason why the critical threshold discussed in section 5.2 has not incorporated GNC change information.

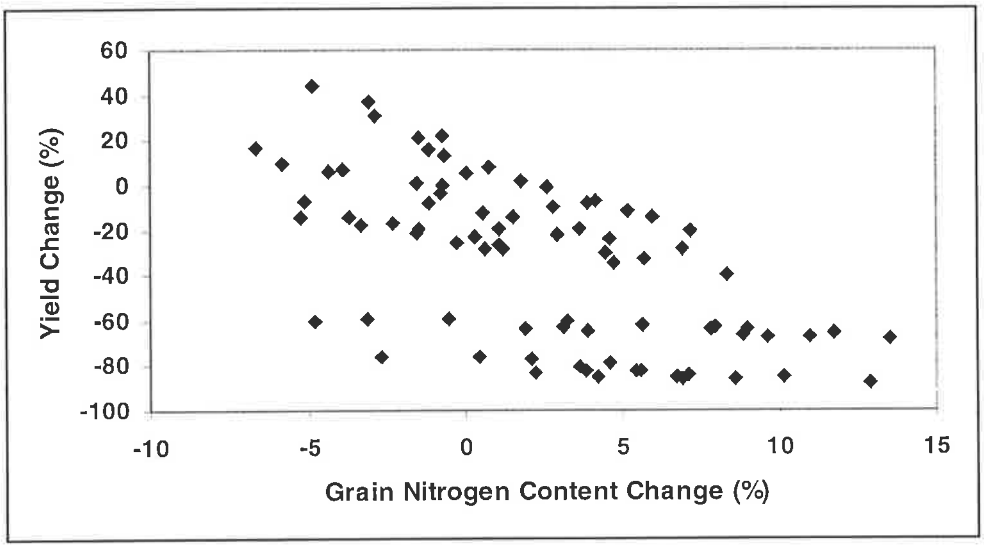


Figure 7.24 Reverse relationship of grain nitrogen content to grain yield. Each point is for each simulation run.

Table 7.3 The most likely change (%) in median grain nitrogen content

Locations	Grain Nitrogen Content Change (%)
Cummins	-3 ~ 5
Keith	-1 ~ 16
Lameroo	-3 ~ 3
Minnipa	-6 ~ 1
Naracoorte	-1 ~ 4
Orroroo	-7 ~ 8
Roseworthy	-3 ~ 5
Wanbi	-5 ~ 0

7.1.3 The Spatial Study

For the spatial study, a different presenting tool was employed-GIS. Grain yield/GNC response were presented in map format, from which information on grain yield/GNC change range across this region, the distribution of median grain yield/GCN change and the impact extent of grain yield/GCN in a certain area to future atmospheric change can be obtained. As indicated in Chapter 6, three atmospheric change scenarios were used in spatial study. They are worst case (rainfall decrease most, temperature increase most, and CO_2 increase least), the most probable case (the most likely atmospheric change scenarios) and the best case (rainfall increase most, temperature increase least, and CO_2 increase most). For details of these scenarios, please refer to Table 6.8b. Change percentage in median grain yield and grain nitrogen content under these three scenarios for each combination of soil and climate are shown in Figure 7.25 and 7.26 respectively. The spatial study attempted to look at the effect of soil variability on median grain yield and median grain nitrogen content under these three scenarios.

Grain Yield Response

Median grain yield is severely affected (Figure 7.25) in the worst case. Grain yield dramatically decreased ranging from -100% to -42% across this region. Of this range, -80% to -70% of grain yield change occurred in most of the study area. Median yield change (-50% to -40%) takes up the second largest portion of this study area mainly distributed in the low rainfall area. Yield decreases most in the higher rainfall region, in most of the low rainfall area and in part of the medium rainfall area. Yield decreases least in the other part of the drier areas. The reason for the lesser impact on grain yield in part of the drier area may be due to the good soil conditions.

Median grain yield still decreases under the most likely atmospheric change scenarios ranging from -58% to -3% across the study area (Figure 7.25). However, the decrease is much smaller than under the worst case due to the amelioration of environment (rainfall decrease less, temperature increase less and pCO_2 increase more). Decrease of grain yield (- 40% to -10%) occurred in most parts of this area. Yield decreases most (-40% to -30%) in most higher rainfall areas and only a small part of the medium and low rainfall areas. Yield decreases least (-20% to -10%) in most parts of the drier areas.

Unlike under the worst case and most probable case, median grain yield increased (Figure 7.25) under the best case due to the increase of rainfall and pCO_2 and decreased temperature. Yield increases from 5% to 124% across this region. An increase of 44-64% takes up most of this area. An increase of 4-24% takes up the second largest area. The area close to Gulf St Vincent benefits the most (median yield increases from 84% to 104%). The higher rainfall area and parts of the low rainfall area benefit less (median yield increases 4% to 24%). This is because current wheat production in the higher rainfall area (495mm annual rainfall) is close to its maximum productive potential. This is in line with the finding in the site-specific study. Further rainfall increase has not much effect on wheat yield in this area. The reason for the lower enhancement of grain yield in part of the low rainfall areas to further rainfall increase may be due to the good soil conditions (higher plant available water capacity). The wheat crop can not take full advantage of the ameliorated rainfall conditions.

Wheat yield was adversely affected under the worst atmospheric change scenario and the most likely atmospheric change scenario with the higher rainfall area influenced most. This indicates that the higher rainfall area will face a big adjustment while the low rainfall area will face a small adjustment. Spatial variability existed in grain yield change across the study area and within the climate divisions. This demonstrated that it is necessary to include soil variability in impact assessment. There are abrupt changes in the response of wheat to climate change at the boundaries between the three climate divisions due to their heterogeneous climate patterns. Median yield responses for each division under the three atmospheric change scenarios are summarised in Table 7.4.

Table 7.4 Distribution of median change in grain yield (%)

Area	Worst Case	Most likely Case	Best Case
Medium Rainfall Area	-80 ~ -70* -60 ~ -50* -70 ~ -60	-30 ~ -20* -20 ~ -10	84 ~ 104* 24 ~ 44
Higher Rainfall Area	-80 ~ -70* -70 ~ -40	-40 ~ -30* -30 ~ 0	4 ~ 24* 24 ~ 64
Low Rainfall Area	-80 ~ -70* -50 ~ -40* -90 ~ -80	-30 ~ -10*	44 ~ 64* 4 ~ 24*

“*” indicates that yield change range takes up a big portion of that area

Grain Nitrogen Content Response

Under the worst case, grain nitrogen content mainly increases, although GNC decreases in some parts of this area (Figure 7.26). The GNC change range in this region is quite wide, from -18% to 42%, depending on location. GNC change mainly occurred in the range of 6-18% increase. GNC increases are greatest in a small part of the higher rainfall areas. Small variation occurred in part of the low rainfall area and in a small part of the medium rainfall area.

GNC mainly presents a decrease trend in this study area under the most likely atmospheric change scenario, although GNC increases slightly in the higher rainfall area (Figure 7.26). GNC changes from -14% to 14%. A GNC change of -8% to -2% occupied most of this region, which is mainly distributed in the medium rainfall area and the low rainfall area. Small variation occurred in the area adjacent to Gulf St Vincent and in a small part of the low rainfall area (-2% to 2%). A GNC change of -14% to -8% takes up the second largest area, mainly concentrated in the low rainfall area.

GNC decreases under the best case except for a very small area between the high and medium rainfall areas where GNC increases (Figure 7.26). GNC changes from -25% to +7% across this region. GNC change ranges from -25% to -13% occupied most of this region, especially in the low rainfall area with the greatest decrease of GNC. Small changes (-1% to 1%) in GNC occurred in the higher rainfall area.

GNC increases under the worst case (rainfall decrease most), with 6~18% increase over most of this region. GNC decreases under the most likely atmospheric change scenario and the best atmospheric change scenario except the higher rainfall areas at the most probable case. GNC decreases most in parts of the drier region under these two scenarios. It can been seen that GNC has an inverse relationship with rainfall and with grain yield. GNC decreases with the increase of rainfall and yield. The N-dilution effect between grain yield and GNC found in site-specific study (section 7.1.2) also applies to the spatial study. With similar plant N uptake level, when grain yield increases due to increased rainfall in a certain year, GNC has to decline proportionally in that year. Spatial variability is also found in grain nitrogen content change across this study area even within the climate divisions. This finding confirms the necessity to incorporate soil variability into impact assessment. GNC responses for each division under the three atmospheric change scenarios are summarised in Table 7.5.

Table 7.5 Distribution of median change in grain nitrogen content (%)

Area	Worst Case	Most likely Case	Best Case
Medium Rainfall Area	6 ~ 18* 18 ~ 30 -6 ~ 6	-8 ~ -2* -2 ~ 2*	-13 ~ -7*
Higher Rainfall Area	6 ~ 18* 30 ~ 42	2 ~ 8* 8 ~ 14 -2 ~ 2	-13 ~ -7* -1 ~ 1* -7 ~ -1
Low Rainfall Area	-6 ~ 6* 6 ~ 18* -18 ~ -6 30 ~ 42	-14 ~ -8* -8 ~ -2* -2 ~ 2	-25 ~ -19* -19 ~ -13

"*" indicates that median grain nitrogen content change range takes up a big portion of that area

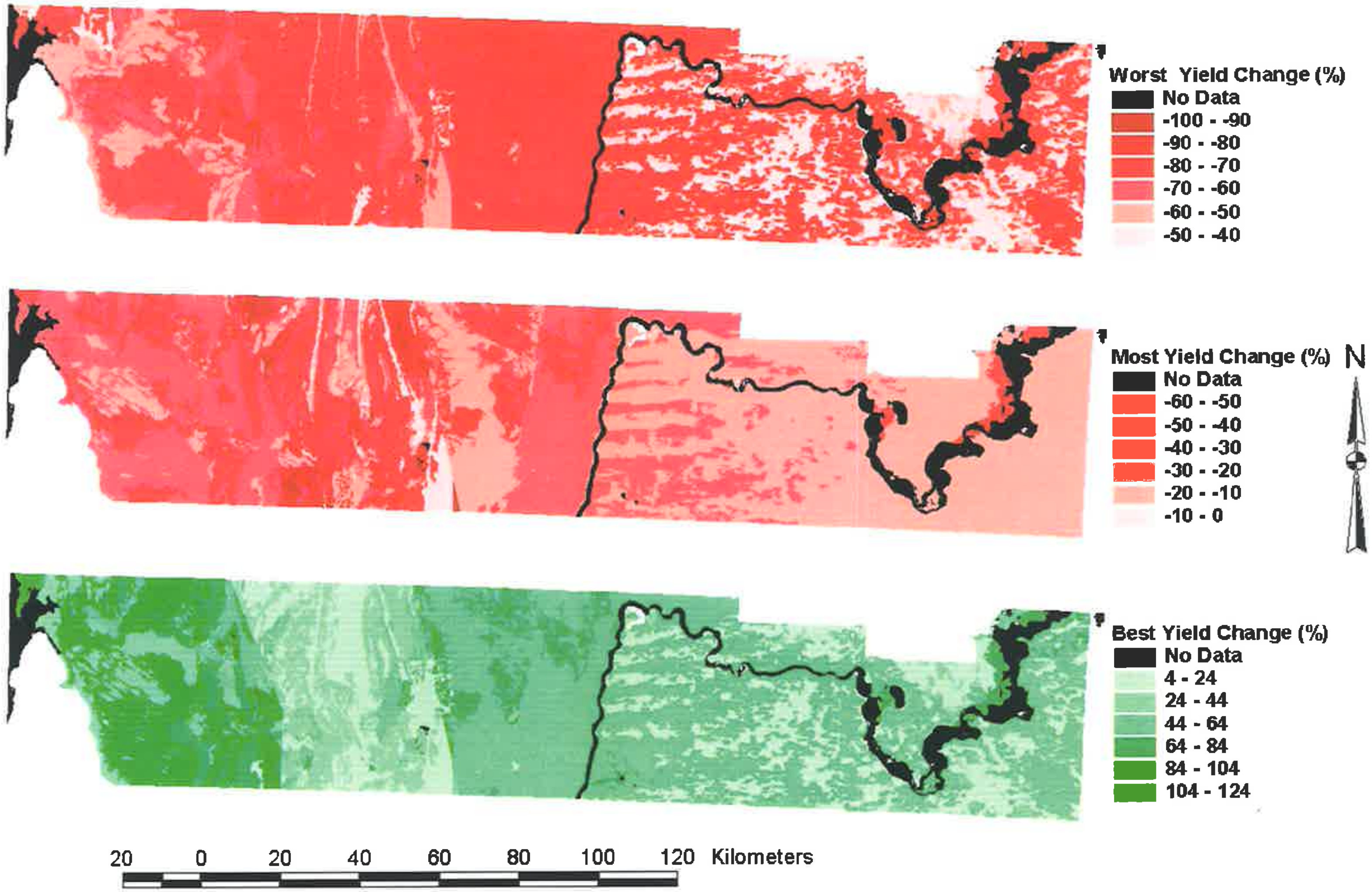


Figure 7.25 Spatial distribution of median change in grain yield under the best case, the most probable change scenario and the worst case

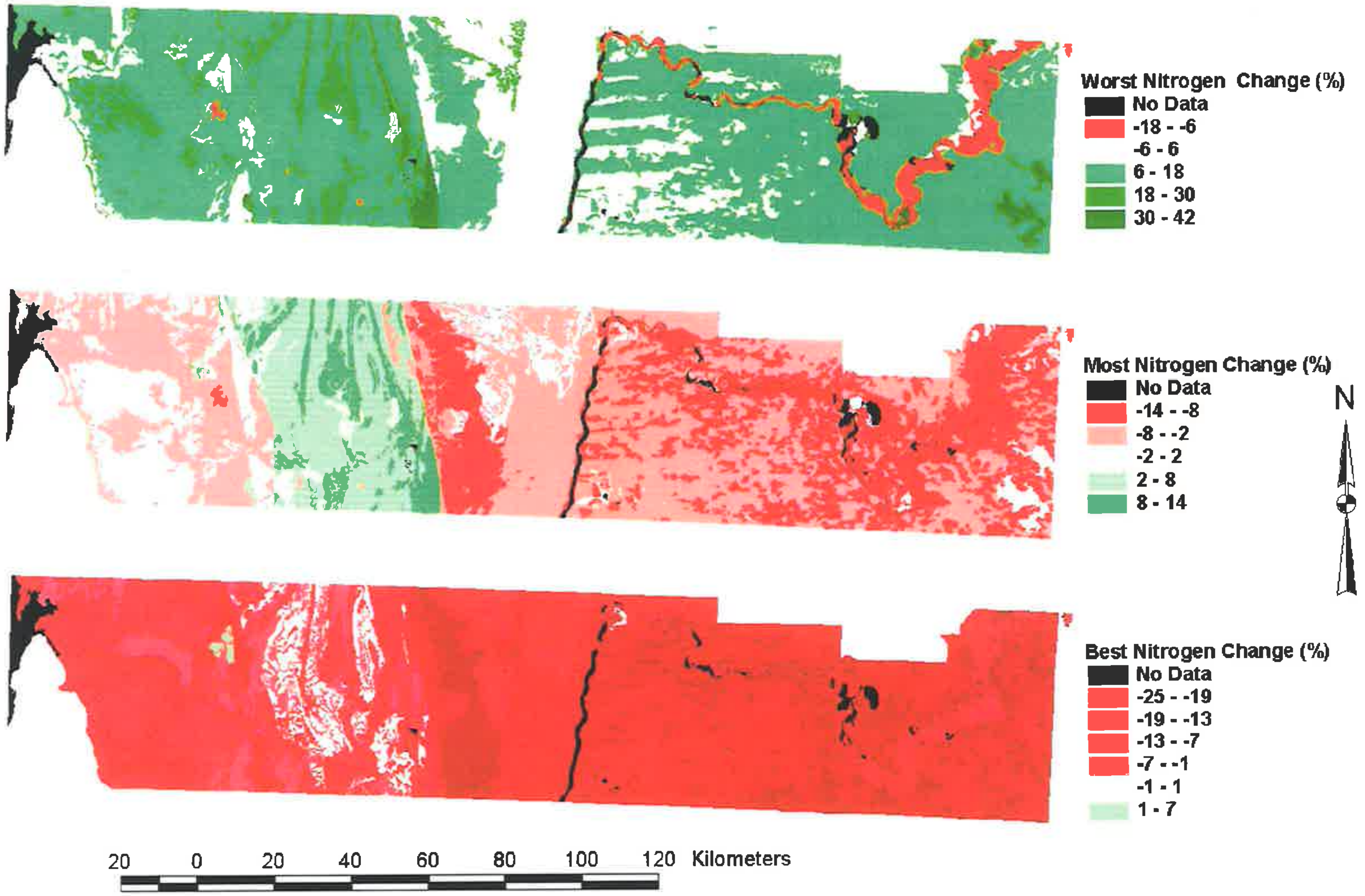


Figure 7.26 Spatial distribution of change in grain nitrogen content under the best case, the most probable change scenario and the worst case

7.2 IMPACT THRESHOLD

7.2.1 Introduction of Impact Threshold

To assess risk, environmental impacts are explored to determine appropriate thresholds. An impact threshold is a generic term for any threshold that can link an ecological or socio-economic impact to environmental state/states (Pittock and Jones, 2003). Impact thresholds can be grouped into two main categories: biophysical thresholds and behavioural thresholds (Jones, 2000b; Jones, 2000c). Biophysical thresholds represent a distinct change in conditions, such as drying of a wetland, floods, breeding events, etc. Behavioural thresholds are set by benchmarking a level of performance, e.g., the yield per unit area of a crop in weight, volume, or gross income (Jones and Pittock, 1997). Behavioural thresholds are often associated with a linear process at the physical scale, where a consequent change in behaviour introduces non-linearity.

Impact thresholds vary widely, contain diverse assumptions, represent many different types of output and exhibit varying degrees of complexity. The simplest thresholds are rules of thumb, where a rough link between environment and a particular outcome has been recognised and is used in practical situations. Thresholds can also be dynamic, and may change over time. Some of these changes may be anticipated by the analysis of autonomous adaptations, especially those linked to socio-economic change (Jones, 2000c).

The identification of thresholds facilitates impact assessment by providing an agreed frame of reference linking different knowledge systems; an agreed point of reference against which to measure future uncertainty; the ability to apply a level of complexity that matches the available knowledge and resources; and an improved focus, by placing the greatest weight on the information most relevant to stakeholders (Jones, 2000c). By addressing outcomes in the initial stages of an impact assessment through the construction of user-defined thresholds, it is possible to identify outcomes that should be avoided, in the case of negative impact, or aimed for, in the case of a positive impact. By quantifying these thresholds as functions of environmental variables, and creating projections for these variables that take account of a comprehensive range of quantifiable uncertainties, the risk of threshold exceedance can be analysed. This information can then be used in a risk assessment to identify windows for adaptation, describing the timing and degree of adaptation needed to prevent 'dangerous' atmospheric change occurring for a particular activity (Jones, 2000b).

7.2.2 Critical Thresholds

Critical thresholds are a special category, being assessed to determine the point at which the risk of an impact becomes 'dangerous' (cf. Parry et al., 1996). Faced with this dangerous impact, farmers cannot adapt. This assessment involves placing values on processes and/or outcomes. The assumptions behind such valuations should ideally be transparent and should be understood by all those affected.

As impacts differ within sectors and regions and vary over time, critical thresholds for different activities and localities will not be reached at the same time or with the same rate of atmospheric change. The concept of what is critical may differ between various groups and may also change over time in response to new information, to adaptive capacity or to changes in social and political perspectives. Environmental scenarios can be used to determine when and where 'dangerous' thresholds are reached in various sectors. This can then be related back to rates of greenhouse gas emissions. By expressing impact thresholds of key climatic variables it is possible to treat many uncertainties associated with projected regional climate change through the analysis of conditional probabilities (Parry et al., 1996; Jones, 2000b).

7.2.3 Determination of Critical Yield Threshold

Yield is a very important economic indicator for the sustainability of crop production. The critical yield threshold for this study was determined under many assumptions and practical situations. According to the annual rainfall of each location received, study sites considered in site-specific study and spatial study were classified into three categories: low rainfall area with annual rainfall < 350mm, medium rainfall area with annual rainfall between 350-420mm and higher rainfall area with annual rainfall > 420mm. The classified areas are listed in Table 7.6. Return (profit) is an economic factor of a certain industry such as the wheat industry. In this case, profit was influenced by many factors such as yield, yield price, variable expenses, interest, allowance for permanent and family labour, allowance for machinery overheads and other overheads, and return on land capital and management. Table 7.6 gives the specific value of some of these factors for each category. The "Constants" is the value shared by all three categories described at the bottom of this table. Based on long-term analysis, the long-term average return on agricultural land in South Australia is close to 3%. Once other values are determined/assumed, in order to obtain the minimum return of 3%, there must be a critical yield corresponding to this return (below which, the wheat industry is not sustainable). Formulas 7.1-7.7 are used to derive critical yield threshold combined with the information provided in Table 7.6. The critical yield threshold can be derived by substituting equations 7.3-7.7 into equation 7.2 and by substituting equation 7.2 into equation 7.1. The calculated critical yield for each category is shown in Table 7.6 (last column). If prevailing economic conditions are different to those assumed in the current study, it is a relatively simple procedure to modify the assumptions.

Table 7.6 Specification of factors involved in critical yield threshold calculation (data source: Cooper, pers. communication)

Locations	Annual Rainfall (mm)	Rainfall Areas	Grain Price ($/ha)	Value of Machinery ($)	Land Value ($/ha)	Critical Yield Threshold (t/ha)
Moorook	258.79	low	170	50,000	300	0.98
Orroroo	341.9					
Wanbi	303.8					
Minnipa	362.2					
Lameroo	388.4	medium	165	75,000	1000	1.45
Owen	420.66	higher	170	100,000	2000	1.87
Kapunda	494.59					
Keith	467.9					
Cummins	430.5					
Naracoorte	578.3					
Roseworthy	440.3					

Constants: Interest Rate: 10%; Labour Hour: 1.2hs/ha; Labour Price: $11/hr; Farm Size: 500ha; Rate of Depreciation on Machinery: 16%; Allowance for Other Overheads: $5,000; Long Term Average Return on Agricultural Land: 3%.

$$\mathbf{LTAR = NM / RLCM = 3\%} \qquad \mathbf{(7.1)}$$

Where
LTAR: long term average return (3%)
NM: net margin
RLCM: return on land capital & management-land value

$$\mathbf{NM = GM - IN - APFL - AMO - AOO} \qquad \mathbf{(7.2)}$$

Where

GM: gross margin
IN: interest
APFL: allowance for permanent and family labor
AMO: allowance for machinery overheads
AOO: allowance for other overheads

$$\mathbf{GM = CY * YP - VE} \tag{7.3}$$

Where
CY: critical yield
YP: yield price
VE: variable expense

$$\mathbf{IN = interest\ rate * VE / 2} \tag{7.4}$$

Where
VE: variable expense

$$\mathbf{APFL = labor\ hour * labor\ price} \tag{7.5}$$

$$\mathbf{AMO = value\ of\ machinery * depreciation\ rate / farm\ size} \tag{7.6}$$

$$\mathbf{AOO = total\ overheads / farm\ size} \tag{7.7}$$

7.2.4 Probability Analysis of Critical Grain Yield Occurrence

Once the critical yield for each category of rainfall is obtained, the relative critical yield change can then be calculated based on median baseline yield for each location of site-specific study. The approximate relative critical yield change represented by a bold line for each location is shown in Figure 7.7-7.14. Table 7.7 compared the critical yield and median baseline yield for each location. The relative difference between these two is listed in the fourth column of this table.

Table 7.7 Difference between critical yield and median baseline yield

Locations	Rainfall Division	Critical Yield (t/ha)	Relative Critical Yield (%)	Median Baseline Yield (t/ha)
Orroroo	low	0.98	-27.20%	1.36
Minnipa			-25.23	1.32
Wanbi			+16.66%	0.85
Lameroo	medium	1.45	-20.34%	1.83
Cummins	high	1.87	-38.78%	3.05
Keith			-54.48%	4.11
Naracoorte			-68.71%	5.98
Roseworthy			-48.48%	3.63

Cummins

The critical yield (1.87 t/ha) is 39% less than the median baseline yield, which is most likely to occur in the climate change window and the window between rainfall and pCO_2. The probability of this occurring is around 40% in the window between temperature and pCO_2 (Figure 7.7).

Keith

The critical yield (1.87 t/ha) is 55% less than the median baseline yield, which is least likely to occur in the climate change window and the window between rainfall and pCO_2. The probability of this occurring is 30% in the window between temperature and pCO_2 (Figure 7.8).

Lameroo

The critical yield (1.45 t/ha) is 20% less than the median baseline yield, which is most likely to occur in the three atmospheric change windows (Figure 7.9).

Minnipa

The critical yield (0.98 t/ha) is 25% less than the median baseline yield, which is most likely to occur in the window composed of temperature and pCO_2. The probability of this occurring is 80% in the climate change window and the window between rainfall and pCO_2 (Figure 7.10).

Naracoorte

The critical yield (1.87 t/ha) is 69% less than the median baseline yield, which will not occur in the atmospheric change windows. This means that there is low risk of not exceeding the critical yield threshold for wheat in Naracoorte.

Orroroo

The critical yield (0.98 t/ha) is 27% less than the median baseline yield, which is most likely to occur in the three atmospheric change windows (Figure 7.12).

Roseworthy

The critical yield (1.87 t/ha) is 49% less than the median baseline yield. The probability of this occurring is 70% in the climate change window and the window between rainfall and pCO_2. The probability of this occurring in the window between temperature and pCO_2 is 40% (Figure 7.13).

Wanbi

The critical yield (0.98 t/ha) is 17% more than the median baseline yield. The probability of this occurring is 50% in climate change window and the window between rainfall and pCO_2. The probability of this occurring in the window between temperature and pCO_2 is zero (Figure 7.14).

In general, the probability for critical yield to occur is higher in the drier environment except in Wanbi where current production practice is below critical yield threshold (critical yield is greater than baseline yield), let alone under atmospheric change. However, the probability of critical yield occurrence in the higher rainfall areas is low, as in Keith and Naracoorte.

7.3 RISK ANALYSIS

Risk is defined here as the conditional probability of not exceeding the critical yield threshold, which is also termed as conditional probability elsewhere in this thesis for conciseness. The reason for using conditional probability rather than probability is that the procedures to produce probabilistic scenarios involve some extra assumptions (section 6.4.1). Higher conditional probability means higher risk of wheat production under that atmospheric change scenario. For example, if the conditional probability is 60% in certain location, which means 6 years in 10 wheat production in that location will be economically non viable.

The probability of not exceeding the critical yield for each location has been calculated under 80 atmospheric change scenarios in the site-specific study and for each combination of soil and climate under 3 cases in the spatial study. Conditional probability is divided into 5 levels for the convenience of quantifying the risk with <20% conditional probability assigned as very low level, 20%~40% as low level, 40%~60% as medium level, 60~80% as high level, >80% as very high level.

7.3.1 Site-Specific Study

Individual Effect of Rainfall, Temperature and pCO_2 on Risks of Wheat Production

As stated in section 7.1.2, Keith and Minnipa were the two sites chosen to study the individual impact of environmental factors on wheat production risk. This section is related to Table 7.1 and Figures 7.3, 7.4 and 7.5. The same atmospheric change scenarios used in section 7.1.2 apply to this section. The critical yields for Keith (1.87t/ha) and Minnipa (0.98 t/ha) were drawn in Figures 7.3, 7.4 and 7.5 as a vertical line. As a result the conditional probability of not exceeding the critical yield can be easily estimated and visualised from these figures for each location under different atmospheric change scenarios.

Rainfall Effect on Risks of Wheat Production

In Keith (Figure 7.3), the conditional probability of not exceeding the critical yield increased under R1 (54%), R2 (42%), and R3 (37%: the most probable conditional probability) compared with the baseline conditional probability 14%. Conditional probability is slightly lower under R4 (13%) and R5 (12%) than baseline conditional probability. Large variation of risk existed among rainfall scenarios except between R4 and R5. The results shown here demonstrate that rainfall decrease will greatly increase wheat production risk. Rainfall increase brings risk back to the baseline situation. It seems that rainfall increase has not much effect on wheat production risk, implying that current rainfall is not a limiting factor in wheat production at this location.

In Minnipa (Figure 7.3), the conditional probability of not exceeding the critical yield increased under R1 (81%), R2 (60%), R3 (53%: the most probable conditional probability) and R4 (45%) compared with the baseline conditional probability 42%. Conditional probability under R5 (30% rainfall increase) is 33%: lower than current risk level. Risk for wheat production is reduced considerably under R5 with around 30% of rainfall increase. This demonstrates that rainfall is a limiting factor in wheat production at Minnipa. This result is quite different from that in Keith. Large variations in risk also existed among rainfall scenarios in Minnipa.

Rainfall has a negative relationship with risks of wheat production and has large effects on wheat production risks in these two locations.

Temperature Effect on Risks of Wheat Production

Figure 7.4 shows the temperature effect on wheat production risk at these two locations. In Keith, the overall conditional probability of not exceeding the critical yield increased from T1 (31%) to T4 (42%) compared with the baseline conditional probability (14%). The same influential pattern of temperature on risks of wheat production has been found in Minnipa. The conditional probability increased from T1 (50%) to T4 (59%) compared with the baseline conditional probability (42%). It can be seen that temperature has a positive relationship with risks of wheat production. However, the difference between temperature change scenarios is not large, indicating that temperature has less effect on risk than does rainfall.

pCO_2 Effect on Risks of Wheat Production

The potential impact of pCO_2 on risks of wheat production in Keith and Minnipa is shown in Figure 7.5. In Keith, the overall conditional probability of not exceeding the critical yield increased from C4 (31%) to C1 (38%) compared with baseline conditional probability (14%). The overall conditional probability for Minnipa increased from C4 (51%) to C1 (57%) compared with baseline conditional probability (42%). The results show that pCO_2 has an inverse relationship with risks of wheat production. The variation between pCO_2 scenarios is not great, implying a lesser effect of pCO_2 on wheat production risks than rainfall.

Large variation among rainfall scenarios existed in these two locations implying a significant effect of rainfall on wheat production risks. An inverse relationship between rainfall and risks in wheat production has been found from this study. Small variation among temperature and pCO_2 scenarios has been found indicating a lesser effect of temperature and pCO_2 on risks of wheat production in these two contrasted sites. A positive relationship between temperature and risk as well as a negative relationship between pCO_2 and risk have been found.

Combined Effect of Environmental Factors on Risks of Wheat Production

The conditional probability of not exceeding the critical yield threshold for the combined effect of environmental factors on risks of wheat production is depicted in a risk response surface, combining the probabilistic atmospheric change scenarios as shown in Figure 7.27-7.34 for the

8 locations. The same procedures for the construction of median yield response surfaces apply to the construction of conditional probability response surfaces.

Cummins

The conditional probability of not exceeding the critical yield (1.87t/ha) under baseline is 34% in Cummins. Conditional probability of 17%~74% occurred in the climate change window and the window between rainfall and pCO_2. Conditional probability of 38%~81% covered the plane between temperature and pCO_2.

Conditional probability of not exceeding the critical yield threshold mainly increased under future atmospheric changes. The most likely conditional probability comprising the three atmospheric change planes is 38%~47% (medium level of risk).

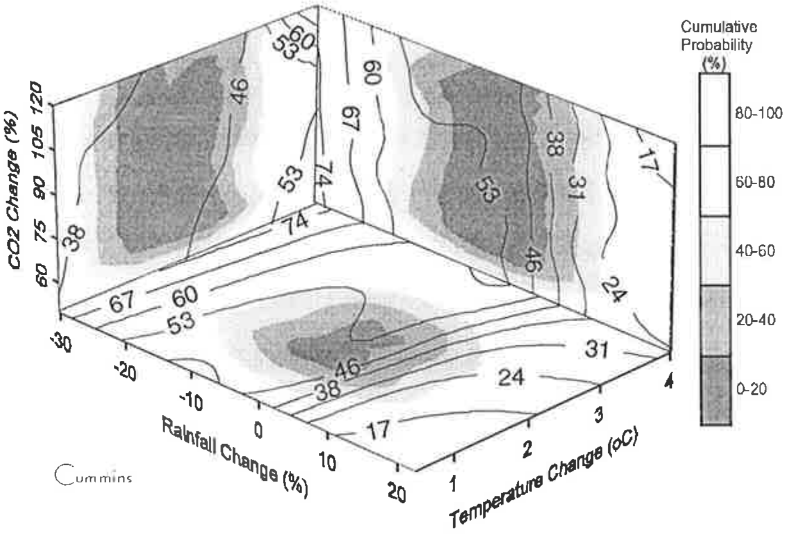


Figure 7.27 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Cummins

Keith

The conditional probability of not exceeding the critical yield (1.87t/ha) under baseline is 14% in Keith. Conditional probability 16%~58% occurred in the climate change window and the window between rainfall and pCO_2. Conditional probability: 32%~58% covered the plane between temperature and pCO_2.

The conditional probability increased under future atmospheric changes compared with the baseline probability. However, the most likely conditional probability comprising the three atmospheric change planes is still low (29% ~ 37%: low level of risk).

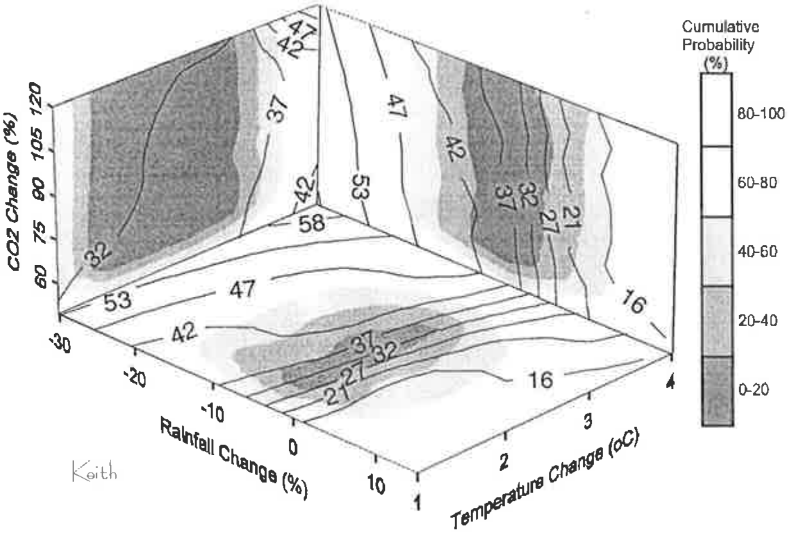


Figure 7.28 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Keith

Lameroo

The conditional probability of not exceeding the critical yield (1.45t/ha) under baseline is 44% in Lameroo. Conditional probabilities of 32%~78%, 32%~72% and 49~72% occurred in the climate change window, the window between rainfall and pCO_2 and the window between temperature and pCO_2 respectively.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. The most likely conditional probability comprising the three atmospheric change planes is 49%~58% (medium level of risk).

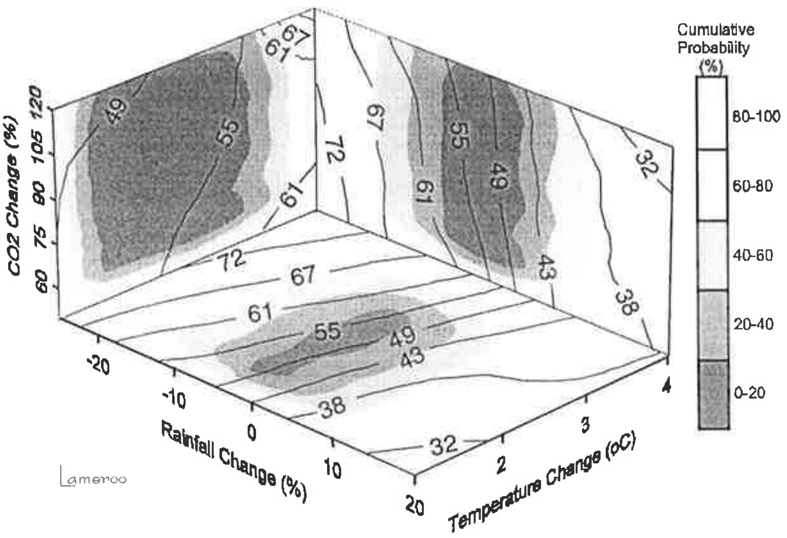


Figure 7.29 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Lameroo

Minnipa

The conditional probability of not exceeding the critical yield (0.98 t/ha) under baseline is 41% in Minnipa. Conditional probability of 31%~83% occurred in the climate change window and the window composed on rainfall and pCO_2. 51%~83% conditional probability covered the window between temperature and pCO_2.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. The most likely conditional probability comprising the three atmospheric change planes is 51%~60% (medium level of risk).

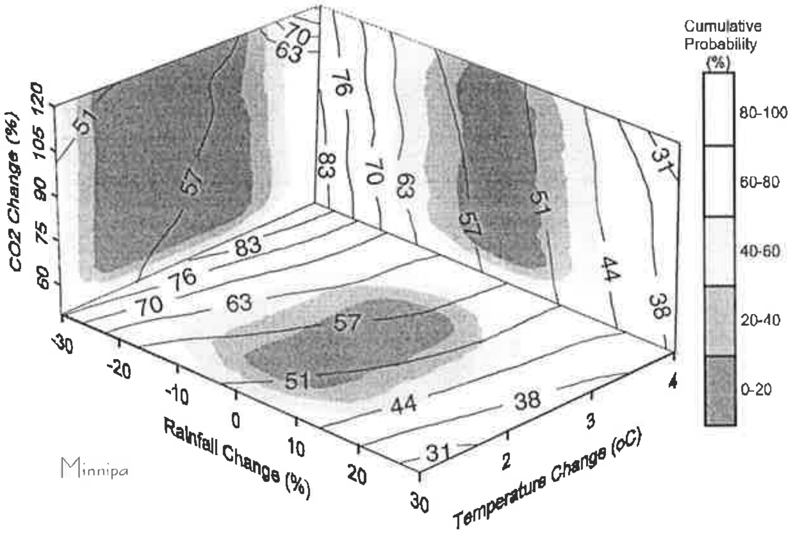


Figure 7.30 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Minnipa

Naracoorte

The conditional probability of not exceeding the critical yield (1.87t/ha) under baseline is 5% in Naracoorte. 4%~25% conditional probability occurred in the climate change window and window between rainfall and pCO_2. 9%~22% conditional probability covered the plane between temperature and pCO_2.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. However, the most likely conditional probability comprising the three atmospheric change planes is still very low: 8%~12% (very low level of risk).

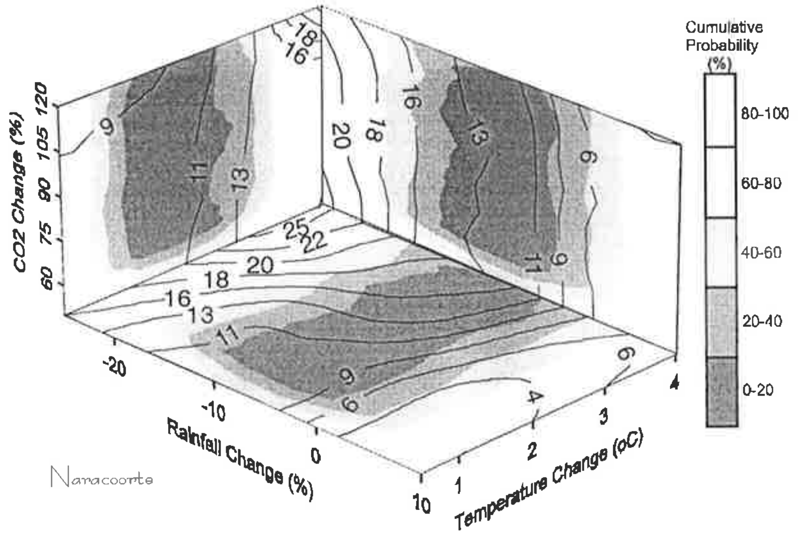


Figure 7.31 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Naracoorte

Orroroo

The conditional probability of not exceeding the critical yield (0.98 t/ha) under baseline is 37% in Orroroo. 30%-74% conditional probability occurred in the climate change window and the window between rainfall and pCO_2. 52%~74% conditional probability covered the window between temperature and pCO_2.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. The most likely conditional probability comprising the three atmospheric change planes is 49%~64% (medium risk level).

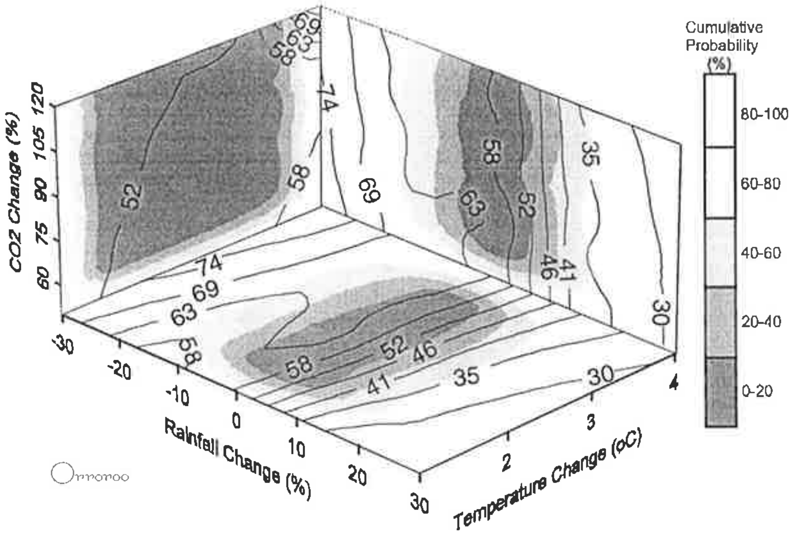


Figure 7.32 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Orroroo

Roseworthy

The conditional probability of not exceeding the critical yield (1.87 t/ha) under baseline is 27% in Roseworthy. 23%~70% conditional probability occurred in the climate change window and the window between rainfall and pCO_2. 46%~70% conditional probability covered the window between temperature and pCO_2.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. The most likely conditional probability comprising the three atmospheric change planes is 43%~48% (medium risk level).

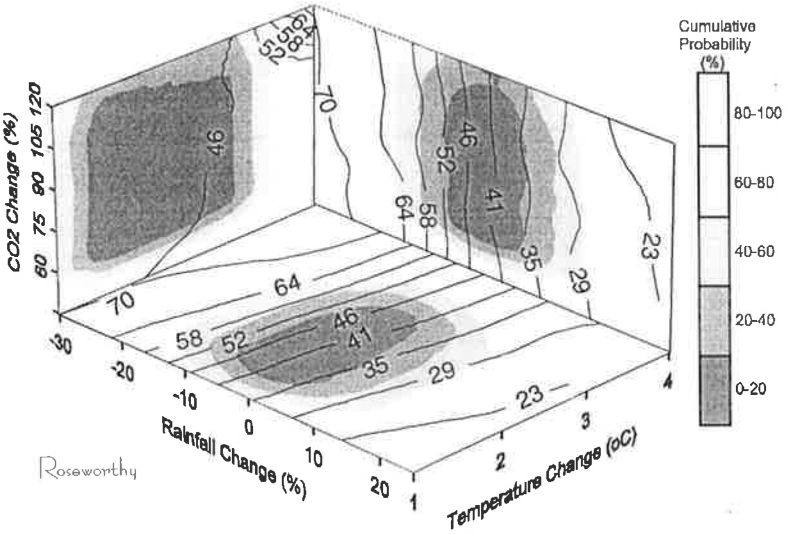


Figure 7.33 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Roseworthy

Wanbi

The conditional probability of not exceeding the critical yield (0.98 t/ha) under baseline is 56% in Wanbi. 44%~88% conditional probability occurred in the climate change window and the window between rainfall and pCO_2. 66%~88% conditional probability covered the window between temperature and pCO_2.

Conditional probability mainly increased under future atmospheric changes compared with baseline probability. The most likely conditional probability comprising the three atmospheric change planes is 64%~74% (high level of risk).

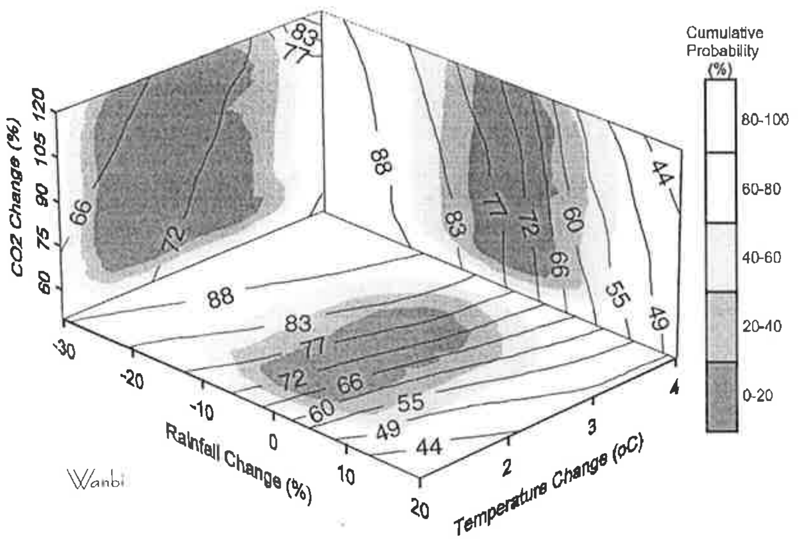


Figure 7.34 Conditional probability of not exceeding the critical yield threshold under future atmospheric change scenarios in Wanbi

Summary

The conditional probability increased under future atmospheric changes compared with the baseline probability. The most risky outcome occurred in the upper left hand corner of the climate change window where rainfall decreases most and temperature increases most. The most risky outcome occurred in the lower left hand corner of the plane between rainfall and pCO_2 where rainfall decreases most and pCO_2 increases least. The most risky outcome occurred in the upper right hand corner of the plane between temperature and pCO_2 where temperature increases most. The least risky outcome occurred in the positions opposite to those mentioned above.

Conditional probabilities under baseline and the most likely atmospheric change scenario were listed in Table 7.8. Several conclusions can be made from this table. There is low risk of not exceeding the critical yield threshold for wheat production in Cummins, Orroroo and Roseworthy under current conditions. Risk enhanced to medium level under the most likely atmospheric change scenarios. Risk maintained the medium level of the current situation under most likely atmospheric change scenario in Lameroo and Minnipa. Very low risk of wheat production in Keith and Naracoorte was found under current condition. Under the most likely atmospheric change scenario, risk was maintained at the same level as in current conditions in Naracoorte, risk was increased but to low levels in Keith. Wheat production in Wanbi is at risk even under baseline (medium level). Wheat production is even more risky (high level) under the most likely atmospheric change scenario.

Table 7.8 Comparison of conditional probability of not exceeding the critical yield threshold under baseline and the most likely atmospheric change scenario (%)

Locations	Baseline	The Most Likely Scenario
Cummins	34 (low)	38~47 (medium)
Keith	14 (very low)	29~37 (low)
Lameroo	44 (medium)	49~58 (medium)
Minnipa	41 (medium)	51~60 (medium)
Naracoorte	5 (very low)	8~12 (very low)
Orroroo	37 (low)	49~64 (medium)
Roseworthy	27 (low)	43~48 (medium)
Wanbi	56 (medium)	64~74 (high)

7.3.2 Spatial Study

The spatial analysis of the conditional probability of not exceeding the critical yield threshold is presented in a similar way to the spatial analysis of grain yield and grain nitrogen content (Figure 7.35).

Under baseline, the conditional probability ranges from 9% to 96% across this region. Conditional probability of 59%~71% occupies most of the low rainfall area, which means current wheat production in this area is at risk. Part of the low rainfall area has low conditional probability (9%~22%) probably due to the good condition of the soil. The medium rainfall area has a medium range of conditional probability 35%~59%. The higher rainfall area has a lower conditional probability of 9%~35%.

Under the worst case, conditional probability increased, ranging from 38% to 100%, which indicates that wheat production is more risky than under the baseline. High conditional probability (89%~100%) takes up most of this study area, mainly distributed in the medium rainfall area and the low rainfall area. Most parts of medium rainfall area has a 78%~100% chance of not exceeding the critical yield. Some part of low rainfall area has relatively lower conditional probability of 48%~58%. Conditional probability of 58%~78% occurred in the higher rainfall area.

Under the most likely atmospheric change scenario, conditional probability is nearly back to the baseline situation, changing from 18% to 97%. Higher conditional probability of 63%~74% takes up most of the low rainfall area. The medium rainfall area has a medium level of risk with a conditional probability of 41%~63%. The higher rainfall area has low level of risk with a conditional probability of 29%~41%.

Under the best case, the conditional probability of not exceeding the critical yield decreased to a range of 5%~82% indicating reduced risk compared with the baseline. A conditional probability of 27%~49% takes up the most of the low rainfall area. The medium rainfall area has a medium level of conditional probability 27%~38%. Lower conditional probability 5%~16% occurred in the higher rainfall area and some parts of the low rainfall area.

Conditional probabilities under different atmospheric change scenarios and different climate divisions are summarised in Table 7.9. The risk for wheat production increased at least one level under the worst case for each rainfall area compared with the baseline risk level. Under the most probable case, conditional probability maintained the same level as that under baseline conditions. Risks for wheat production in this region decreased at least one level under the best case compared with that of baseline. It seems that parts of the drier area have a higher risk than other areas for wheat production across all scenarios.

Table 7.9 Distribution of conditional probability (%)

Area	Baseline	Worst Case	Most Likely Case	Best Case
Medium Rainfall Area	35 ~ 59* 9 ~ 22 59 ~ 71	78 ~ 100* 58 ~ 68	52 ~ 63* 63 ~ 74 41 ~ 52 18 ~ 29	27 ~ 38* 16 ~ 27
Higher Rainfall Area	9 ~ 22* 22 ~ 35*	58 ~ 78* 38 ~ 58	29 ~ 41* 41 ~ 52 18 ~ 29	5 ~ 16* 16 ~ 27
Low Rainfall Area	59 ~ 71* 22 ~ 35* 47 ~ 59 71 ~ 96	89 ~ 100* 48 ~ 58* 78 ~ 89	63 ~ 74* 18 ~ 29* 74 ~ 85 85 ~ 97	27 ~ 49* 5 ~ 16* 49 ~ 60

"*" indicates that range of conditional probability takes up a big portion of that area.

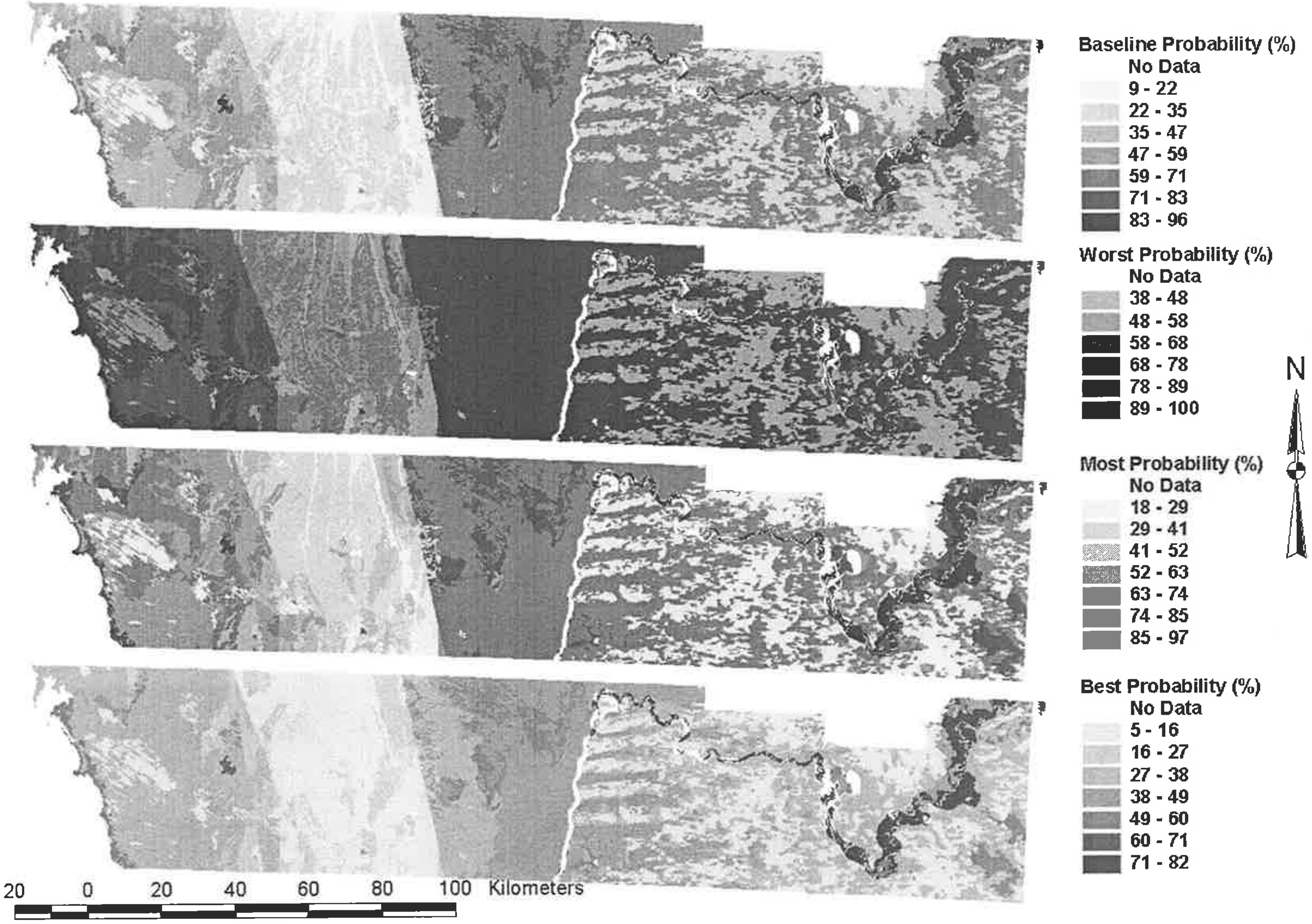


Figure 7.35 Spatial distribution of conditional probability of not exceeding the critical yield threshold.

7.4 CONCLUSION

Future atmospheric change will have significant effects on median grain yield. Median grain yield reduced by 0~41% across all locations and areas under the most likely scenario. Of those environmental factors, rainfall change is more important than temperature and pCO_2 change in most locations. Some atmospheric change impacts on grain nitrogen content are projected. Grain nitrogen content changes from -14% to 16% under the most probable scenario across the study sites and study areas. Obviously, grain yield is more sensitive than grain nitrogen content to future atmospheric changes. The benefit arising from increased grain nitrogen content in some locations is too little to offset the adverse effects of grain yield resulting from atmospheric changes. Under the most probable atmospheric change scenario, the conditional probability of not exceeding the critical yield threshold using "current agricultural technology" will increase in all locations and areas with Lameroo, Minnipa, Orroroo, Wanbi (in the site-specific study), median rainfall area and low rainfall area (in the spatial study) no longer viable (a conditional probability of not exceeding the critical yield threshold >= 50% is regarded as nonviable farm economy). Faced with these outcomes of grain yield, grain nitrogen content and the conditional probability of not exceeding the critical yield, adaptations should be put forward to counteract these adverse effects resulting from future atmospheric change. This is discussed in the next chapter.

8. RISK MANAGEMENT/TREATMENT

Chapter 7 showed that wheat yield will vary considerably, grain quality will substantially change, and the conditional probability of not exceeding the critical yield will increase under future atmospheric changes. The most likely yield change, most likely grain nitrogen content change, and the most likely conditional probability are summarised in Table 8.1 for the selected sites and areas within the site-specific study and the spatial study. The most likely grain yield/ grain nitrogen content/conditional probability changes were obtained when three of environmental factors (regional rainfall, regional temperature and atmospheric pCO_2) are at their most likely scenario.

Three conclusions can be drawn from this table. First, the most likely grain yield will decrease across all the locations and areas. Second, the most likely conditional probability will increase indicating a more risky environment for wheat production. Last, the most likely grain nitrogen content will increase or decrease depending on locations and areas. Benefits from a small increase in grain nitrogen content in some locations are outweighed by the adverse impact on South Australian wheat production resulting from future atmospheric change. This chapter considers some ways to minimise those adverse effects brought about by atmospheric change.

Table 8.1 Most likely changes in grain yield, grain nitrogen content and risk level

Studies	Locations	The Most Likely Median Yield Change (%)	The Most Likely Median GNC Change (%)	Baseline Conditional Probability* (%)	The Most Likely Conditional Probability** (%)
Site-Specific Study	Cummins	-33 ~ -7	-3 ~ 5	34	38 ~ 47
	Keith	-38 ~ -14	-1 ~ 16	14	29 ~ 37
	Lameroo	-31 ~ -1	-3 ~ 3	44	49 ~ 58
	Minnipa	-35 ~ -5	-6 ~ 1	41	51 ~ 60
	Naracoorte	-26 ~ -1	-1 ~ 4	5	8 ~ 12
	Orroroo	-33 ~ 0	-7 ~ 8	37	49 ~ 64
	Roseworthy	-41 ~ -23	-3 ~ 5	27	43 ~ 48
	Wanbi	-34 ~ -7	-5 ~ 0	56	64 ~ 74
Spatial Study	Medium Rainfall Area	-30 ~ -20	-8 ~ -2 -2 ~ 2	35 ~ 47 47 ~ 59	52 ~ 63
	Higher Rainfall Area	-40 ~ -30	2 ~ 8	9 ~ 22 22 ~ 35	29 ~ 41
	Low Rainfall Area	-30 ~ -10	-14 ~ -8 -8 ~ -2	59 ~ 71 22 ~ 35	63 ~ 74 18 ~ 29

* Conditional probability of not exceeding the critical yield threshold under baseline (historical climate and current atmospheric pCO_2) (Table 7.8)
** Conditional probability of not exceeding the critical yield threshold under the most likely atmospheric change scenarios (Table 7.8)

8.1 TWO PARALLEL WAYS OF RISK TREATMENT/MANAGEMENT

Risk treatment consists of two complementary actions, adaptation to anticipated atmospheric changes and mitigation of atmospheric change through reductions in greenhouse gas emissions. Both of these actions will reduce the risk of critical thresholds being exceeded. Risk treatment/management contains two tiers of information: the assessment of adaptation and mitigation and the implementation of adaptation and mitigation options (Jones, 2000b; Jones, 2000c).

Adaptation is the adjustment in the ecological, social or economic systems in response to actual or expected environmental stimuli, their effects or impacts. It refers to changes in processes, practices or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in environment. It involves adjustments to reduce risk to wheat production resulting from a potentially changed environment (IPCC, 2001). Mitigation strategies aim to stabilise greenhouse gas concentrations in the atmosphere at levels preventing "dangerous " anthropogenic interference with the climate system. Mitigation is currently being addressed at the national and international level and relates to the stablisation of emissions to prevent dangerous atmospheric change occurring (Jones, 2000b).

There are several major differences between adaptation and mitigation. The most crucial difference is to whom the benefits of action accrue. Except for 'no-regret' options, benefits of mitigation will become a globally shared public good. Adaptation actions will predominantly benefit agents that adapt in the case of private sectors or gains that will be shared by the community in the case of local-regional public goods and services, like food protection. The second important difference between mitigation and adaptation decisions relates to the timing of policy options. If climate protection were needed, policies and technologies that help reduce GHG emissions at the lowest possible social costs will be required immediately. On the adaptation side, in contrast, the bulk of the more significant impacts of climate change may be felt in 30, 50 or 100 years from now. This leaves a longer time period to steer the development of climate sensitive sectors so that their climate vulnerability will be lower, and more importantly, to develop technologies that will help reduce the remaining negative impacts by the time they really happen.

In terms of public policy agenda, mitigation decisions have to be made today in the context of current short-term economic problems, social challenges, and policy debates. Adaptation and adaptation related analyses will have to be developed in the context of long-term socio-economic and technological development, with a special view to economic and technological trends in climate sensitive sectors and environmental systems. Adaptation is an essential part of agricultural impact assessment. Thus, detailed adaptation options are discussed in this chapter.

8.2 ADAPTATION

Identifying the likelihood that a critical threshold, or a lesser threshold identifying a degree of harm may be exceeded, opens a window for adaptation, where options for risk treatment can be investigated. Adaptation is important in atmospheric change issues in two ways, one relating to the assessment of impacts, the other to the development and evaluation of response options (IPCC, 2001a).

Understanding probable adaptation strategies is essential to impact assessment, and hence fundamental to estimating the cost and risk of atmospheric change (Fanhauser, 1996; Yohe et al., 1996; Tol et al., 1998; UNEP, 1998; Smit et al., 1999; Pittock and Jones, 2000). The extent to which ecosystems, food supplies and sustainable development are "in danger" depends on their exposure to atmospheric change effects and on the ability of the impacted system to adapt. Adaptive strategies are influenced by multi-scale factors-at farm, national and global levels-and their integration into decision making. The farm scale adaptations operating through socioeconomic changes may affect, for example, farm sizes or diversification to non-agricultural land use via changes in profitability. The regional/national scale adaptations operate through policy responses aimed at market support or environmental regulation, such as the recognition of soils as a nonrenewable natural resource, or concerns over water quantity and quality. Two types of adaptation are identified in atmospheric change terminology: autonomous adaptation and planned adaptation. Farm level adaptation corresponds to autonomous adaptation while national and global level adaptation corresponds to planned adaptation.

8.2.1 Autonomous Adaptation

Evaluating risk and identifying feedback is likely to result in autonomous adaptation. Autonomous or spontaneous adaptations are considered to be those which take place, invariably in reactive response (after the initial impacts are manifest) to environmental stimuli as a matter of course, without directed intervention of a public agency. Autonomous adaptations are widely interpreted as initiatives by private actors rather than by governments, and are usually triggered by market or welfare changes induced by atmospheric change and its anticipation (Leary, 1999). Autonomous adaptations form a baseline against which the need for planned anticipatory adaptation can be evaluated (IPCC, 2001a).

The following are possible strategies for South Australian farmers to use when adapting to projected impacts from future atmospheric change.

- Adjust planting dates in relation to timing of opening rains and timing of end of growing season
- Apply new varieties with heat, drought and salt tolerance
- Moisture conserving practices such as stubble retention, chemical fallow etc.
- Crop substitution while considering changes in relative prices of input factors and agricultural commodities, the evolving technological and agronomic conditions behind them, and other factors affecting farmer's profit
- Change land use from crop production to grazing especially in Wanbi, where even current wheat production is at risk, let alone under future atmospheric changes.
- Diversifying income sources (and therefore risk-spreading)
- Minimum and reduced tillage technologies, which, in combination with planting of cover crops and green manure crops, offer a substantial possibility of reversing existing depletion of soil organic matter, soil erosion and nutrient loss, and to combat potential further losses due to climate change
- Buying crop insurance

- Investing in irrigation is possible in the Southeast of South Australia, but it is not possible to apply irrigation in other areas of the wheat production area due to limited water sources
- Fallowing, an effective way to conserve soil moisture
- Enhancing the understanding of the critical yield threshold concept

Farmers would adjust their choices to fit the new conditions and could lessen the potential damage and in some cases make themselves better off than before (Mendelsohn, 2000). It is estimated that adaptations taken by farmers could allow them to avoid over half of the potential adverse impacts of climate change on agriculture (e.g., El-Shaer et al., 1996, Darwin et al., 1995). But the mix of measures depends on the local context of soils, climates, economic infrastructure and other resources (Rosenzweig and Parry, 1994). Adaptation options will be more limited where a climatic element is marginal, such as low rainfall, or where physical circumstances dictate, such as restricted soil types. Even where adaptations are possible these may only be feasible in response to short term or small variations in climate. At some points, a need may arise for a major and costly reconfiguration. Considerable costs could however be involved in coping with climate-induced yield losses and gains, for example in learning and gaining experience with different crops, or if irrigation becomes necessary. In some cases, a lack of water due to climate change might mean that the increased irrigation demands can not be met. Six factors will affect a farmer's level of adaptation:

- The planning horizon for wheat production
- The farmer's ability to adapt to current climate, especially climate variability.
- The acceptability of adaptations by farmers largely depends on a combination of economic, regulatory and cultural factors that will be site-specific.
- Knowledge of autonomous adaptations
- The farmer's experience in long-term planning
- The farmer's perception of uncertainty

Adaptation decisions in private sectors operating under free market conditions will largely be made as part of business as usual and will rely on analytical frameworks compatible with their management culture -autonomous adaptation. The flexibility of private sector actors and thus the range of options they are able to consider in adapting to any external impact can be severely constrained by market distortions or by a lack of resources to implement any transformation.

This can be confirmed by the fact that losses from climatic variation and extremes are substantial and, in some sectors, increasing. These indicate that autonomous adaptation has not been sufficient to offset damages associated with temporal variations in climatic conditions. The ecological, social and economic costs of relying on reactive, autonomous adaptation to the cumulative effects of atmospheric change are substantial and largely avoidable through planned, anticipatory adaptation (IPCC, 2001a). Planned adaptation will be required and the importance of public policy will be greater.

8.2.2 Planned Adaptation

Adaptation is an important policy response option along with mitigation. There is a need for the development and assessment of planned adaptation initiatives to help manage the risk of atmospheric change. Planned adaptation occurs in response to a formal adaptation assessment. Planned adaptations, which are referred to as "intervention strategies" (Smith et al., 1996), can be either reactive or anticipatory (undertaken before impacts are apparent). Planned adaptation is often interpreted as the result of a deliberate policy decision on the part of a public agency, based on an awareness that conditions are about to change or have changed, and that action is required to minimise losses or to benefit from opportunities. Planned adaptation has the potential to reduce vulnerability and realise opportunities associated with atmospheric change, regardless of autonomous adaptation. Implementation of adaptation policies, programs and measures will usually have immediate benefits. The costs of adaptation are often marginal to other management or development costs (IPCC, 2001a).

Response from Government and Governmental Agencies

Governments can be helpful if there are externalities associated with adaptation. Governments could subsidise desirable changes and regulate undesirable actions with important externalities. Governments could intervene in these circumstances to encourage individuals to incorporate the externalities into their decision making. If governments can demonstrate that private adaptations involve large new externalities, they should attempt to manage these situations efficiently. A second justification for government action on private adaptation concerns information. Some adaptations may require that decision-makers learn a substantial amount of information about future climates, their impacts and possible adaptation options. The information costs may be too high for individuals to acquire. Government could become involved in collecting and dispersing information about future climates. They could provide forecasts explaining how the weather is expected to change over time, who is likely to be affected, and what they could do to adjust. Provision of climate information and seasonal forecasts can help land users to manage for climate variability and change, to optimise their management strategies, including reducing farm input in potentially poor years. A third justification for government involvement in private adaptation is equity. Although private adaptation is efficient, it may not be considered just. Private adaptation is paid for by the victims. In many circumstances, society has stated that the polluter should pay for the costs and damages from pollution (Esty and Mendelsohn, 1998). Governments might get involved in private adaptation to shift the burden of the costs from the victims to the polluter (Mendelsohn, 2000). In addition, enhancing adaptive capacity at global scale, national scale and local scale; training and education; identifying present vulnerabilities; genetic resources and intellectual property rights protection; agricultural extension; food security; marketing and distributing systems; commodity and resource policy reform are all possible adaptive strategies to cope with atmospheric change impacts. The following issues are discussed in detail.

- Research new technologies to maintain current viability of wheat production
- Improved forecasts of commodity prices and long-term trends in supply and demand, taking into account seasonal climate and El Nino Southern Oscillation forecasts. This will be especially important for atmospheric change impacts and will require understanding of global effects
- Provide decision support
- More appropriate adaptation strategies with other environmental problems considered

Adaptations by Researchers

Conducting research programs is one of the main measures in coping with adverse effects from atmospheric change especially through breeding high quality varieties. Genetic modification is a long-term solution.

- Select cultivars that exhibits heat tolerance during reproductive development, high harvest index, small leaves and low leaf area per unit ground (to reduce heat load) to promote adaptation to high temperature and high pCO_2 environment

- Breed cultivars with early maturity characteristic due to shortened development process of wheat by increased temperature
- Breed drought tolerant varieties to adapt to decreased winter rainfall
- Breed cultivars with higher grain protein where grain nitrogen content was adversely affected by changed environment
- Breed cultivars with higher water use efficiency (WUE). For example, some modern wheat cultivars compared to that of old wheat cultivars were associated with faster development, earlier flowering, improved canopy, and higher harvest index. Increased recognition of the importance of improving water use efficiency, improvement in instruments for measuring many of these traits and increased co-operation among interdisciplinary scientists will increase the opportunity to breed plants for more efficient water use. APSIM-Wheat model can be used to conduct sensitivity analysis on water use efficiency. For example, how much improvement in WUE should be made to achieve critical yield threshold under the most likely atmospheric change scenario in Minnipa with the assumption that the critical yield for this location is 980 kg/ha and the current water use efficiency is 20 kg/ha/mm? WUE can be manipulated by applying APSIM-Wheat model until median grain yield for the most probable environmental scenario is greater than the critical yield threshold. The difference between the current WUE and the new WUE is the breeding target that should be put forward to counteract the adverse effect resulting from the atmospheric changes
- Design and apply deeper root systems, which may be needed for sustainability. These systems will need to capture water and nutrients that would otherwise pass the root zone and cause degradation problems. The design of such systems will entail research into rotating and mixing configurations of plants, manipulating phenology, modifying current crops and pastures through plant breeding, including molecular genetics, and possibly commercialisation of wild species and endemic biological resources.

Implications for Market

Over 80% of the wheat produced in South Australia is currently exported. Decrease of grain yield across all sites and areas, decrease of grain nitrogen content in some locations and areas and increase of risk level across all sites and areas will have significant influence on the South Australian economy. A decreased grain yield and an increased risk level of wheat production under the most likely atmospheric change scenario would indicate a decrease in export from South Australia, less profitability to farmers and less stability of wheat production. SA export earnings would decline to $378 million by 2080 (assuming a 20% reduction in grain yield under most likely atmospheric change scenarios and keeping wheat production area unchanged) based on a value of $473 million in 2000. Decreased grain quality means a decrease in the class of grain price, and, along with the decreased grain yield, will exacerbate the above situation. Although an increase of grain nitrogen content in some locations is predicted, the benefits resulting from this increase in grain nitrogen content cannot counteract the decrease in grain yield.

Changes to wheat production in South Australia due to future atmospheric change also have implications for countries, which import South Australian wheat grain. A decreased export of South Australian wheat grain may lead to an increase of grain price and bring about hunger where people can not afford the increased price if wheat production in other parts of the world is also adversely affected. If wheat production thrives elsewhere, the South Australian wheat industry will be even more adversely affected. Improved forecasts of commodity prices and long-term trends in supply and demand, taking into account seasonal climate and El Nino Southern Oscillation forecasts are effective ways to cope with the biophysical and socioeconomic impacts. This will be especially important for atmospheric change impacts and will require understanding of global effects. An increase in exports of value-added and processed products is another possible strategy to cope with future market change.

Adjustments for the Wheat Industry

Government can provide decision support to changes in the wheat industry. Possible changes will occur in wheat storage and transport; wheat products produced and the replacement of the wheat industry by other commodities such as livestock.

Some adjustments can be made by the wheat industry in response to changed wheat production. Much lower grain production means that less storage and fewer grain export ports would be needed in SA. This analysis is quite helpful in infrastructure investment and in lessening unnecessary expenses. Changes in grain nitrogen content will lead to different products being produced in South Australia. Slightly higher grain nitrogen content will benefit bread rather than biscuit and noodle production. It is noted that wheat production in some locations is at risk under the current situation (e.g. Wanbi). Future atmospheric change will increase the risk level. If the above adaptations can not effectively counteract the adverse effects resulting from atmospheric change (or the farm economy is no longer viable), introduction of livestock production or some other as yet unidentified enterprises may be necessary. The alternative is retiring this land from economic pursuits.

Integrated Adaptation Strategies

Adaptations to other driving forces such as land degradation, the globalisation of commerce and trade and social and technological change also need to be considered. Vulnerabilities associated with climate change are rarely experienced independently of non-climatic conditions. Adaptation measures are likely to be implemented only if they are consistent with existing policy criteria, development objectives, and management structures, or integrated with decisions or programs addressing non-climatic stresses. Impacts of environmental stimuli are felt via economic or social stresses, and adaptations to the environment (by individual, communities and governments) should be evaluated and undertaken in light of these conditions.

8.3 CONCLUSIONS

It is projected that South Australian wheat production will face severe challenges from future atmospheric change: grain yield will decrease, the risk of nor exceeding the critical yield threshold of wheat production will increase, grain nitrogen content will increase or decrease depending on location and area under the most likely change scenarios. By 2080, SA export earnings may be reduced to A$378 million from A$473 million in 2000 assuming grain yield decline by 20% and wheat production area is the same as before. Faced with this situation, possible adaptation strategies at farmer level (autonomous adaptation) and governmental level (planned adaptation) have been put forward to cope with the detrimental impacts. Although the effectiveness of the adaptation strategies has not been quantitatively evaluated in this project, there is a potential for APSIM-Wheat model to do this in a continuing study. The limitations of this research are analysed and further research needs are identified in the next chapter.

9. CONCLUSIONS

This chapter is a summary of this project including its scientific findings, strengths and weakness. Further research needs are pointed out based on limitations associated with this study.

9.1 SUMMARY AND SYNTHESES

This study assessed the potential impacts of future atmospheric change on South Australian wheat production in 2080. Downscaled outputs of 9 GCMs/RCMs were assigned probabilities by applying Monte Carlo Random Sampling techniques and fed into the APSIM-Wheat model to assess the possible impacts of atmospheric changes on median grain yield, median grain nitrogen content, economic viability and frequency of total crop failure. Two parallel studies: a site-specific study and a spatial study, were involved in the project. The individual effect of environmental factors on grain yield, frequency of total crop failure and economic viability at two locations and the combined effects of environmental factors on median grain yield, median grain nitrogen content and economic viability at eight locations were evaluated in the site-specific study. The combined effects of environmental factors on median grain yield, median grain nitrogen content and economic viability in a region of the Mid-Lower North (-34° ~ -34.5° N) of South Australia was analysed in the spatial study.

Conclusions from this study are made from the following facets:

- Responses of impact indicators to environmental factors,
- Impact difference between higher rainfall and low rainfall areas
- Comparison between site-specific study and spatial study
- The most likely impact outcomes
- Methodology assessment
- Limitations as well as further research directions

Median grain yield is positively correlated with increasing rainfall and atmospheric pCO_2 and inversely correlated with increasing temperature. In contrast, median grain nitrogen content has a positive relationship with temperature and pCO_2 and has an inverse relationship with rainfall and grain yield due to the N-dilution effect. The conditional probability of not exceeding the critical yield has the same relationship with environmental factors as grain nitrogen content. Median grain yield (-100% ~ +124% of baseline median grain yield) and conditional probability (4% ~ 100%) across all locations, areas and atmospheric change scenarios was more sensitive to future atmospheric changes, especially rainfall change. Rainfall exerted a major effect on these two impact indicators. Grain nitrogen content, however, was less sensitive to future environment changes with a smaller change range (-25% ~ +42% of baseline grain nitrogen content) across all scenarios and locations and areas.

Higher rainfall areas are facing a greater decline in median grain yield compared to lower rainfall areas. This is because the baseline yield for higher rainfall areas and low rainfall areas is quite different. Even though they have the same percentage yield change, the difference between the two new yields (absolute value) is very large. The higher rainfall area is affected more, as projected in the spatial study. This conclusion is demonstrated by an example. The baseline median grain yield for Keith (representative of higher rainfall area) and Minnipa (representative of low rainfall area) is 4099 kg/ha and 1294 kg/ha respectively. If both of these locations have the same amount of yield decrease percentage, e. g., 20%, the changed new yield for these two locations will be 3279 kg/ha for Keith and 1035 kg/ha for Minnipa respectively.

The most likely grain yield change and the most likely grain nitrogen content change range from -41% to 0 and -7% to 16%, respectively, in the site-specific study. The most likely median yield change and the most likely grain nitrogen content change are -58% to -3% and 14% to 14%, respectively, in the spatial study. These indicate that the most likely median grain yield change range and the most likely median grain nitrogen content range in the spatial study are slightly wider than that of in site-specific study. The same finding has also been found for the whole range of median yield response and whole range of median grain nitrogen content response across all locations and areas and all atmospheric change scenarios.

The most likely median grain yield will decrease (-58% ~ 0%) across all locations and all areas. The most likely grain nitrogen content (-14% ~ 16%) will decrease or increase depending on locations and areas. The risk of not exceeding the critical yield threshold under the most likely atmospheric change scenario will increase at least one class in most locations and most areas. These outcomes suggest that South Australian wheat production will face severe challenges from future atmospheric changes. Under the most probable atmospheric change scenario, the conditional probability of not exceeding the critical yield threshold using "current agricultural technology" will increase in all locations and areas with Lameroo, Minnipa, Orroroo, Wanbi (in site-specific study), median rainfall area and low rainfall area (in spatial study) no longer viable (based on not exceeding the critical yield threshold in greater than 50% of seasons).

Adaptation strategies to cope with the above adverse effects on South Australian wheat production resulting from future atmospheric changes have been addressed in the form of autonomous adaptation options and planned adaptation strategies as listed in chapter 8. Changes in production activities and management adaptations (such as improved wheat genotypes and reliable seasonal forecasts etc.) could play an important role in mitigating the detrimental impacts of atmospheric change.

The most important contribution of this work lies the rigorous approaches adopted, which have not been used before in this field. Three stages are featured in this study. The first is the quantification and management of the uncertainties, which surround atmospheric change impact assessment, ranging from the projection of greenhouse gas emissions, the projection of global warming to the projection of local climate change. Second is risk analysis, which corresponds to the uncertainty range through the introduction of critical yield threshold. The levels of atmospheric change were linked to the levels of impact through the use of risk assessment. These two features were carried out through both the site-specific study and the spatial study. Another feature of this study is the spatial variability analysis of simulated results through the spatial study by applying GIS technology. A large variation of impact outcomes within the same climate division has been found in the spatial study due to soil variability largely due to plant available water capacity (PAWC) indicating the necessity of including soil variability in agricultural impact assessment.

Adoption of these methodologies increased the accuracy and credibility of projected impact outcomes. Assessment of atmospheric change impact on wheat production based on the first two features is more accurate, comprehensive and complete than previous studies. The reason for this lies in the fact that impact assessment based on this approach covered all possible atmospheric change scenarios. Furthermore, probability was attached to atmospheric change scenarios and attached to the impact indicators. The most likely impact responses can be obtained from this approach. The employment of GIS in the atmospheric change impact study improved assessment accuracy due to its ability to manage the spatial soil and climate database (soil variability was incorporated into this study). The impact outcomes based on this methodology were given in more detail and presented in map format, which provides a useful way for visually assessing the impact on wheat grain yield and grain nitrogen content. By scrutinising this impact map, policy makers and the wider community will know where wheat production is most and least affected.

Adaptation strategies aimed at minimising the adverse effect of atmospheric change on wheat production will be more applicable, practical, effective and economical based on this enhanced assessment. The attachment of probability to atmospheric change scenarios and to impact outcomes and the quantification of risk level in wheat production make future planning and policy making more practical and applicable. For example, it is easier to make decisions on how much effort should be made to cope with the most likely adverse effect and increased risk in South Australian wheat production due to atmospheric change. The detailed impact information provided by the spatial study will make adaptation strategies (management adjustment) more effective, economical and practical than without this information.

Risk assessment is a more appropriate methodology for impact assessment than the "prediction" of unique outcomes based on projecting a sequence of events beginning with greenhouse gas emissions, the projection of climate change using climate models, and the projection of impact through using impact models. The risk assessment framework presented in this study moves impact assessment beyond simple sensitivity and vulnerability assessment towards the goal of forecasting specific impacts under expected atmospheric change. This is a major step forward in atmospheric change impact assessment.

9.2 LIMITATIONS

Some limitations apply to this study, although substantial improvements have been made in uncertainty management, in impact spatial variability analysis, in the adoption of risk analysis and in the incorporation of grain quality impact and the physiological effects of increased atmospheric CO_2. Limitations exist in study scope and the applicability of the APSIM-Wheat model and in the construction of atmospheric change scenarios.

9.2.1 Limitation in Study Scope

Adaptation strategies are assessed qualitatively rather than quantitatively in this study. Qualitative adaptations simply give possible directions of coping with adverse effects of atmospheric change on wheat production. The feasibility and effectiveness of these adaptive options have not been assessed. This may lead to the outcome that the negative impacts have not been counteracted completely by those adaptive strategies or that unnecessary expense is involved in the adaptive processes. More emphasis should be put on quantitative adaptive options. The APSIM-Wheat module can be used to explore the effectiveness of present farm level adaptations (through changing management measures). For the purpose of economically and effectively managing those adverse effects, economic modelling analysis should be conducted based on the quantified impact results.

9.2.2 Limitations on the Applicability of the APSIM-Wheat Module

The APSIM-Wheat model shares all the limitations listed in chapter 2, except the incorporation of grain quality impact and the fertilisation effects of increased atmospheric CO_2. Detailed information on some of the limitations relevant to this project is given here.

- Further work is needed to validate the performance of APSIM-Wheat under South Australian soil and climatic conditions
- Further work is needed to streamline the parameterisation of APSIM. This is particularly the case with deriving soil parameters for PAWC and nitrogen dynamics

9.2.3 Limitations in the Construction of Atmospheric Change Scenarios

Two limitations are involved in the construction of atmospheric change scenarios: ignorance of climate variability and deficiencies in random sampling.

Possible increased climate variability has not been incorporated into the climate change scenarios used in this study. There are three reasons for this. Current GCMs do predict the possible change of climate variability under future climate change. In order to obtain climate variability change information, daily outputs of GCMs are required which means that the mainframe computer should be available for use by the community involved to store and analyse information on climate variability change. However, this prerequisite can not be satisfied at this stage. The second reason is that the integration of changes of climate variability into climate change scenarios is in conflict with uncertainty management. Outputs from a wide range of GCMs/RCMs are required to manage uncertainties stemming from projecting change ranges of pCO_2, global temperature, regional temperature and rainfall. It is impractical to look at changing patterns of climate variability from the daily outputs of so many GCMs/RCMs. The other constraint is that GCMs often disagree at higher spatial and temporal scales so it is difficult to attach any likelihood to changes. That is why there is a consensus to go with probability (many models expressing the range of possible outcomes). However, predicted El Niño frequencies will increase along with the 'mean' climate change, which will have very significant consequences for agriculture production. So the need to incorporate increased climate variability remains a challenge.

Some problems exist in random sampling of atmospheric pCO_2, global temperature, local temperature and local rainfall. It is not hard to see that uncertainties arising from the projected pCO_2 range have not been managed very well. The most likely pCO_2 takes up a large part of the window between temperature and pCO_2 and the window between rainfall and pCO_2 (shown in the five dimensional plots in chapter 6). Improvement can be made by setting relationships between pCO_2 and global temperature, letting pCO_2 (forcing in W/m2) drive the temperature range. Another improvement can be made in methods of sampling, incorporating regional dependencies between temperature and rainfall (Hulme and Brown, 1998; Hulme and Carter, 1999), which offers potential for reducing the uncertainties within probabilistic scenarios.

Furthermore, default assumptions of probability should be avoided. Every step should be described, making relationships of statistical (in) dependence and probability distribution functions explicit.

9.2.4 Other limitations

The probabilities for not exceeding the critical yield threshold produced by this method are conditional probabilities, since they are based on limited ranges of uncertainty. The soil profile data for the spatial study are composite data since the specific data for common soil units are not available. Further work in this area is warranted as this study demonstrated that differences in PAWC can exert strong influence over wheat response to global atmospheric changes.

9.3 FURTHER RESEARCH NEEDS

The above limitations suggest the following four research priorities:

(a) Quantitatively assess the effectiveness of adaptation strategies to the adverse impacts resulting from atmospheric change. Based on the results from this study, further research to assess the potential of adaptation management change to minimise the impact of atmospheric change on wheat production is warranted. Building on the tools assembled in this study (probabilistic atmospheric change scenarios, soil profile database, APSIM-Wheat model, GIS technology), it will be possible to evaluate potential interventions such as improved wheat genotypes (shorter season maturity, greater drought tolerance, etc.), improved management practices (time of sowing, soil water storage, nitrogen fertiliser, etc.), and economic sensitivity (cost, prices), and the utility of improved seasonal forecasts.

(b) Incorporate climate variability change information to climate change scenarios. Monthly change information of climate variability from Global Climate Models (GCMs) is available and more reliable, which can be incorporated into climate change scenarios. However, the monthly outputs of GCMs can not satisfy the needs of crop models, which require higher temporal climate information (daily weather data) as the driving force. A stochastic weather generator called LARS-WG can solve the above problem and produce long time series climate change information, which can be used by crop models.

(c) Improve the methodology in random sampling procedures, especially between atmospheric pCO_2 and global temperature to better manage uncertainties associated with wheat impact assessment.

(d) Employ Participatory Action Research (PAR) methodologies. Stakeholders should be involved in determining critical yield threshold and in implementing the proposed adaptation measures. The importance of stakeholder or user-defined thresholds has been recognised recently in climate change impact assessments, especially where adaptation is an outcome of the assessment. User defined thresholds are valuable for both the analysis and communication of outcomes as they telescope the uncertainties in operational outcomes into a single item.

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Appendix 1 The Emission Scenarios of the Special Report on Emission Scenarios (SRES)

The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peak the mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into 3 groups that describe alternative directions of technological change in the energy system. The 3 groups A1 are distinguished by their technological emphasis: fossil intensive (A1F), non-fossil energy sources (A1T) or a balance across all sources (A1) (where the balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels (IPCC, 2001 and Anon, 1).

Appendix 2 Acronyms

A1-Mid: climate change scenarios under A1 emission scenario and medium sensitivity of climate system. Readers are directed to Appendix 1 for the specific definition of A1.
APSIM: Agricultural Production System sIMulator
ASW: Australian Soft Wheat
B2-Mid: climate change scenarios under B2 emission scenario and medium sensitivity of climate system. Readers are directed to Appendix 1 for the specific definition of B2.
CERES: Clouds and Earth's Radiant Energy System
CNC: Critical Nitrogen Content
DSSAT: Decision Support System for Agrotechnology Transfer
GCM: General Circulation Model/Global Climate Model
GFDL: Geophysical Fluid Dynamic Laboratory
GIS: Geographic Information System
GISS: Goddard Institute for Space Studies
GNC: Grain Nitrogen Content
IPCC: Intergovernmental Panel for Climate Change
KazNIGMI: Kazak Hydro-meteorology Scientific Research Institute
LAI: Leaf Area Index
LAM: Limited Area Model
PAWC: Plant Available Water Content
PIRSA: Primary Industries and Resources, South Australia
RCM: Regional Climate Model
RUE: Radiation Use Efficiency
SAR: Second Assessment Report
SRES: Special Report on Emission Scenarios
TE: Transpiration Efficiency
UKHIv: The United Kingdom High Resolution GCM Equilibrium Experiment
UKMO: United Kingdom Meteorological Office
UKTR: The United Kingdom High Resolution GCM Transient Experiment
USPCC RARM: US Presidential/Congressional Commission on Risk Assessment and Risk Management

Appendix 3 Glossary

Phyllochrons: leaf time.
Probability: the possibility for an event to occur.
Risk: Risk is the probability that a substance or situation will produce harm under specified conditions. Risk is a combination of two factors: the probability that an adverse event will occur; the consequence of the adverse event.
Thermal time: accumulation of temperature during certain period, denoted as ^{o}Cd.
Top (plant): the above ground part of a plant.

Appendix 4 Environmental Change Information

See attached CD.

Appendix 5 Soil Profile Data

See attached CD.