Drought, Agricultural Production & Climate Change – A Way Forward to a Better Understanding

NIWA Client Report: WLG2008-33
Final version: September 2008

NIWA Project: MAF80303/1

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Prepared for

Ministry for Agriculture and Fisheries

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Executive Summary

This project has been tasked with establishing clear and practical directions that will improve drought and climate change analysis for New Zealand's agriculture. The rationale is to increase awareness of drought and climate change risks, and develop a mechanism that will improve the preparedness and adaptive capacity of the agricultural sector. The key insight emerging from this project is that while New Zealand has made excellent progress in developing methodologies in climate and agricultural sciences, further work can be done in terms of integration and some key areas of specialist research.

Based on an end user workshop and review of current methodologies, the report recommends that New Zealand develop a program of research that encompasses applied risk analysis and enabling science initiatives to maintain high levels of innovation. A draft research program is developed and presented, which proposes a number of projects as a way of progressing drought and climate change risk analysis for New Zealand. A summary is presented on page 64 of this report.

Key enabling research projects include: developing a climate change database and toolkit suitable for use by agricultural researchers; developing a drought and climate change monitoring network; continued development and application of whole farm models and integration with macroeconomic modelling systems; and development of irrigation and groundwater resource modelling capacity.

To ensure high levels of integration a number of applied analysis projects are also proposed including: estimating of trends, production and economic impacts, including updating previous drought risk analysis under climate change; assessment of drought risk management practices to examine climate change resilience; the production of fact sheets documenting specific climate change adaptations; and a national audit of irrigation water resources.

1. Introduction

Agriculture will be one of the first industries to experience the impact of climate change, and New Zealand's awareness of these impacts has been sharpened by the severe drought in 2007/08. For some regions this has been a prolonged event, where drier than average conditions have persisted for some years. This event and the risk of climate change in the future raises two related sets of challenges for agriculture. The first relates to drought events, their impact and particularly how New Zealand can improve drought risk management in the future. The second relates to the prospect of climate change, and what strategic shifts are required to avoid or reduce impacts and even capture benefits over the medium to longer term.

One element in setting New Zealand on a path towards managing these risks more effectively is to examine how they are analysed. The science of global warming and the related field of agricultural risk analysis have seen progress in recent years. New Zealand has developed capacity to analyse drought and climate change, and has clearly identified changes in drought risk and agricultural production under climate change (Mullan et al. 2005; Wratt et al. 2007). While this work has improved the understanding of climate change and drought impacts, it is recognised that there is need to progress it further, particularly in the analysis of impacts and the role of management or 'adaptation'.

1.1 Project objectives and outcomes

The focus of this project is methodological. It is concerned with establishing directions that will improve drought and climate change analysis for New Zealand's agriculture. The project is guided by three interrelated objectives:

- **Develop a drought analysis methodology**: identify how best to build upon the 2005 drought report to produce updated and improved information on drought risk, using probabilistic information derived from the latest climate model scenarios, better estimates of the effects of climate change on potential evapotranspiration deficit and water availability (rivers and groundwater), and an improved understanding of the climate change effects on evapotransiration related to plant stomatal resistance.

- **Develop an agricultural production analysis methodology**: to identify how to produce updated and improved information on likely impacts of climate change on New Zealand agricultural production, by building on the 2007 agricultural production report through: using probabilistic information derived from the latest climate model scenarios, better estimates of the effects of climate change on soil moisture deficit, growing season heat accumulation, and water availability (rivers and groundwater), and the scaling and linkage of process-based agricultural production models (including carbon fertilisation effects) to climate change scenario information.

- **End-user linkage workshop:** to ensure that the suggested scientific methodologies and timelines described in the reports stemming from objectives 1 and 2 are aligned with the practical and policy needs of end users of this information.

The planned outputs of these objectives are reports which:

- describe methodologies to progress from our currently available information and understanding to that which is required to improve our knowledge of the impact of climate change on drought (including multi-year and multi-region drought) in New Zealand, including the expertise and timelines required to action these methodologies (objective one)

- detail the research framework (methodologies and timelines) required to analyse production impacts of climate change, and the best ways to present the resulting information (objective two).

- summarise end user perspectives, identifying any critical issues and defining a research framework with realistic goals (objective three).

This final report amalgamates the outputs of objectives one to three as a single document. This is achieved by presenting background material which develops the general research framework for impact analysis (section two); description of existing New Zealand methodologies with discussion of international and emerging practice for both drought and climate change impact analysis (section three); presentation of end user perspectives from the workshop (section four) and description of proposed methodologies and research targets which will move New Zealand practice forward (section five).

2. Research framework

2.1 Terminology and definitions

The focus on methodologies in this project makes it necessary to introduce a number of technical concepts and terminology. The following definitions provide background for a more thorough examination of both drought and climate analysis methods.

Drought and climate change: in contrast to a mean climate state like 'aridity', drought is a temporally varying phenomenon characterised by an extreme deviation from normal climatic conditions, usually low rainfall. Climate change is a longer term phenomenon, describing the non-stationary nature of the mean climate, for example a region's climate shifting from a 'temperate' to an 'arid' mean state. Both these phenomena are naturally occurring and can be observed in the past and will continue into the future. Recently, scientists have discovered that human activities are changing the global climate system in a way that is influencing the level and rate of change in mean climate. A core concept in this report is dependency between these phenomena, in other words the extent to which changes in the mean climate state are accompanied by changes in the temporally varying phenomena of drought.

Meteorological impact: when a climate variable or measure passes a threshold deemed as important for the system examined. As there is climate variation meteorological impact is usually defined in relative terms to the mean climate, for instance current period rainfall as percentiles of the historical distribution or anomalies from normal. Under climate change the historical distribution is becoming a less reliable benchmark by which to judge relative climate variability. Meteorological impact may also be considered as a combination of climate factors, such as low rainfall interacting with high temperatures and or evaporative potential. There are numerous drought indices (Hisdell and Tallaksen 2000) which have been proposed to analyse such interactions. Meteorological impact may also be characterised by measures of climate processes, such as indexes of the El Niño Southern Oscillation (ENSO).

Hydrological impact: refers to a deficit of water in the landscape, either the soil water balance or surface hydrological system (river flows and major dams and or farm dam storage levels). The landscape acts as a buffer and hydrological drought usually lags meteorological drought. Short duration meteorological droughts may not result in a hydrological drought, which are usually associated with longer term meteorological events, like rainfall deficiencies over many months.

Agronomic impact: a hydrological drought that results in a prolonged downturn in farm production. Useful indicators are grass growth, crop yields, livestock condition and numbers. While there is generally a close relationship, agronomic drought may not necessarily follow hydrological drought. The seasonal timing of rainfall events can influence production—this is sometimes known as 'rainfall effectiveness'. In addition, management practices such as pasture species selection, stocking rate, crop production timetables, and supplementary feeding can modify the relationship.

Financial impact: a loss in net farm cash income as a result of agronomic and hydrological drought. Financial losses and recovery lag behind meteorological drought as they are tied with markets and production timetables. The degree of financial loss may not directly relate to the severity of a meteorological or hydrological event. It can be modified by prices, timing of management actions, and individual farm factors such as business size, income diversity and gearing (debt to equity).

2.2 Drought and climate change

Drought characterised by a prolonged rainfall deficiency has a major economic impact on the New Zealand's regional economy through reduced volumes of primary production and potentially downward pressure on farm cash flows and income. Many parts of New Zealand experience seasonal droughts, characterised by production limiting water deficits in mid to late summer. New Zealand also experiences inter-annual drought, characterised by failure of winter and spring rains associated with more prolonged downturns in production. The prospect that future climate change could bring more frequent, prolonged and severe seasonal and inter-annual droughts has been identified in both the international and domestic scientific appraisals (Mullan et al. 2005).

In New Zealand the occurrence and regional distribution of inter-annual rainfall deficits is loosely associated with the El Niño Southern Oscillation (ENSO), which generally explains no more than twenty five percent of the country's rainfall variability. Depending upon the regional setting, rainfall deficits can be associated with either La Niña or El Niño events. New Zealand's rainfall is also influenced by local factors like topography, the southern ocean and smaller scale synoptic patterns. These interact with ENSO, giving rise to New Zealand climate variability. The Interdecadal Pacific Oscillation (IPO), a longer term fluctuation describing the difference between the sea surface temperatures in the Pacific and Indian oceans, has also been shown to modify ENSO at a decadal scale (Folland et al. 2002; Wang and An 2001). The interaction or 'state' of these processes contributes to observed decadal scale variability in the frequency and duration of rainfall deficits in New Zealand and other parts of the world.

Climate change is a longer term process that involves change to the mean state of climate. The notion that climate is non-stationary is not new, and there have been decadal scale shifts in climate variability in the last 100 years. Anthropogenic climate change has been identified as an additional forcing factor, with the warming of the earth's atmosphere given increasing greenhouse gases from human activities. A warming trend attributable to increased greenhouse gasses has been identified in measurements taken over the last century, and this trend is highly likely to continue and strengthen in the coming century.

Under a generally warmer, and where rainfall doesn't increase dramatically, a subsequently drier environment, the nature of drought is also likely to change in the future (Nicholls 2004). Under mid range climate scenarios there is strong likelihood that droughts will increase in intensity and duration, particularly in regions that are currently drought prone (Mullan et al. 2005). The changed thermal environment has also been shown to bring benefits like extension of the pasture growing season, but this is also regionally variable (Wratt et al. 2008). While there is a high level of confidence in the thermal processes and effects of climate change, confidence levels are moderate for future precipitation patterns. Current projections of the future state of rainfall yielding processes affecting New Zealand, like ENSO, are not consistent between climate models (Collins 2005; Meehl et al. 2007).

2.3 Climate risk management and agriculture

Concepts from risk management are increasingly being used in climate impact assessment, as they provide an approach that is able to establish appropriate responses that treat risk even when there is considerable uncertainty (Clark 1999, Katz 2002, Pittock 2003, Whetton et al. 2005, Meehl et al. 2007). The Australian New Zealand Standard (AS/NZS 4360, Figure 1) summarises the stages of risk management, and its application to climate and agricultural hazards is outlined in Clark (1999). Risk management follows a series of stages including: a preliminary stage, where context and risk identification are undertaken; analysis stages where formal examination of risk is carried out; and decision making stages where risk is accepted or treated. Risk management is iterative and also involves monitoring and communication activities.

This project endorses risk management as an overarching framework by which to examine and establish directions for climate change and drought analysis. The focus of this report is the risk analysis stage of this process, and in particular the practice of climate change and drought risk analysis. Both of these involve the integration of climate science with various specialised 'impact sciences', such as hydrology, agronomy and economics. Risk analyses can be usefully categorised as either qualitative or quantitative (Clark 1999).

Qualitative or 'semi-quantitative' assessment may take a hypothetical or synthesis approach. The hypothetical approach involves considering climate change projections and proposing potential levels of impact given system knowledge from experts. This is a more flexible and comprehensive method than quantitative assessment, particularly when a well validated impact model is not available. In risk management this occurs either early on in the process as part of the risk identification stage or later as a means of synthesising information for use by decision makers (Clark 1999).

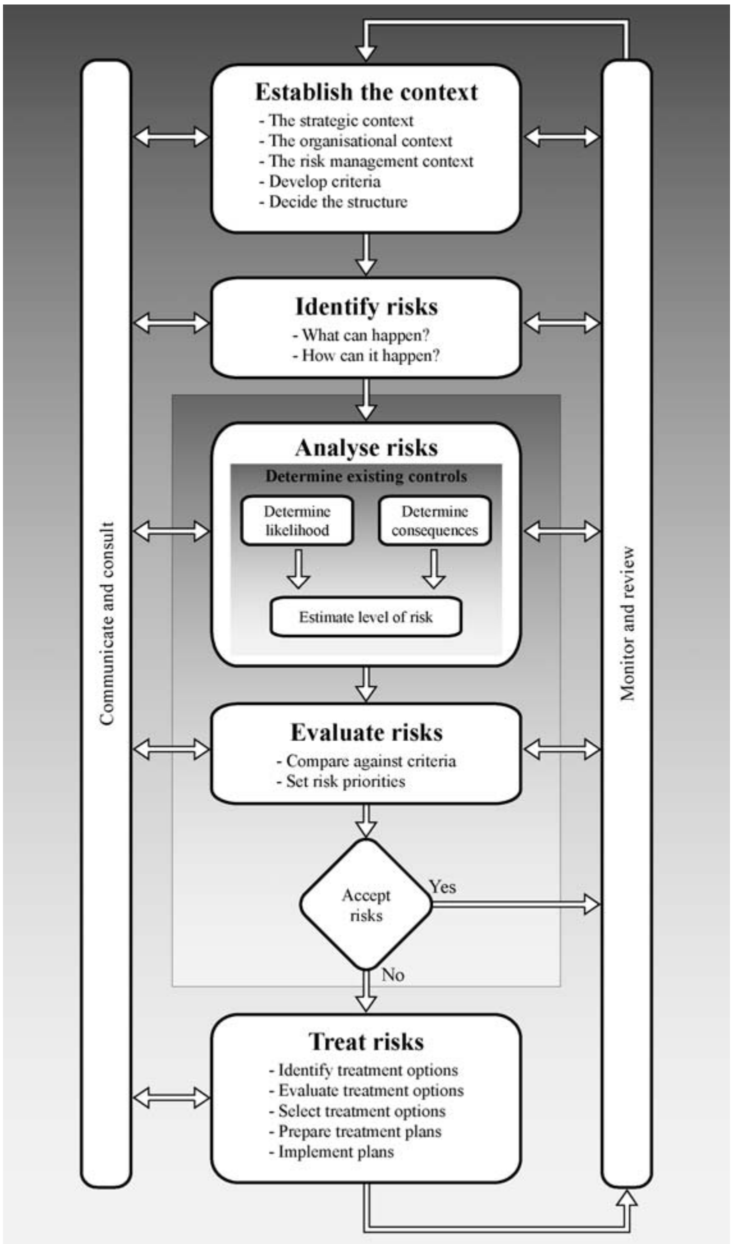

Figure 1. The Australian and New Zealand standard for Risk Management (AS/NZS 4360)

Synthesis or 'consensus' risk analysis involves interpretation of many quantitative risk analyses. This may be carried out when there is overt complexity or uncertainty in knowledge of the system's relationship with climate, or when there are divergent scientific results (Clark 1999). In risk management, this approach may be used after a formal risk analysis to provide decision makers with guidance. Many decision making activities involve this type of integration and application to decisions. The IPCC's 3rd and 4th impact assessment reports are an example of this approach, where a range of assessments were used to assign a likelihood, level of consequence and attribution of scientific uncertainty to a given impact.

Quantitative impact assessment is the objective analysis of risk (consequences and likelihood) of climate variability and or change on a given sector or location. It is implemented when the problem has been fully identified, and the expense of a full quantitative study justifiable as this level of rigour quite often involves new research. Agricultural risk analysis generally involves determining the consequences and likelihood by use of a simulation model which describes the linkages between climatic factors and the function of an agricultural system. Impact models may be coupled, in various levels of proximity and feedback, to climate models and or measured climate data. One advantage of quantitative impact assessment is that it allows the integration of climatic factors in the impact system and the simulation of the non-linear responses, which are important in hydrology and agriculture.

International best practice in drought risk analysis has involved the development of integrated early warning systems, where the data collection, management and analysis are automated, updated in near real time and communicated to stakeholders (Box 1). Increasingly the means of communication is the internet, but in some cases the systems are also supported with traditional communication activities given low internet usage rates in rural communities. The development of these systems has involved cross institutional integration of climate data collection and analysis activities so that the services are automated and decision makers receive pertinent and timely information for drought mitigation planning. Efforts on the climate science aspects of drought monitoring are now mature, providing considerable information about meteorological drought. Advances in Australia, the US and South Africa highlight the extension of the systems to report hydrological drought using soil water balance models. Further extensions to deal with stream flow, the production impacts and notably the economic consequences of drought have been lacking. Nelson et al (2007) describe a prototype system where both economic and production impacts are considered across Australia.

Climate change risk analysis is a special case because it involves examining potential future risks to agriculture given high levels of uncertainty, partcualrly beyond the thermal processes and at local scales. There are a number of limitations in the climate science, and efforts to extend analysis beyond the meteorological sphere are only starting. This is described in more detail in section 3. To date, none of the drought monitoring systems described in Box 1 has been extended towards analysis and communication of longer term climate change risk.

Box 1. Drought Early Warning and Monitoring Systems

International best practice in drought risk analysis has involved the development of drought monitor and early warning systems (WMO 2006, Whilite et al. 2000). This involves: automating the collection and management of climate data in near real time; integrated modelling and analysis of drought; and delivery of the information to end users to provide early warning, increasingly (but not exclusively) using the internet. This supports the preparedness of drought mitigation plans so that management is proactive not reactive. No efforts have attempted to integrate longer terms climate change risk analysis with the shorter term forecasting and historical analysis that are typical in drought assessment. Three key examples are:

United States Drought Monitor: The National Drought Mitigation Centre at the University of Nebraska maps individual and combined analysis of drought indices including rainfall, the Palmer Drought Severity Index and soil moisture model output. Maps are available including current conditions relative to history and seasonal forecasts. The output is communicated through: http://drought.unl.edu/dm/monitor.html

South African Development Community Drought Monitoring Centre: provide historical analyses of rainfall and a number of meteorological indexes. These are communicated as pre-generated reports suitable for local community use and interpretation at http://www.sadc.int/dmc/

National Agricultural Monitoring System (Australia): provides information to support the preparation of Commonwealth, State and Community drought response. It displays a broad range of climate, agricultural impact and land use information. It generates maps, local level analysis and pre-generated reports through an on line map interface at http://www.nams.gov.au/ . Some of the analyses, such as pasture growth outlooks are integrated with industry delivery systems and education programs, such as Meat and Livestock Australia's Climate to Pasture Growth Outlook at http://adl.brs.gov.au/growthoutlooktool/index_login.php.

New Zealand's efforts match and in some cases are at the forefront of international best practice. NIWA produce seasonal outlooks and deliver standard reports and analyses through the web interface Climate Explorer (http://climate-explorer.niwa.co.nz)

2.4 Risk analysis for agriculture

A risk management process does not have to carry out all the levels of analysis identified above and one level can be used to trigger another—this avoids unnecessary efforts which can hinder effective risk management in some circumstances. Figure 2 is a schematic detailing how different levels of analysis can trigger another for a climate change and drought risk management process. These three levels of analysis take risk management through the identification and formal analysis stages to a level that that provides information for adaptation. In New Zealand, and for most economies, there has been considerable effort in moving from level one onto level two risk analysis for climate change—there has been a strong focus on assessing the climate drivers and the physical impacts on production. For New Zealand, Mullan et al (2005) and more recently Wratt et al. (2008) have clearly identified climate change risks to agriculture by examining climate drivers as agro-climatic indices and running broad area models.

Undertaking stage two and particularly stage three level analyses are the focus of this report. The major difference between these levels of analysis is the system boundary. Level three analyses extend the level two production impact analysis to account for economic aspects such as farm cash flow under drought or climate change. Importantly stage three analyses also examine the influence and the costs and benefits of different management regimes—for climate change risk analysis this is also known as ‘adaptation’ or building ‘resilience’, while for drought risk analysis this is ‘drought mitigation’. Because of the imperative to examine the role of management level three analyses extend risk management to the point of implementing tangible on ground actions. Level three analyses are more integrated, costly in terms of resources, and given the current status of methods likely to involve a degree of new research.

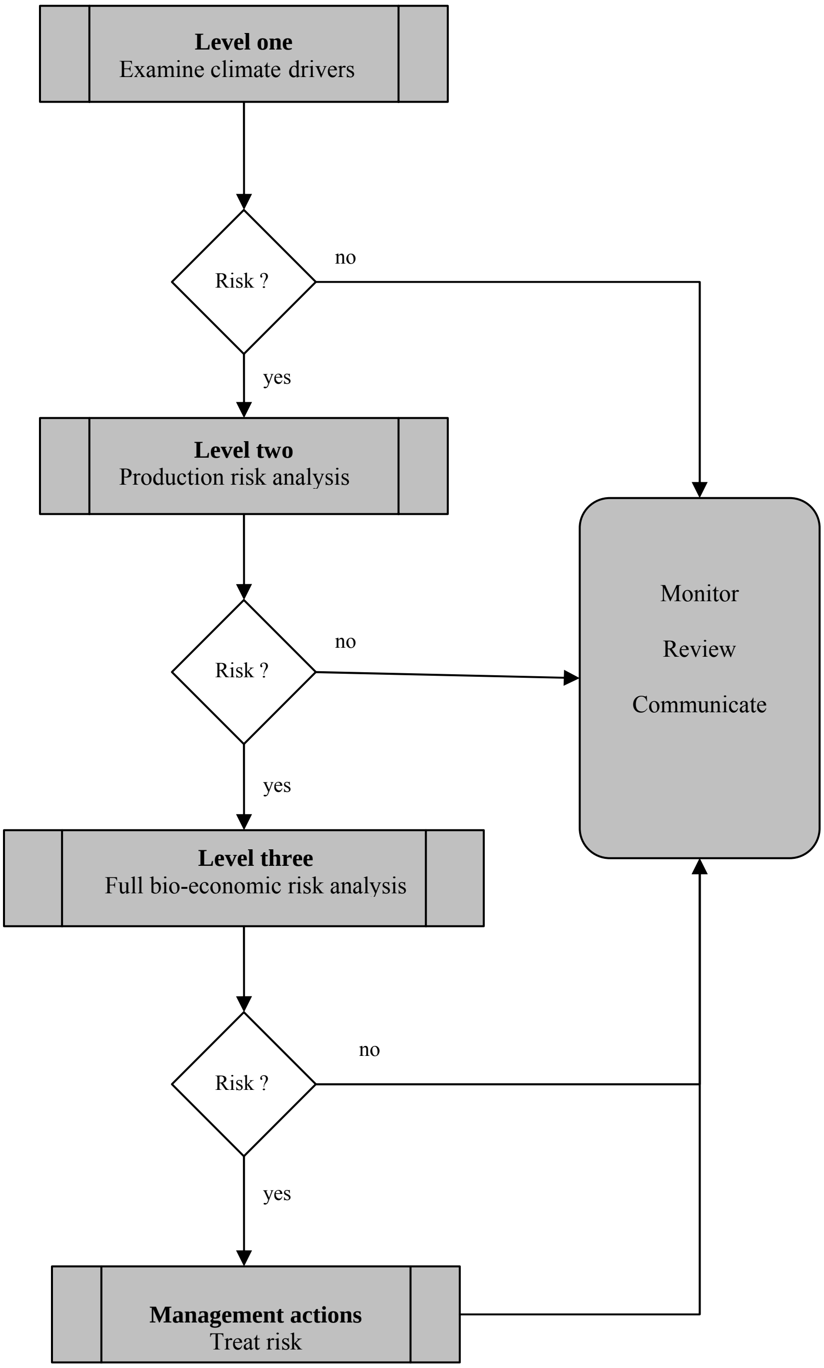

Figure 2. General levels of climate change and drought risk analysis for agricultural risk management.

Figure 3 is a schematic describing the general methodological stages of either a stage two or stage three climate risk analysis. Broadly it involves the integration of an impact model with climate forcing data that have been modified in some way to reflect climate change. Generally, drought risk analyses are driven with historical data and short run forecasting methods, although there are examples where detailed climate models are used. Climate change risk analysis can use observational data to provide analogues of past climate as a guide to the future. In cases where climate scenarios are used from the IPPC's suite of General Circulation Models (GCMs), this involves downscaling the climate forcing data to the level of relevance of the impact model. There are many variants to the stages of this process and even more technical methodological choices to be made within each stage—it is rare for two climate change impact assessments to be identical in their specific methodology.

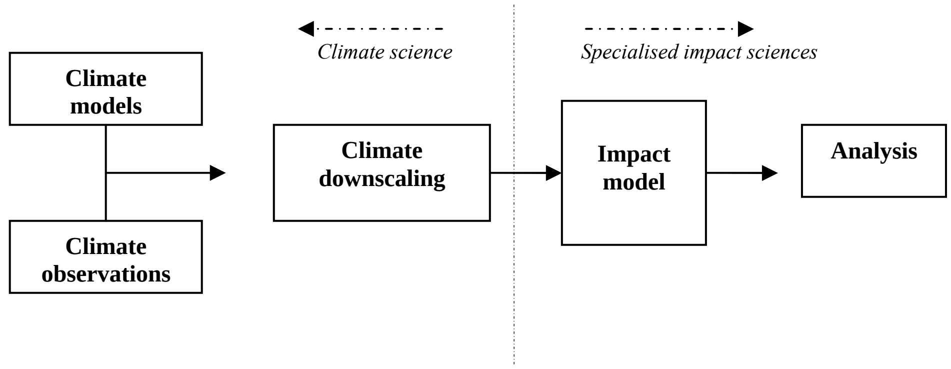

Figure 3. General stages of a level two to three climate risk analysis for agriculture.

Scale is a critical factor governing the selection of methods. In agricultural risk assessment spatial scales can be characterised as farm, regional and national level while temporal scales can consider seasonal (within a year), annual, decadal (around 5–10 years) or long term time frames. Scale has an important influence on methods because it governs the appropriate choice of climate models, downscaling algorithms and impact model. Different end users also have preference for information at alternative scales. For example pertinent information for a farmer may be analysis of localised risks, while knowledge of how that risk varies across the country may be of marginal benefit.

3. Review of climate risk analysis methods

To simplify the description of methodologies used in climate risk assessment in agriculture this section has been divided into three sections. The first section overviews methods used in the climate science domain of risk analysis. The second examines those found in the specialised impact sciences. The third section reviews some additional aspects of integrated risk analysis. The discussion provides general information about climate risk analysis for agriculture more broadly, with emphasis on methods that analyse climate change.

3.1 Climate science

There are a broad range of methodological choices concerning the collation and treatment of the climate drivers in a risk analysis. Figure 4 is a schematic summarising the main choices, tracing different methods branches through to the type of analysis they support.

The first major decision is whether to use global scale General Circulation Models (GCMs) to provide forcing data. If observations are used this focuses the analysis on agricultural sensitivity supporting examination of which levels of climatic change, or in drought applications the degree of historic variability, that lead to an impact. This approach uses observed history as either a statistical summary or event based analogue. It is the most common approach in drought risk analysis. It can also be used in climate change risk analysis when additional steps are taken to bias the selection of analogues toward a climate change type future or to simply apply a range of change factors assumed by the researcher. The strength of the approach is that it avoids some of the uncertainty encountered when using climate models. The chief disadvantage is that it assumes that the past 100 years is a guide to the future—this assumption is not physically plausible given anthropogenic climate change. This methodological branch relies on the strength of the agricultural simulation used, and this will be explored in section 3.2.

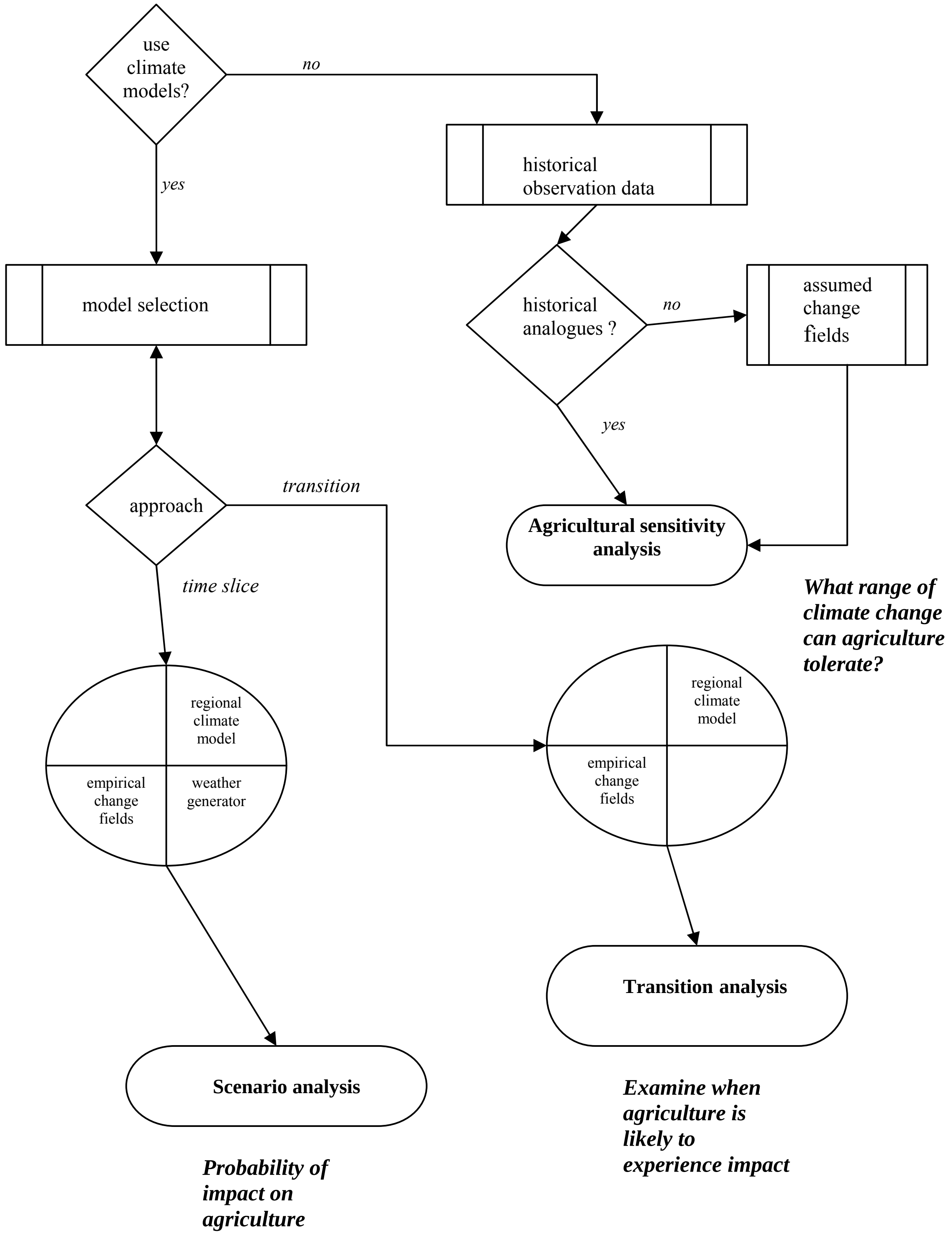

Figure 4. The general methodological choices in the climate science domain of agricultural risk analysis.

The second major branch of Figure 4 uses climate models to support two types of analysis: transitional studies which examine when agriculture is likely to experience an impact; and scenario (time slice) studies which examine the probabilities of impact at a given point in time (decade) in the future. Both approaches are the core of long term (2050–2100) climate change impact assessment. The scenario approach is probably the more common choice because it reduces the computational expense of an analysis. There have been very few studies using this methodology branch to examine drought in the medium term future (5–20 years). However, drought forecasting at seasonal timescales (1 to 3 months ahead) is increasingly using output from global climate models.

The circles in Figure 4 represent the need to employ some type of temporal and spatial downscaling technique in a scenario or transition risk analysis. There are a broad range of methodological choices within this aspect of climate science. As described in section 3.1.2, decsions are important because on the one hand the choice of method dictates the types of inference that can be made, while on the other it can add considerable time and expense to an analysis with little gain in precision or applicability.

It is also important to recognise that using climate models is a relatively new area of agricultural risk analysis compared to using historical observations. This is particularly important to recognise in climate change risk analysis as methodological choices are rapidly evolving, and they are usually made when there has been little hard testing and comparison between methods, or the implications only partially understood or assumed. As described in section 5, there is a rationale to continue methodologically grounded research in climate change risk analysis. The following sections explore some of the methods summarised in Figure 4 in more detail.

3.1.1 Climate model selection

If GCMs are to be used in a risk analysis a model selection process is required. There is an overriding practical requirement to reduce the data to a level that is practical for a risk analysis. There is also a scientific argument because not all GCMs are equal when explaining climatic processes that influence regions of the world—this is not saying that rejected models are inferior, but they have been developed and parameterised to study other global processes that do not heavily influence New Zealand's climate. In climate change risk analysis it is now standard practice to use an ensemble of GCMs to account for inter-model differences in the simulation of climate processes. The model selection processes is concerned with rationalising the number of models in an ensemble to those that realistically approximate the broad synoptic and other systems that influence New Zealand climate.

The recent expansion in the use of ensembles in risk analysis has been supported by improving the availability of GCM data to the broader research community. The Intergovernmental Panel on Climate Change (IPCC) Inter-model Comparison Program archives output from all experiments used in the third and fourth assessment reporting process. The fourth assessment report GCM output are generally available to the research community free of charge for a subset of emissions scenarios and most variables. A number of control experiments, 20th Century simulations and future scenarios are available for each model, usually as integrals of a number of model runs which account for different starting conditions.

One of the implications of taking the ensemble approach in agricultural risk assessment is the large amount of data. If the five variables needed to run an agricultural simulation were sourced from all AR4 GCMs, for three emissions scenarios at a daily time step, this would be in the order of 17 million data points for one GCM grid square. If the time step is changed to monthly this reduces to approximately 600,000 data points. When these data are passed through a spatial downscaling scaling technique the number of data points increases further, before any sort of agricultural simulation is attempted. Hence there is a practical argument to reduce the amount of climate data for use in risk analysis through a combination of careful model selection, scaling algorithms and selection constraints.

Model selection generally involves assessing the ability of GCMs to simulate processes of interest. For example Collins et al (2005) developed an index to measure the ability of a GCM to capture the ENSO process; based on weighted error scores for ENSO frequency measured using sea surface temperatures (SST's) across the equatorial pacific; the ability to capture the monsoon; and measuring high and low resolution frequencies in SST's. Whetton et al (2005) describe a number of statistical measures, and give guidance about matching model selection to proposed use. Such scores can be used to weight the 24 members of the ensemble so that those of highest precision influence the analysis more than those that do a poor job of explaining processes.

New Zealand research (NIWA, *pers. com.* Mullan 2008) has assessed the ability of the AR3 and now the AR4 models to replicate the main climatic features of the central and southern pacific. Based on these results, and the availability of data, a subset of 12 models has been selected for further use in climate change analyses. These are listed in Table 1, along with the New Zealand and global average temperature changes for different time periods.

Table 1. Annual temperature changes (°C) relative to 1980–1999 for 12 GCMs forced by the SRES-A1B scenario. Changes are shown for different end periods, for both the global average and downscaled New Zealand average.

Model (Country)	Global change	Change to 2030-49		Change to 2080-99	
	to 2090-2099	Global-avg	NZ-avg	Global-avg	NZ-avg
cccma_cgcm3 (Canada)	3.10	1.47	1.27	2.99	2.69
cnrm_cm3 (France)	2.75	1.30	0.87	2.60	1.83
csiro_mk30 (Australia)	1.98	0.65	0.54	1.84	1.13
gfdl_cm20 (USA)	2.90	1.29	0.82	2.83	1.96
gfdl_cm21 (USA)	2.53	1.31	1.22	2.44	2.16
miroc32_hires (Japan)	4.34	2.00	1.35	4.15	3.44
miub_echog (Germany/Korea)	2.86	1.19	1.12	2.76	2.23
mpi_echam5 (Germany)	3.31	1.09	0.33	3.15	1.75
mri_cgcm232 (Japan)	2.20	0.97	0.71	2.16	2.07
ncar_ccsm30 (USA)	2.71	1.57	1.19	2.63	2.11
ukmo_hadcm3 (UK)	2.90	1.24	0.66	2.79	1.56
ukmo_hadgem1 (UK)	3.36	1.35	1.14	3.22	2.21

Note: Information on these models can be found in Chapter 10 (Meehl et al., 2007) of the IPCC Fourth Assessment Report, and on website http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

3.1.2 Climate downscaling

GCMs are used to study the dynamics of large scale global processes and for the IPCC ensemble the model structure and parameterisation has focussed on properly accounting for the global system at very broad spatial and climate time scales. For all impact assessments further treatment of GCM output is required so that the data are relevant to the local spatial scales at which impacts occur—for many agricultural applications weather type time scales and regional to farm spatial scales. The practice of downscaling is a diverse and rapidly changing area of climate science in its own right, and it is not possible to provide a detailed overview in this report.

The IPCC guidance information (Wilby et al. 2004) categorises downscaling methods as empirical, stochastic or dynamic. Empirical approaches use known relationships between climate variables observed at the lower scale and predictors from indices of the broader climate process at GCM scale. Stochastic downscaling relies on the internally generated dynamics, usually spatial and temporal autocorrelations and cross correlations between variables at the finer scale to generate a climate variable given information from broader climate process (GCM) scale. Dynamic downscaling uses regional climate models (RCM), which simulate processes and feedbacks occurring at the finer scale (e.g topography, land use and local synoptic patterns), given forcing from a the broader process (GCM) scale.

The choice of downscaling methods needs to be governed by the type of application, and the validity of the assumptions for that particular application (Wilby et al. 2004). Table 2 provides some of the general advantages and limitations of downscaling methods that have been used in New Zealand. Internationally and in New Zealand empirical and stochastic downscaling methods are currently used far more widely than the dynamic methods in agricultural risk analysis. There are practical limitations that restrict widespread use of RCM's, such as availability of data, transportability of the models as well as high computational resource requirements.

The majority of downscaling methods use assumptions which mean they project the mean state of the climate over the long term, and like GCMs they should not be used to predict the *timing* of individual climatic events. This includes temporally varying phenomena like inter-annual drought and on weather time scales extreme high rainfall and or temperature events. Different scaling methods also vary in terms of their ability to predict the climatic probabilities of extreme events. For example, scaling assumptions are embedded in the empirical methods which mean that the tails and the mean of a climate variable's distribution are linearly dependent. Analysis using physically based models highlights that this dependency is highly non-linear. There is an expectation that over time RCMs coupled to improved GCMs might increase confidence in the analysis of extreme weather states and or drought states.

As a general rule the further the level of disaggregation required the more uncertain the downscaling methods. For example, it is extremely difficult to devise a downscaling method for a farm scale study based and a single climate station, particularly for making inferences about the frequency of extreme weather events. There tends to be less uncertainty when the analysis problem is centred on a region or sub regional scale (for example a network of 10 or more climate stations spatially averaged) for making inferences about change in the mean climate.

Methods of downscaling can be very difficult to validate and compare, particularly for future climates because there is no objective measure of the state of future processes. It is possible to evaluate methods based on past climate, but considerable work is required to evaluate if error is the result of the forcing GCM or the downscaling method.

The research effort in downscaling has focussed on single variables for use in either climate analysis or other impact sectors, and not always for use by an agricultural simulation model. Methods have tended to focus on rainfall and/or temperature. This may create limitations, for example agricultural impact analysis requires approximation of changed and or preservation of the seasonal dependence between 5 core variables: rainfall, maximum and minimum temperatures, radiation, and potential evaporation. For some models additional or different variables are required like wind, soil or leaf temperature and crop/pasture canopy level irradiance.

The sensitivity of agricultural models to these variables, and or the seasonal dependencies between these variables, also differs depending upon the type of system simulated. Hence the suitability of a given downscaling method is not universal for all agricultural practices and models. The 'integration' of climate by an agricultural system means that it may be possible to validly use simpler downscaling methods. For example, Roberston et al. (2007) showed that temporally smoothed rainfall data did not have a large impact on the calculation of long term annual wheat yield at the regional scale (a broad agro climatic measure) compared to simulations where the day-to-day noise was preserved. It did however modify individual station results.

Table 2. The main approaches, benefits and limitations of climate downscaling methods currently implemented in New Zealand.

Method	Benefits	Limitations
Empirical	Preserves seasonal dependence Practical technique ready to implement	Assumes parameters are valid in the future Limited number of variables available (rain and temperature) Does not support extreme value analysis Questions over accuracy because of linearity assumptions
Stochastic	Generates long runs of data suitable for risk analysis	Difficult to parameterise Can be computationally expensive Tends to under estimate dispersion (extremes) May not preserve seasonal dependence Limited number of variables available
Analogue	Preserves seasonal dependence. Preserves extremes. Guide for decadal scale planning and what-if studies All observed variables available	Assumes past is a guide to the future Limited by observation data availability prior to 1970 Not suitable for extreme change scenarios and beyond 2040.
Dynamic (RCM)	Physically based Greater number of variables available Improved precision and accuracy. Enables analysis of extremes	Limited number of global models (ensemble approach not currently possible). High computational and implementation costs

The reality is that most downscaling efforts may require a combination of methods. For New Zealand, the United Kingdom's Environmental Agency Rainfall and Weather Impacts Generator (EARWIG) provides a useful benchmark (Kilby et al. 2007). It is software whereby a range of climate change data are delivered to impact researches at regional and local scales for different uses. Methodologically it:

- uses observations to define current climate;
- uses a RCM to derive change factors for temperature and rainfall, given GCM boundary conditions;
- uses a stochastic model of daily rainfall fitted to current climate, which is then refitted to future climate using future factored daily rainfall statistics;
- uses a weather generator to simulate other variables, which is based on regression relationships between rainfall and those parameters, for both future and past climatology.

The following is a general description of a suite of downscaling methods, focussing on work that has been undertaken in New Zealand with some relevant international examples.

Empirical downscaling

The method used to empirically downscale output from GCM's to a finer scale in New Zealand is described in Mullan et al. (2001). Relationships (a three parameter linear regression model) are developed using broader scale NCEP re-analysis data and observed rainfall or temperature all at the monthly level. Two 'Trenberth' atmospheric circulation indicies serve as prediction variables, and are calculated from the NCEP mean sea level pressure fields: Z1 (mean sea level pressure (MSLP) at Auckland minus MSLP at Christchurch; an index of the strength of the zonal airflow across New Zealand) and M1 (MSLP at Hobart minus MSLP at Chatham Islands; and index of the meridional airflow across New Zealand). In the latest implementation of the methodology, the observation data are the virtual climate station gridded data (VCS, Tait et al. 2006), providing a coverage for the whole of the country. The residual sum of squares is calculated from the observed and predicted monthly station anomalies and minimised using linear least squares to determine the three parameter values. The three estimated parameters are then applied to future Trenberth indices calculated using MSLP and future rainfall and temperature data from 12 GCM models for the A1B emissions scenario for given time slices, currently 2030–2049 (midpoint reference year 2040) and 2080–2099 (midpoint reference year 2090).

This method provides monthly change fields (from the baseline period 1980–1999, midpoint reference year 1990) for each 0.05° latitude/longtide (approximately 5km) gridpoints in the VCS network. To provide climate change scenario data for use in impact modelling or analysis of climatic variables, the monthly change fields are applied to the daily VCS data by matching each month's change field to the day within the month. To date this method is used for rainfall and temperature, with daily estimates of future potential evapotranspiration made using a regression-based approach (Mullan et al. 2005). This approach is the current methodology used for New Zealand as published in the MFE Local Government Guidance Notes (2005, 2008). It was also used as the basis of the drought risk analysis under climate change described by Mullan et al. (2005).

Stochastic downscaling

Stochastic climate generators exploit the autocorrelation structure in observations and use these to simulate runs of climate data. The major issue is to obtain sequences that conform to the mean climatology, but also the natural variability, the extremes and other time series characteristics. Generators like LARS-WG, WGEN (Semenov et al 1998) and CLIGEN (Scheele et al 2001) have been used internationally as a means of providing longer runs of data suitable for climate risk analysis at sites where there are only a few years available. These approaches use either Markov chains in either full or hidden forms (the Richardson type generator) or empirical distributions of wet-dry spells.

Testing of these approaches has shown that they perform well in estimating the mean climate, but not as well in estimating higher moments. This is attributable in part to assumptions made about time in the generators, for example generating rainfall is a day-by-day process. Other approaches have relaxed these assumptions, like the Neyman-Scott cluster model which characterises rainfall by clusters of cells making up storm events, or small scale rain bearing structures that may last hours or over many days.

NIWA has applied Richardson type generators to define rainfall, temperature and radiation fields (Thompson and Mullan 2001 a, b). Stochastic downscaling has been incorporated into the CLIMPACTS system to generate future scenarios, including input into simple agricultural models (Warrick et al 2001). Such weather generators have mainly been applied at single sites independently, but NIWA has done considerable research on multi-site generators to simulate rainfall patterns for input into hydrological models (*pers. com* Thompson and Sansom 2008).

Regional climate models

Regional climate models are higher resolution physical simulations of climate for a limited area of the globe. Typically the resolution might range from 30 to 50 km, which contrasts to a GCM which might have a resolution of about 300 km. Unlike many GCMs, RCMs do not generally have an ocean component. They simulate the main atmospheric-land processes that influence climate. RCMs are nested within a GCM and variables like atmospheric winds, temperature and humidity from a GCM as boundary conditions.

NIWA has been implementing the RCM PRECIS to simulate New Zealand climate under historic (or control) as well as for a limited number of future scenarios. The model requires boundary conditions from the United Kingdom Met Office model HadAM3P or reanalyses such as ERA-40. Currently the model has been used to simulate the A2 emission scenario and a number of control and experimental runs.

3.1.3 Analogues

As described previously analogues can be taken of past climate to be used as a guide for what may happen in the future. This approach is common in drought risk analysis to provide information that can be used in the formation of drought mitigation planning. Selection of individual analogues is usually and arbitrary process, for example comparing current conditions with a select event in the past. Generally statistical summaries are used, such as dividing historical variability into terciles or percentiles.

Projections from GCMs can be used to build analogues (and statistical moments) of future climate by using them to select past climatic events. Sansom and Renwick (2007) used projected changes from a GCM for the A1B scenario to sample the 100 year historical rainfall records selectively for past conditions that may be analogous to mean New Zealand conditions approximately 50 years into the future. This is appealing for agricultural risk analysis as many of the scaling and accuracy uncertainties in other methods are avoided, particularly for farm scale and/or examination of decadal scale risks. A limitation is the lack of observational data across New Zealand prior to 1970, which restricts the analogue space. Extreme level climate changes and or those beyond 2040–50 may also not be well represented by this approach as the future climate shifts to something not experienced in the last 100 years.

3.2 Impact science

Agriculture is more exposed to the impacts of climate change than many industries, but the impact is complex as production has a non-linear response to individual climate drivers. Plant photosynthesis is a core process, and it is limited by the availability of energy (solar radiation) and substrate (water), with the base reaction regulated by temperature. Animals through removal of plant growth machinery, management and other process like crop and pasture maturation modify the function of this process. Agricultural science is a broad field, and it is not the intention to provide an overview in this report. Mathematical modelling is a small part of the agricultural science research effort where considerable research activities in biological sciences. However it is a critical activity in climate-agricultural risk analysis because they provide a useful approach to track processes and provide an integrated measure of climatic impact.

3.2.1 Impact model selection

Impact models need to be selected and/or developed that are appropriate for a given task or set of end user requirements (Gaunt and Riley 1997 and Jakeman et al. 2005). The quality of a model needs to be validated either with an independent measure or peer review. For the purposes of this report it is assumed that all models discussed have been appropriately validated, but it is recognised that this aspect of modelling is both resource intensive and fundamental to practice. Generally there are three broad approaches to modelling agricultural fluxes based on the way in which a system is conceptualized and represented:

- the first are models based on physical reasoning where every attempt is made to represent all known processes immediately below the scale of inference. These are also known as *mechanistic*, complex or white box models. Processes are fully explicit and based on reasoning from scientific disciplines including biology, physics and chemistry (Thornley and Johnson 2000). Generally these are used for research purposes to investigate and build greater knowledge about processes. Increasingly models developed with mechanistic reasoning are being applied in decision support.

- the second class of models are *conceptual* where an attempt has been made to simplify the system representation. These models are based on an abstract view of the system by refining the conceptualisation to a subset of main effects. They are also known as simplified, parameter efficient, deductive or grey box models, as in an effort to reduce dimensions some of the processes are represented as empirical parameters. These are used in broad scale applications and spatial modelling, and traditionally as farm decision support.

- the third class of models are *empirical*, with a purely statistical basis and minimal reference to processes. The functional forms of these models are deduced by examination of the properties of data, functions developed and parameters estimated by numeric methods. The approach is also known as statistical or black box modelling, as the physical processes are not explicit in the reasoning of functional forms. These are generally used for prediction and as guides for farm decision making.

Generally, mechanistic models are more complex than conceptual or empirical approaches, having more parameters and equations which need to be formed and estimated. Mechanistic models have almost unlimited precision, while empirical and conceptual models have a definable optimal precision. There is also a relationship between scale and model complexity where it is valid to apply simpler conceptual models, reduced to a few main climatic affects, at regional to national levels. To illustrate some of these principles, approaches for modelling evapotranspiration are detailed in Box 2.

An important aspect of model selection and/or development is the definition of the system boundary—this may also govern how pertinent the output of a model is for a given use.

Box 2- Modelling potential evapotranspiration

Mechanistic

The FAO's derivation of the Penman Montieth equation (Montieth and Unsworth 1990, Allen et al. 1998) is a reference mechanistic approach because it is based on a full range of processes influencing transfer of water to the atmosphere, including resistance from soil and plants. An example 'FAO-56 style' style equation is:

$$E_p = \frac{\Delta\left(R_n - G_s\right) + 86.4\rho c_p \delta / r_a}{\lambda\left(\Delta + \gamma\right)}$$

where E_p is potential soil evaporation, Δ is the slope of the saturated vapour pressure deficit curve (kPa^oC^{-1}), R_n is the net radiation ($MJm^{-2}d^{-1}$), G_s is the soil heat flux ($MJm^{-2}d^{-1}$), ρ is the air density (kg m^{-3}) C_p the specific heat of the air (kJ kg^{-1} $^oC^{-1}$) and δ the vapour pressure deficit (kPa), r_a the aerodynamic resistance (s m^{-1}), λ the latent heat of vaporization (MJ kg -1) and γ is the psychometric constant (kPa^oC^{-1}).

Conceptual

There are also simpler algorithms based on partial representations of processes, such as Priestly Taylor, Blaney Criddle and Heargreaves E_p (Allen et al. 1998). The radiation based Priestly Taylor equation is reproduced here as an example. It calculates E_p as a function of the latent heat of vaporization and the heat flux in a water body:

$$E_p = \alpha\left(\frac{s}{s+\lambda}\right)\left(\frac{\left(Q_a - Q_x\right)}{L}\right)$$

where α is an empirically defined constant, s is the slope of the saturated pressure temperature gradient, λ is the psychometric constant, Q_x is the change in heat stored in a water body ($MJ/m^2/day$), L is the latent heat of vaporization (MJ/kg) and Q_n is the net radiation supplied as an independent variable ($MJ/m^2/day$) .

Empirical

It is also possible to model evapotranspiration empirically. For example Xu and Sing (2002) derived a modified form of the Blaney Criddle (BC) algorithm:

$$Ep = \left(\lambda R\right)\left(T + \beta\right)$$

where R is incoming shortwave solar radiation and T is the mean air temperature (^oC/week). The parameters λ and β are constants obtained by calibration and the equation is known to exhibit moderate to high accuracy when well calibrated (Xu and Singh 2002).

Figure 5 is a schematic describing system boundaries in livestock modelling. In general, most modelling concentrates on the soil water and pasture system boundaries, and there has been considerable research effort towards modelling pasture and crop responses under climate variability. A smaller number of models have fully coupled climate-water balance-pasture-animal subroutines and simulate actual livestock production in an open system. A smaller number of 'whole farm system models' integrate further into the management system boundary so that management effects like stocking rate strategy can be explored. There are very few examples of 'bio economic models' where through a whole systems framework the impacts of economic and climatic externalities to a farm can be simulated.

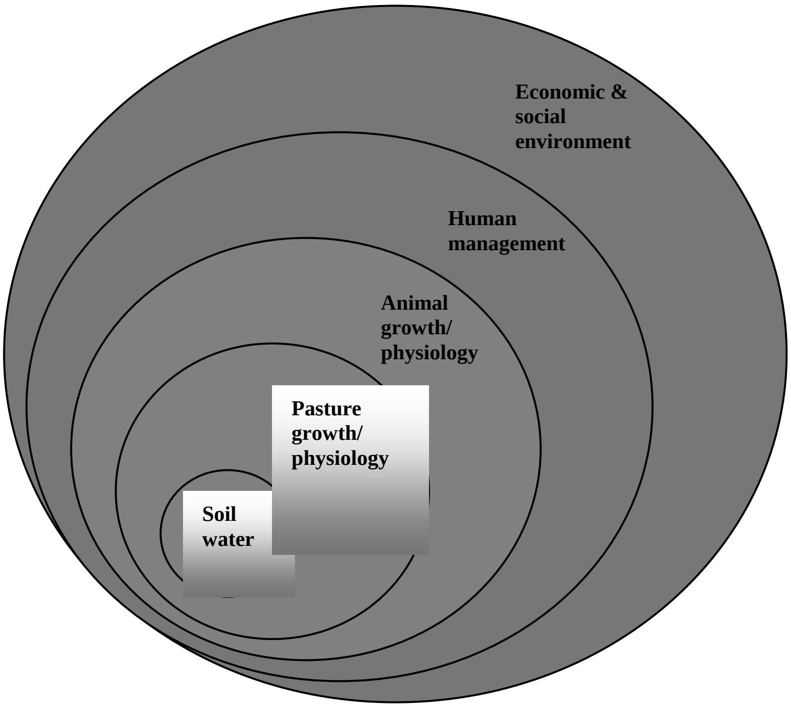

Figure 5. General system boundaries of livestock-crop simulation models.

In practice models usually take a mixed approach, particularly if they are attempting to expand the system boundary. For example:

- a number of New Zealand pasture growth models utilise the linear relationship between evapotranspiration and growth, and use a conceptual soil water balance with an empirical equation to predict growth (for example Fowler et al 2006).

- a number of econometric models use indices of pasture growth as a summary of overall production to predict total factor productivity, and use empirical equations to integrate the biophysical variability influencing farming system with the macro economic environment (see Nelson et al. 2007 for an example).

- some agricultural models do not have a functioning soil water balance or pasture growth subroutine, but use farmer input or long term estimates of pasture growth. New Zealand's FARMAX and Australia's GRAZFEED are examples of feed budgeting tools that use this approach for producer decision support. The MIDAS model, which is used as a research tool, takes this approach to model optimal farm business structures and management tactics for mixed operations in Western Australia.

For integration with climate science the data requirements of a model are important—agricultural climatology is a research field that is in part concerned with calculating climate variables of relevance to plant and animal function in agricultural systems. Modern agricultural models generally require the input of five core climate variables, rainfall, maximum temperature, minimum temperature, radiation and evaporation. The general practice is to use variables at the daily time scale, as this reduces the data requirements to a manageable level, while summarising climate variability at the response frequency most important to plants and soil water. There are variations where some models require finer (hourly) or coarser climate (weekly or monthly) data and/or additional variables such as wind, soil or leaf temperature and more specific measurement of radiation such as leaf irradiance.

Models also require specification of parameters which govern the mathematical relationships used to predict phenomena. Methods of parameter estimation are diverse in agricultural modelling, but may be grouped into prior methods (expert estimation, direct measurement) and post prior methods (finding parameter values using measurement data and a computer algorithm). Agricultural models vary widely in terms of the number of parameters (also an indicator of model complexity), their sensitivity to changes in individual or a number of parameters and whether or not parameters have a physical meaning. Along with mathematical formation, parameter estimation and sensitivity analysis are the fundamental technical tasks of model development—it is assumed that all models discussed have undertaken the necessary work which ensures that functional forms and parameterisation are robust.

3.2.2 New Zealand models

New Zealand has a number of agricultural simulation models that have been developed and shown to be robust. They range from mechanistic models, thought conceptual models used as farm decision support system through to empirical models that are used for prediction. Table 3 references a number of models that appear suitable for application in climate change and drought risk analysis. This is not a comprehensive listing and it is likely that there are a number of others currently applied across New Zealand agriculture.

Table 3. Brief description of some of the Agricultural models developed for use in New Zealand

Model	Description	Uses
Pasture-livestock production		
EcoMod/DiaryMod (Johnson et al 2007)	Mechanistic. Soil-Pasture-Animal-Management	Farm level dairy industry analysis. Paddock or multiple paddocks. Physical analysis of nutrient flows, carbon Dioxide fertilisation
Farmax	Conceptual. Soil-Pasture-Animal-Farm economics. Based on the McCall pasture model.	Dairy industry model Whole farm analysis Gross margin calculation
Baisden et al. 2007 (cited in Wratt et al. 2008)	Empirical Soil-Pasture model	National scale prediction of pasture growth
Cacho et al. 1995	Empirical-Conceptual Soil-Pasture-Animal-Management	Whole farm systems analysis
Massey University (Zhang et al. 2007)	Empirical Climate-Pasture	Spatial (North Island) assessment of climate change impacts on pasture growth
Auckland University (Fowler et al. 2007)	Conceptual-Empirical Climate-pasture	Examination of climate change impacts in the Waikato
Crops		
Sirius (Jamieson et al. 1998)	Conceptual-Mechanistic Soil water-crop-management	Farm scale analysis of crop productivity for both dryland and irrigated crops
CLIMPACTS (Kenny et al. 1995)	Range of conceptual and empirical models for kiwi fruit, C4 grasses and arable crops (maize)	Examining and establishing climate change impact thresholds

3.2.3 Agricultural risk analysis

Risk is quantified using the output of the physical models which create the integration between climate and agricultural production. Simply, the calculation involves determining the probability of a consequence. The probability is determined by an analysis of the distribution of model output. The type of consequence is determined by the systems boundary of the model. Metrics might include for example: rainfall deficit; soil water deficit; pasture growth; pasture quality; animal weight; reproductive output; animal numbers; gross margin; farm cash income; and farm debt to equity ratios.

This suite of metrics would encompass a full definition of drought risk, going from climatic and hydrological drought, through production to financial drought. The reality is that most assessments do not cover this spectrum. For example, the international examples of national drought monitoring systems described in Box 1 focus heavily on meteorological drought, with some extension to hydrological drought by use of soil water balance models. A subset of metrics can be devised so that the more convenient measures become 'risk indicators' (White and Bordas 2000). For the indicator approach to provide valuable information there needs to be an identification of 'critical thresholds'.

3.2.4 Threshold establishment

Establishing thresholds is an important, and sometimes under-examined aspect of climate risk assessment for agriculture. This report highlights two examples where threshold establishment has been undertaken that moves analysis away from biophysical thresholds towards 'critical thresholds' where social, economic and environmental risks are integrated but the measures are convenient:

1. The first is the work of Stephens (1998) who established critical thresholds for dry land cropping systems in Australia for drought risk analysis. Based on detailed examination of farm productivity, financial performance data and models a threshold of two failed seasons was found, where this is the type of risk that is generally beyond the capacity of current farm businesses to manage. The criteria could then be determined, and extrapolated across the country by using simple metrics of wheat yield from well-validated systems and national level models, without the need to repeat the more substantive analysis across the country.

2. Kenny et al. (2000) demonstrated the establishment of different thresholds for New Zealand agriculture under climate change: *management thresholds* which would prompt a change in management practices such as cultivation or stocking rate; *risk thresholds* which would prompt a technology change within the existing farming system such as a move to a new crop or pasture cultivar; and *geographic thresholds* where current production systems would become unviable and there would need to be an adjustment of industries into alternative land use.

Establishing critical thresholds can be carried out in a number of ways. Kenney et al. (2000) used a model sensitivity analysis harnessing the CLIMPACTS system. Stephens et al. (1998) used a combination of detailed modelling and farm monitoring and benchmarking networks. Thresholds are also not static over time and can change as farming improves its risk management strategies—in climate change science this is similar to 'adaptation' or in systems theory to 'resilience'. Table 4 outlines some adaptation research identified in the consultation workshop for this project. There are other dimensions to adaptation, notably social and community resilience processes, which are recognised but beyond the frame of this project. From a modelling perspective adaptations can be examined by modifying either the structure of a model to include new or changed processes and or the parameters of a model to reflect changes in biological and other thresholds.

3.3 Integrated analyses

The following example analyses illustrate the integration of climate and agricultural science in climate change risk analysis.

3.3.1 New Zealand drought risk analysis

NIWA's current methodology for analysis of climate change risk is summarised in Figure 6 and described in Mullan et al. (2001) and Mullan et al. (2005). This approach to climate change impact assessment is characterised by the use of change fields. While the approach is common in international practice, it restricts an analysis to inference about mean changes in agricultural climatology. NIWA's current implementation of the method for the assessment of drought is based on models and scenarios from the IPCC's third assessment report (TAR♦) and is currently being

♦ The IPCC maintains an archive of data from a number of General Circulation Models (GCM) they have used to construct assessment reports. These are provided by 24 peak climate research institutes around the world. TAR GCM outputs were collated in the period 1998-2002. Another set of simulations were collated in 2001-2005 for the fourth assessment report (AR4).

updated with models for AR4 models. The empirical downscaling is described in section 3.1.2. A time slice strategy is used, referencing the 2030s and 2080s as points of change relative to the 1980s.

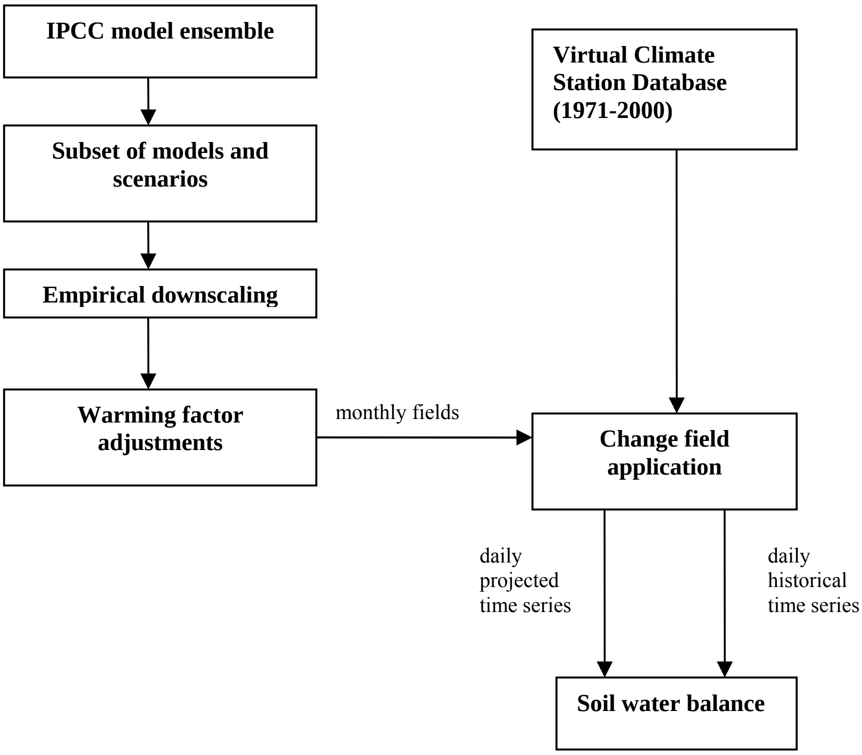

Figure 6. Summary of the downscaling procedure used by Mullan et al. (2001) and Mullan et al. (2005) for studying climate change impacts in New Zealand.

The downscaling methods provide daily rainfall, temperature and evaporation as a time series suitable for input to an agricultural simulation model. The approach has also been coupled to a simplified conceptual water balance model, and potential evapotraspiration deficit (PED) calculated to provide an indicator of hydrological and agronomic drought (Mullan et al. 2005). A limitation of the current approach is lack of feedback from plant function on the calculation of evapotranspiration deficit.

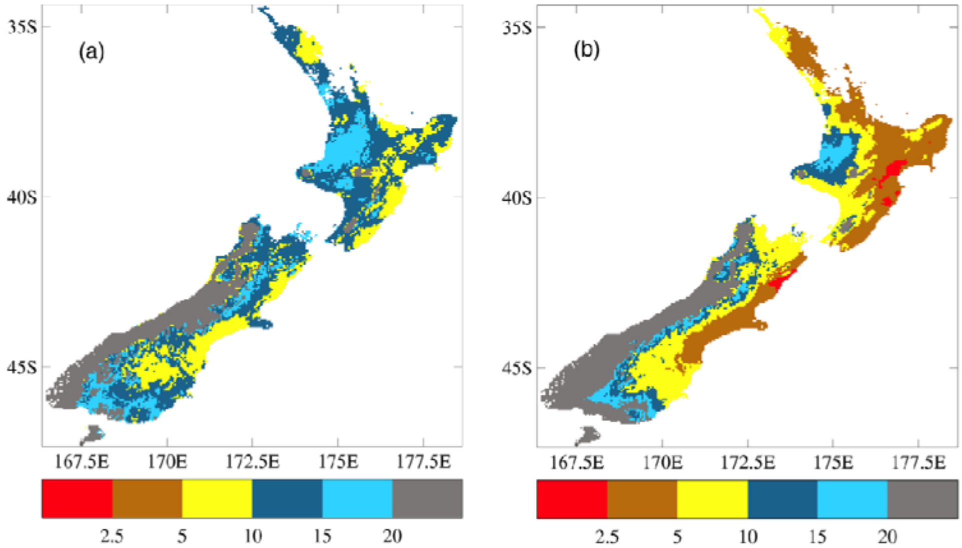

Figure 7. Projected average recurrence interval (years) in the 2080s under the (a) "low-medium" and (b) medium-high" climate scenarios, for the driest annual conditions that currently occur on average once every 20 years. Indicator is potential evapotranspiration deficit.

Key output from this method is shown in Figure 7 and Figure 8. This level of analysis was able to assess the changing levels of the drought recurrence interval across New Zealand under climate change scenarios. Some variations in international practice to the approach include: use of alternative methods in evaluating which global climate models to use (Carter 2007; IPCC 2005; Whetton et al. 2005); choice of alternative base periods; different algorithms for either spatial or temporal downscaling (Baron et al. 2005; Busuioc and Giorgi 2006; Carter 2007; IPCC 2005; Wilby et al. 2004); and methods for validating the procedures (Carter 2007; IPCC 2005; Whetton et al. 2005). Changing the current NIWA methodology to reflect some of these variations would likely result in little or no net improvement, however there is need to update the approach with the most recent set of climate change projections.

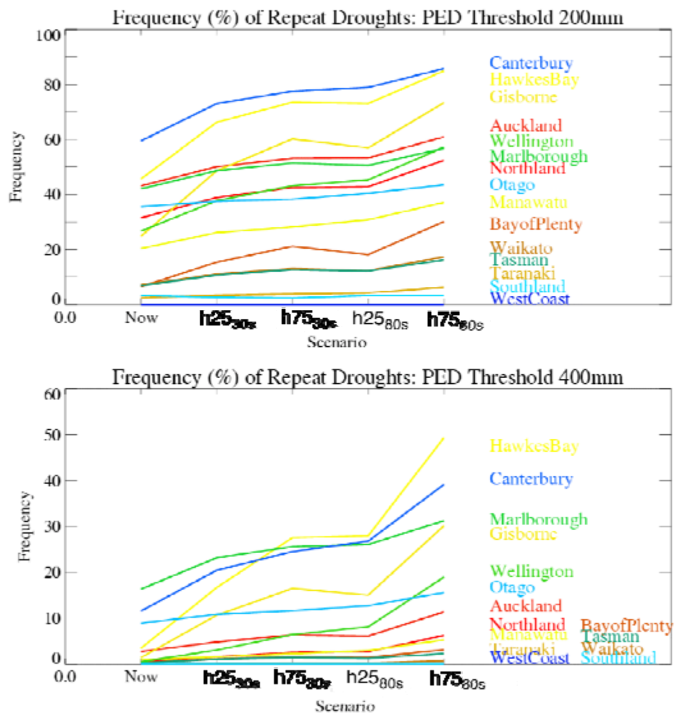

Figure 8. Frequency of consecutive droughts at specified PED thresholds of 200 mm (upper panel) and 400mm (lower panel). Results are shown for all 15 Regional Council regions, and for the current climate ('now') and the four future scenarios.

3.3.2 Agricultural sensitivity analysis

This approach uses output from GCMs to inform risk analysis and is an example of a 'top-down' approach where broad level models have been driven by downscaled climate (Figure 9). There are examples of 'bottom-up' approaches which rely on understanding the diversity of vulnerability between individual management (farm) units and risk analyses that examine adaptation (Pielke et al. 2007). The scale of such analysis relies on the development and application of farm and paddock level models, which are more physically detailed and generally more sensitive to management and local landscape factors. Many of these models have been developed by specialists in agricultural sciences (e.g. in New Zealand – AgResearch, Crop and Food Research, Dairy NZ) and their system boundary can extend to the micro-economics of the farming system.

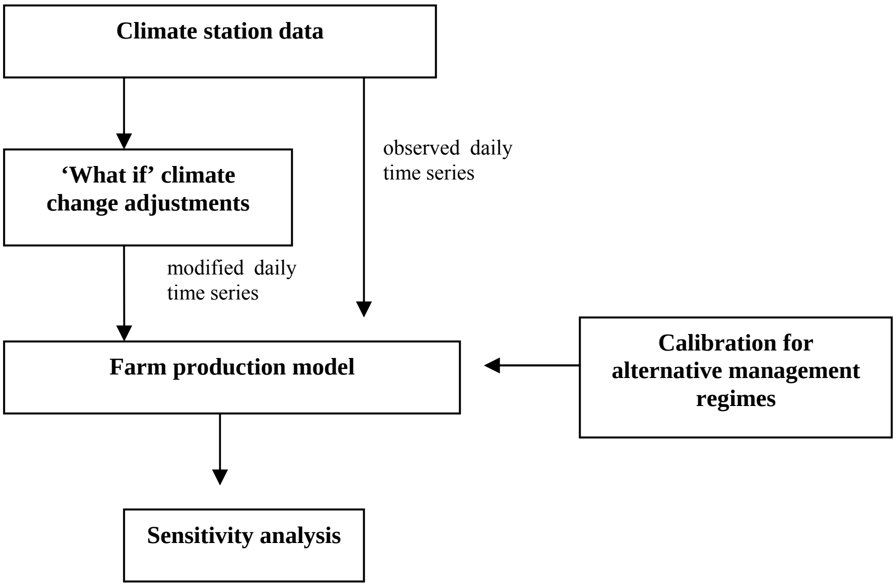

Figure 9. The general stages of 'what if' climate change impact assessment.

An example of this approach is provided by Howden et al. (2001) who examined the risk of climate change to Australian wheat crop production (Figure 9). The study took a what-if approach, where climate observations were modified by incremental change factors assumed by the analyst. Given a range of future climates, the crop model APSIM was run given different calibrations that reflect alternative management regimes or adaptations. The analysis method allowed inferences to be made about the sensitivity of agricultural systems to a broad range of climate changes, given interaction between changes in temperature, rainfall, carbon dioxide levels and levels of adaptation. The resulting analysis demonstrates different levels of sensitivity of an agricultural system to temperature and rainfall change and how it is modified by adaptation (Figure 10)

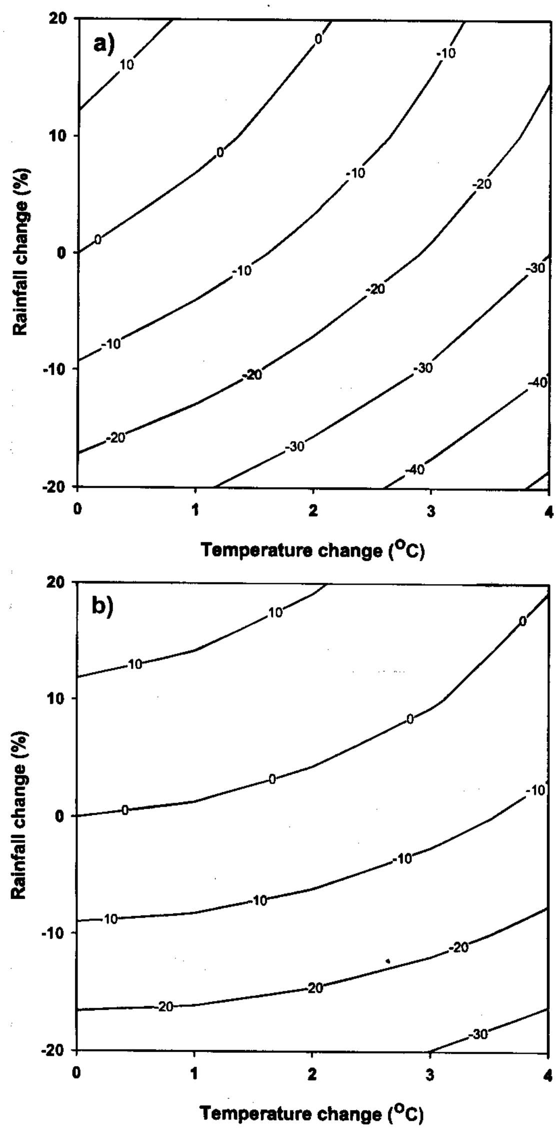

Figure 10. Example output from a sensitivity analysis of Australian wheat production to changes in climate, carbon dioxide levels and adaptation (Howden et al 2001). Analysis for Emerald in Queensland. a) is no adaptation b) adaptation

The advantage of the what-if approach is that it provides local level guidance about which management tactics reduced or increase risk given climate change. The approach also avoids the downscaling problem, which can be a source of error in climate change risk analysis (Hall and Mckeon 1998). The quality and relevance of the sensitivity analysis is dependant on the detail, validity and comprehensiveness of agricultural simulation models. It is important to consider the level of detail in each model and the extent to which the mathematics is based on mechanistic or empirical relationships—this is particularly important if a study aims to explore the potential net impacts of carbon dioxide fertilisation on farm production (Thornely and Cannell

1997). Ideally farm scale models are thoroughly calibrated with observations made at a case study site. They take a case study approach, assuming an individual farm as a reference point for regional level practice.

3.3.3 National to regional scale risk analysis

One of the limitations of the what-if approach is that while it provides local level guidance; examination of regional to national level variability is often required. Analyses at these scales could use the 'biophysical indicator' approach to examine critical thresholds and/or use of these indicators to couple climate risk analysis to econometric models (for example refer to Nelson et al. 2007). Baisden (cited in Wratt et al 2008) used a simplified empirical model of pasture growth coupled to the downscaling method summarised in Figure 6 to undertake national level assessment of pasture growth under climate change across New Zealand.

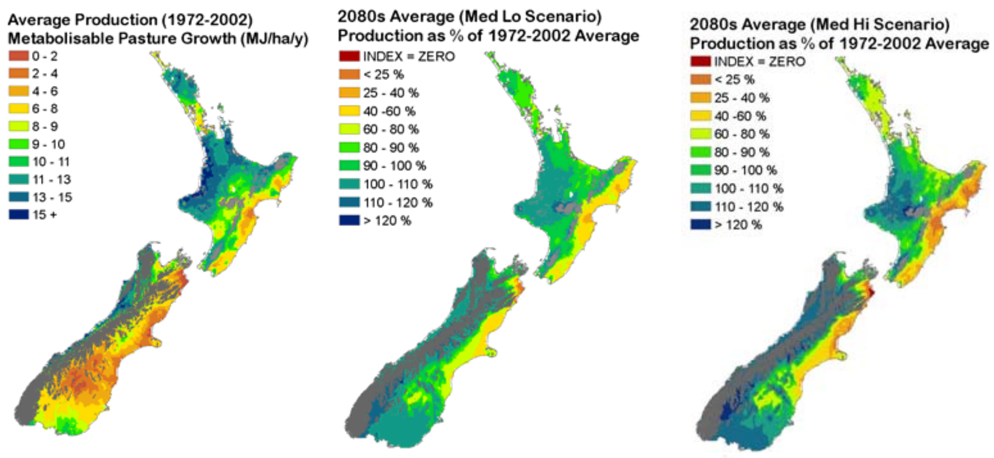

Figure 11. Example output from a national level analysis of pasture growth under climate change (Baisden cited in Wratt et al 2008).

The example output in Figure 11 highlights considerable regional variability in impact in the future scenarios, ranging from net decline to increase (the projected change in production for New Zealand as a whole is close to zero). The output of this type of regional to national level study has limited relevance for an individual producer seeking guidance about risks and management on their farm. It is however important information in making industry and policy level decisions about farm adjustment pressures and location shifts in farm viability in the future.

3.3.4 Uncertainty analysis

The risk analyses described so far are 'deterministic' in that they use an impact model as a predictive tool to translate climate change scenarios to agriculturally meaningful indices, usually as 'one-off' model runs. In this frame of thinking climate change risk analysis is dominated by two perspectives on uncertainty:

1. Use models based on physical reasoning where every attempt is made to represent all known processes. The practical consequence is that to capture variability the most detailed mechanistic model must be implemented. Inevitably this leads to risk analysis being focussed on small scales with tight restrictions on the system boundary, for example paddock level investigations of pasture response. This is sometimes described as a 'pure science' approach.

2. Implementing models with a 'no-regrets' assumptions. That is undertaking analysis despite the uncertainties, either known or unknown. Typically more empirical and conceptual approaches are used in order to expand the system boundary and or spatial scale. This is sometimes described as a 'practical science' approach.

An alternative is to employ Bayesian methods from uncertainty analysis where work is undertaken to estimate error (Morgan and Henrion 1990). In a climate-agricultural risk analysis this may involve generating alternative parameterisations and or using different models, and perturbing the entire chain from climate model to agricultural impact metric given a range of solutions. This frames climate change risk analysis in a full probabilistic sense, as a collection of likely outcomes rather than a deterministic prediction. This approach is now common in the analysis of the climate drivers in large multi-GCM model ensembles.

An example of this approach for a regional scale analysis of pastoral production is provided by Clark (2007) and summarised in Figure 12. It is a Monte Carlo risk analysis of both uncertainties in a climate model ensemble and a conceptual impact model. The climate models are evaluated and weighted according to their ability to predict the base climate and a range of change fields determined.

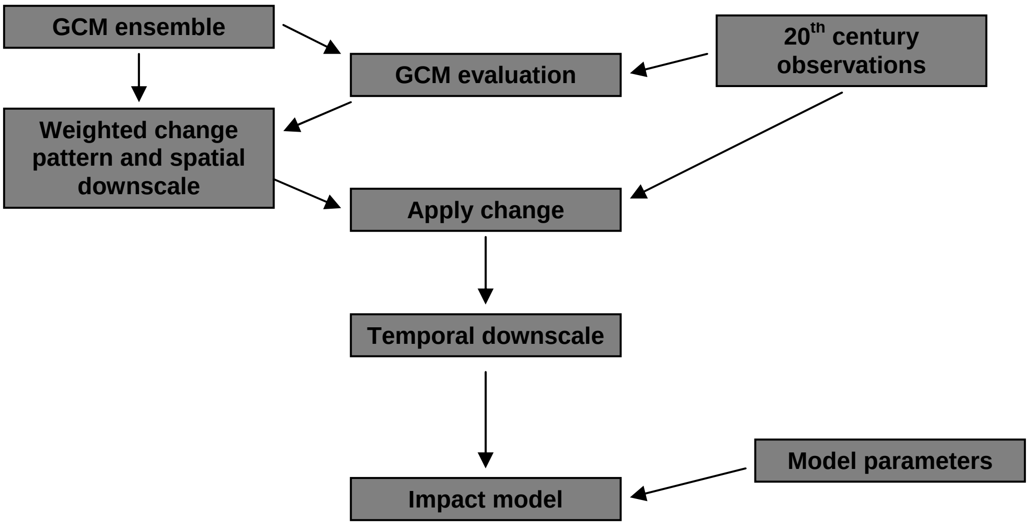

Figure 12. Summary of the uncertainty analysis (Monte Carlo) approach (Clark, 2007).

The impact model is fitted to a broad range of field data, encompassing variability across different management regimes so that a range of alternative impact model parameterisations are attained. Both the impact model and climate ensemble are then perturbed given their respective ranges to give an ensemble of potential impacts. Example output of such perturbation for pasture biomass for one 0.05 degree grid in an agricultural region is shown in Figure 13.

In uncertainty analysis, and to some degree agricultural sensitivity analysis, large data sets are produced. If a climate model ensemble is used the amount of data increases further. Careful thought needs to be given to constraining the resulting 'impact ensemble' by the experimental design. Large ensembles can be well described by standard risk analysis: calculating the probabilities of exceeding thresholds; and formal statistical analysis can be applied to test significant differences between ensemble members (e.g. Jones 2000; Katz 2002).

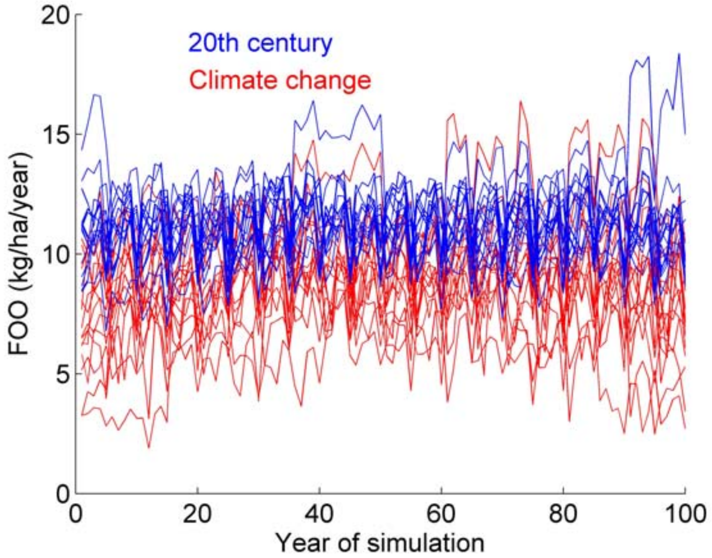

Figure 13. Example output (FOO is food on offer, pasture biomass prior to animal intake) from a Monte Carlo risk analysis of climate change (Clark 2007).

Figure 14 is an example of how a large ensemble can be analysed using probability density estimators, in this case for a sub-region of the sheep wheat belt in Western Australia. There are hundreds of thousands of data points for each probability density function (PDF). They highlight the diversity and most likely values given different combinations of management, land scale heterogeneity and climate change. An experiment was performed to test the sensitivity of this system to the precision in the climate models, by weighting the climate change model ensemble by either the most precise for predicting the 20th century, or alternatively the worst case model output. The PDFs summarise the mean change attributable to climate, and there is seasonal variability around the results. Hence the negative shifts, which are the most likely outcomes in stocking rate, biomass and live weight change, constitute a serious loss of productive potential in these systems.

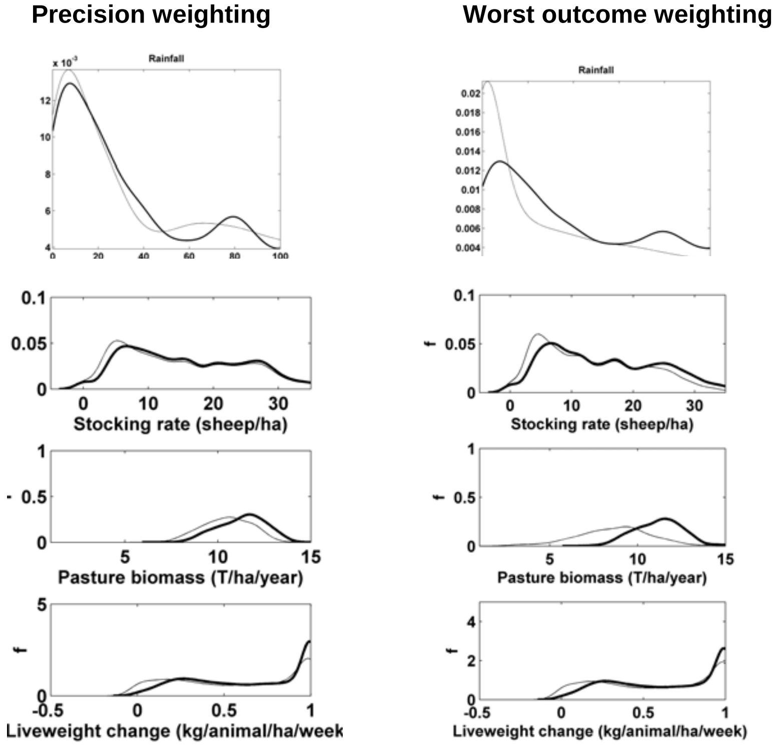

Figure 14. Probability density functions of changes in *mean* output of agricultural indices for base (1970-2000, black line) and projected (2040-2050, grey line) given two alternatives to weighting an ensemble of GCM rainfall. Results summarise variability across a sub region in southern Western Australia, accounting for diversity in management (Clark 2007).

4. Consultation workshop

4.1 Background and aims

A one day workshop was held at NIWA in Wellington on the 8 of May 2008. The goal of the workshop was to establish end-user requirements for information and advice on how climate change is likely to affect drought and agricultural production in New Zealand, and to establish science-based methodologies and timelines required to develop appropriate updated analyses based on the latest climate change scenarios.

Invited attendees included representatives from MAF, MfE, Regional Councils, Fonterra, DairyNZ, PGG Wrightson, Meat and Wool NZ, Federated Farmers, Selwyn Plantation Board, Auckland UniServices Ltd, Aqualinc Research Ltd, Earthwise Consulting Ltd, AgFirst Consultants, AgResearch, GNS Science, Crop and Food Research, and NIWA. A concise version of the background material (section 3 of this report) was provided to attendees prior to the workshop. The day involved a number of short presentations from representatives, focusing on what is being done now and what needs to be done in the future. Open panel based discussion was used as the mechanism to canvass perspectives, generate end user feedback and discuss the material presented

4.2 Proposing the way forward

The presentations, setting out a range of views for the way forward in climate change and drought risk analysis are summarised as either ‘industry requirements’ or ‘science directions’. The industry requirements cover perceived end user needs, strategic positioning for industries, through to some desired research goals for individual industries. The science directions provide statement of current capability of the individual research institutes, as well as planned directions of future research.

4.2.1 Industry requirements

Foundation for Arable Research

The key industry requirements for arable farmers are research projects focussed on both water resource management and water use efficiency. Improving these areas was seen as a core component of fostering climate change adaptation and improving drought risk management in the future.

There have been incremental improvements in plant and agronomic technologies in New Zealand over the last 10 years, particularly for crops like peas, wheat, maize and clover. There is opportunity and need to package these improvements in whole farm crop and pasture growth models to demonstrate their efficacy for farmers. This type of modelling and risk communication would ensure that the farming sector is both risk aware and promotes rapid adoption of technologies. Research enabling the widespread application of the models is seen as strategically important, for example centralising and improving the management of climate data on a daily time for all of New Zealand (for both historic and projection analysis) and integration of crop models with regional climate models.

A concerted effort is required to improve irrigation scheduling and minimise the wastage of irrigation water for crop production in New Zealand. This was seen as both an opportunity where wide spread improvements in efficiency could be made as well as a threat if water resources become scarce. Improvements in this area encompass adoption of better technologies, changing management practices with better soil water and crop transpiration monitoring, and development of integrated regional water resource use plans.

There is also a case for a more strategic effort in risk communication and consultation with industries, to ensure that the full research development and extension cycle is completed in an optimal timeframe. A high level of interaction between scientists and farmers is seen as an important success factor in the future.

FAR ran workshops in the Waikato and Ashburton during May 2008 to communicate the risks of climate change in the rural community. The workshops were funded through MaF's sustainable farming fund, and reports on the workshop are currently being produced (MaF SSFc07/001).

Federated Farmers

The key to enable farmers to make effective decisions is to provide timely, useful information in an accessible format. It is recognised, however, that timeframes will vary with the type of information. Model-based information needs to be useable and its limitations understood. Distribution constraints also need to be taken into account, for example internet access to information, tools and data is limited in rural New Zealand because of limited broadband coverage. Improving levels of risk awareness will require harnessing existing rural networks, and bringing climate change adaptation and drought risk management into the mainstream of rural thinking.

Horticulture NZ

There is limited need for research and development on greenhouse gas mitigation compared to livestock industries. Climate change is likely to bring both positives and negatives for the industry, and a concerted analysis and risk communication exercise is warranted to improve the industries awareness. There is concern that with warmer winters, crops requiring cold vernalisation to set fruit may have productivity impacts. A warmer environment would also increase the risk of incursions from some pests and diseases, for example the risk of Papaya Fruit Fly establishment would be higher in the northern half of the North Island. The prospect of increases in rainfall and storm intensity under climate change would create infrastructure risks. Decreased frost risk would clearly be an advantage, with new areas suitable for horticulture operations opening up. A key to managing climate change in the future will be access to irrigation water to manage seasonal shortages derived from increased evapotranspiration deficit. Generally growers have limited interest in how models work, but are more interested in the results and if they are reliable or not.

Meat and Wool NZ

A more coordinated response to drought risk is required than current practice, aimed at fostering early response and better planning. This was seen as a key to managing both short run climate variability and the risks of long run climate changes for the beef, wool and lamb industries. A focus is required on the east coast of both islands initially as these are the most severely affected areas, and based on the Mullen et al. (2005) analysis this area is also the most vulnerable to changes to drought frequency under climate change.

The sheep and beef industries are likely to face the biggest challenges given the current economic climate and limited adaptation options. By and large farmers have adapted to the current conditions, and leading farmers are highly effective risk managers, but there is a portion of the industry that is lagging. If the 2007/08 drought persists, and/or there is increased drought frequency under climate change, gearing of sheep meat, wool and beef businesses would change and intensify existing adjustment pressure. At present most of the flatter land with water access is adjusting into dairy or other higher value industries where there are opportunities. Hence, the ability to adapt by irrigation in future is probably going to be minimal. Stock water is important, so water storage is important to the sector.

In terms of adaptation research, Meat and Wool NZ has been involved in plant technology improvements, particularly the breeding and integration of more resilient clovers into the farming system. The species are high yielding and produce good quality feed before summer drought. More information is needed on matching plant species to the micro climatic environments of New Zealand and there is currently work with Lincoln University and FoRST, especially for ryegrass and clovers with higher water use efficiency.

There is need for highly localised information to support on farm decision making for both drought risk management and climate change. Sheep and beef operations are extensive, and cover a range of climates and soil types, even on one property in many cases. At present, Meat and Wool New Zealand is working with farmers to enhance management, with an emphasis on the environment and longer term sustainability. For example, there is a program to undertake individual land environmental plans.

Pasture planning initiatives are encouraging farmers to record information about their business performance. Dairy is currently the leader in monitoring production performance, but sheep and beef are making substantial progress in this area. The challenge going forward is leveraging off this information, managing it and using it in education and training programs. This is seen as a vital learning process going forward in improving drought risk management and climate change adaptation.

Meat and Wool NZ is currently working with Universities and CRI's to emphasise the need for whole systems management, and climate variability and change are important drivers. As irrigation is generally not an option in the extensive industries, they are fully exposed to the risks of climate variability and change, as well as price signals. Generally the industry wants the best advice possible, realising that weather and seasonal forecasting as well as climate projection is not a perfect science. It is important to recognise that they want the best information possible and need quality assurance, but they don't necessarily need to run models themselves or understand their mechanics. If the precision and accuracy of models can be improved that is obviously going to be a significant influence on how farmers will respond.

4.2.2 Science directions

Climate science—NIWA

NIWA is well positioned to provide climate data to impact modelers for analysis of historic climate variability, real time monitoring and climate change projections. The suite of methods described in section 3.1 and 3.3.1 provide a good platform to build on for undertaking climate change risk analysis for agriculture. There are a number of datasets currently available (e.g. historical climate data from the National Climate network and virtual station data network) and projected future change fields for precipitation and temperature based on the IPCC third and fourth assessment models. Ongoing work at NIWA seeks to improve the quality, precision and applicability of these datasets. Some potential climate change research directions at NIWA that could support agricultural impact analysis are:

- update the Mullan et al. (2005) drought analysis using the new IPCC AR4 climate change scenarios. Given exiting research efforts there is now an expanded operational climate change model ensemble (12 models) which can be used for this task. There is potential, if the analysis is updated, to use a more mechanistic approach to simulating potential evapotranspiration deficit.

- test the use of weather generators, and improve those that are currently available, for application in climate change risk analysis for agriculture and other sectors. This may in part focus on exploring means to improve the simulation of rainfall dispersion (extreme events), address current limitations which assume climate is stationary so they can be applied in transient studies, efficient and robust parameter estimation and testing them through application with impact models.

- investigate if improvements can be made to the current empirical downscaling algorithms. For example, it may be possible to use an alternative functional form and more variables to reduce errors in the downscaling of rainfall.

- expand NIWA's current programme of regional climate modeling. There is a need to build on the preliminary work undertaken so far to validate the RCM (sensitivity and control experiments), and produce simulations across the full range of SRES greenhouse emissions scenarios for at least three driving GCMs. This is a significant area of work which will provide New Zealand with an adequate ensemble, which includes physically based simulations of regional non-linearities, for use in risk analysis.

- continue to integrate the climate science with impact models. There are plans through foundation research to loosely couple the RCM with a glacier model, snow-ice model and catchment hydrology models through pilot studies with regional councils. As yet there are no plans to integrate the output with agricultural models.

NIWA's current approach regarding climate change scenario development is to pursue research in both the empirical and dynamic downscaling methods. It is not envisaged the RCM will replace the empirical methods in the short to medium term as there are both advantages and disadvantages in each approach (Table 2).

Coupling the empirical downscaling or RCM based climate projections to a broad suite of agricultural models is currently not part of NIWA's FoRST-funded research programmes. There is considerable potential to make progress in agricultural risk analysis by pursuing these activities. There is also considerable potential to fully automate data and information delivery systems for near real time analysis. Work done in 2007/08 funded by MAF (including this project) clearly demonstrates that there is significant scope for multi-organisation collaboration in New Zealand (e.g. between NIWA, AgResearch, Landcare Research, Scion, GNS Science, Dairy NZ, Crop and Food Research, HortResearch, and others) to produce world-class assessments of climate change impacts.

Farm systems modelling—Dairy NZ

Dairy NZ have developed a conceptual whole farm model that has considerable potential for application in climate change risk analysis. It uses observed time series of weather and is a fully integrated biophysical-farm business model. Currently it is used to examine historic climate variability, and among other functions, provides information that assists farmers in planning for climate driven feed deficits. The systems boundary of the model extends into management, allowing both tactical and strategic management to be examined, and it has the structural flexibility to be set up for any actual dairy farm. Factorial experiments can also be created to examine differences between management regimes and or local conditions. Currently the system is operational in near real time ingesting data from 89 climate stations via NIWA's web-based data access portal (CLIFLO). Testing is underway to run the system using NIWA's virtual station network, which potentially extends the coverage across the country. There is also considerable interest in applying 15-day multi-model weather forecasts, produced by NIWA, to the whole farm model.

Generally the value of whole farm modelling for climate change risk analysis is not for prediction but rather system design. It is a convenient environment by which to explore management alternatives and or investigate the role of new technologies in adapting to climate change. The whole farm systems model allows investigation of farming resilience in productivity and profitability given different environmental exposures. Undertaking such adaptation risk analysis is seen as feasible, particularly with further collaboration with AgResearch (EcoMod), crop modellers, the whole farm model run at Texas AML (PCRANCH) and NIWA.

Experimental and modelling research—AgResearch

AgResearch have focussed on global change, a multi-driver process of modification in agricultural systems. The general strategy over many years of research has been strong interaction between data and models, and feeding the emerging understanding of systems processes into impact assessments and adaptation. The grazed free air chamber experiments (FACE) have improved the understanding of processes like carbon dioxide fertilisation, nutrient and carbon turnover (mineralisation) in soils and absorption into pastures, and animal rumination and methane production. It is possible to replicate assumed environmental conditions some 25 years out by saturating the pasture canopy with carbon dioxide at 475ppm. Future rainfall is relatively easy to replicate, but creating warmer conditions is more difficult in the open environment.

In conjunction with the experimental research, EcoMod has been developed, which takes a mechanistic approach to simulating processes at paddock to whole farm scale. The feedback between the model and experiments means that the model is better able to simulate a broad range of environmental effects in a farming system—two key functions of the model for New Zealand Agriculture are its ability to analyse outputs of greenhouse gas and nitrogen losses from dairy farming systems. Process based models are important for adequately identifying non-linearities and trade offs in impact and adaptation assessments, for example: estimating the reduced protein available in plants at higher carbon dioxide levels; temperature and carbon dioxide interactions limiting photosynthetic response; and faster recovery from drought with higher carbon dioxide.

Applied modelling—Crop and Food Research

For crop producers, climate change present opportunities like increased yield potential given carbon dioxide fertilisation, a longer growing season given reduced frost risk under warmer conditions and shorter crop rotation under higher temperatures. It also brings threats such as water stress, crop failure under extreme events and an increase in disease and pest incursions. The key questions are assessing how climate change will impact on productivity and can actions (adaptations) be taken to avoid the impacts or enhance opportunities.

Over many years Crop and Food Research have developed a number of simulation models. They are largely mechanistic and conceptual models of soil-crop-environmental systems that have been extended with management and farm business subroutines. The suite of models place New Zealand in a strong position to carry out adaptation research. While it is possible and valuable to continue to work on the underlying mechanisms, there is also a case to apply existing models to practical applied questions now.

Crop and Food scientists argue there is a need to streamline adaptation and impact research and ana;ysis. An integrated research effort should make downscaled GCM data available, preferably through a regional climate model, to provide climate statistics for a weather generator. This can then be used to simulate the length of data required for a risk analysis. Coupled with factorial experiments and multiple impact model runs analysis of the role of management in avoiding impacts can be carried out. It is important to use and continue to develop methods that account for non linearity in both the climate and impact systems.

Forestry—Scion Research

Scion was funded in 2007/08 by MAF to examine a suite of models for climate change impact and adaptation research for the forestry sector. These models are designed to examine climate variability and change at a range of scales, process (including carbon dioxide fertilisation, nutrient supply) as well as examine interactions with other hazards, such as pests and diseases. The models are capable of examining both wood quality and product, or the suitability of different environments for different species. The project is a collaborative effort between Scion, NIWA and Landcare Research. Early results from this work (for a small number of sites) have established that the models can be effectively linked to climate change projections, and that there is significant scope to further develop the analyses with multiple climate scenarios at the national scale.

National scale analysis—GNS science

There is need to integrate the range of local and small scale models and data emerging from agricultural systems analysis into a national framework. This provides a national coverage for policy makers, industry and farmers of individual events like drought, and also an assessment of the regional distribution of climate change impacts (section 3.3.3). It also provides the necessary level of system integration for macro economic analyses of the impacts of climate change (e.g. through an extension such as the

EcoClimate research consortium). The development and application of a simplified conceptual crop and pasture model is an important aspect of the overall research effort and understanding of climate change.

Currently GNS has a operational simplified model of mean New Zealand wide production based on soil water deficit, growing degree days and soil particle size analysis, based on long term average climate data. It does not simulate seasonal variability, or the influences of carbon and nitrogen cycling. This limits the capability of the current system to address drought risk management, as well as multi-driver global change research questions.

To bridge this gap, GNS is proposing to further develop the BiomeBGC model, which has been developed by the National Centre for Atmospheric Research (NCAR) (Thornton and Rosenbloom, 2005). It has a number of features which make it suitable for national level application and integration with more local scale modelling efforts: it is relatively simple; it is sensitive to atmospheric carbon dioxide, nitrogen cycling and feedbacks. Initial testing shows that it is able to replicate the long term average pasture growth rate from the more detailed EcoMod, and also agrees with some available field data well.

Water resources-NIWA

NIWA has a strong focus on examining climate variability implications for water resources under scenarios of climate change. For example, a river flow drought index has been developed and catchment scale climate-landscape-hydrology river flow models developed. These have been applied to select catchments, for example the Rangitata. Analysis of stream flows in the south west of the South Island has revealed the existence of decadal scale climate change in that part of New Zealand—defined long runs of low and high flow associated with a long term climate index the Interdecadal Pacific Oscillation (IPO) which appears to modify ENSO frequency. There are a number of core activities needed to improve the analysis of current climate variability and by extension climate change, particularly the availability and quality of field measured climate and hydrological data.

Climate change research is feasible, but water resources have a highly non-linear response to climate variability. Hence the current empirical downscaling methods are not precise enough, in terms of their simulation of extreme events, to use with confidence in hydrological impact risk analysis. In the future, integration of detailed catchment scale hydrological models with regional climate model output is planned.

4.3 Gap analysis

Records of the discussion sessions at the workshop were analysed to produce a gap analysis (Table 5). This identified eight issues that were seen as having a high priority for the agricultural sector, but where current research directions appear limited. The implications for climate and or agricultural research activities are also identified. Table 4 extends the analysis of the workshop discussion further by identifying areas of adaptation and associated enabling research development and extension activities.

Table 4. Adaptation research identified at the end user workshop.

Adaptation	Example	Enabling research, development and extension
Plant species selection and breeding	Sowing new resilient plant species.	Plant breeding. Experimental trials Model evaluation of feasibility.
Changed production timetables to match shifts in seasons	Out of season lambing	Experimental trials Model evaluation of feasibility.
Improved water use efficiency	On farm monitoring of water, productivity and management, so that farming systems experiment and 'learn'.	Network technology distribution. On farm trials and demonstration
Risk communication	Improved information access by cross media communication strategy reflecting different pathways of information transfer to the farm decision making table.	Market research. Pilot studies to assess information transfer
Industry adjustment driven by shifts in market forces and climate drivers	Changing the enterprise mix (e.g move from 10% crop, 90% sheep meat to 20% crop, 80% dairy). Exiting agricultural production.	Integrated market and climate risk analysis. Biophysical feasibility assessment using models and experimental trials. Education courses. Financial analysis and planning courses.
Avoid climate change through irrigation	Farm uses ground water for supplementary irrigation	Ground water assessment and monitoring. Establish regional water plan to ensure ongoing security and sustainable use.

Table 5. Gap analysis—issues arising from workshop discussion.

Issue	Discussion	Implications for climate research	Implications for agricultural research
Timeframes of analysis and planning	Current analysis timeframes (e.g 2040, 2090 time slices studies) have reduced relevance. Decadal scales (e.g 10-20 years) are more relevant. Most producers plan on a shorter time scale (next year to 5 years out).	Decadal scales analysis is less precise and not as well developed. Further work with RCM required. Establish methods for selecting analogues to provide decadal stratification of climate data for risk analysis	
Climate change in context	Decision makers are equally interested in other aspects of the future, particularly climate change interaction with international markets, the impact of mitigation (emissions trading) with markets, and relative production impact with trading partners, including biosecurity risk.		Boarder base of integrated R&D required, including international trade analysis (economics), biosecurity and pest risk assessment, and farm scale analysis of both price and climate variability.
Hydrological drought and water access	Management and access to water, as a way of avoiding potential climate change impacts, is a critical issue.	Linking hydrological (catchment, storage and river flow) systems with climate forecasts and projections	
Climate change is not a crisis	Seen as a crisis, but not the case. Benefits from climate change should be frequently presented.	Strategic risk communication plan required.	
Emphasis on adaptation research	Call for a strong emphasis on adaptation research. Producers require more guidance about what actions need to be taken, rather than identification of impacts	Probabilistic based analysis required to define the 'adaptation space' given full recognition of a range of climate outcomes.	More emphasis on defining, developing and evaluating adaptation actions under climate change (see Table 4).
Capturing existing knowledge	Recognition that many adaptation pathways may already be known.		Undertake and communicate the results of a review of existing adaptation knowledge
Assessing 'Mal-adaptation'	Risk that a hasty decision to follow a particular adaptation pathway could lead to a sunk cost.	Probabilistic based analysis required to examine full range of outcomes.	Feasibility assessment of adaptation proposals required.
Risk communication	Information flow can be poor at the grass roots level, for example drought risk awareness under climate change is low in some sectors	More 'bottom-up' research is required with high levels of interaction between farm decision makers and research providers. Strategic risk communication plan required.	

4.4 Summary

The major common themes emerging from the workshop presentations and discussion were:

- Availability and management of data for risk analysis needs to be improved, for both the climate drivers and impact monitoring, for knowledge development and or quality assurance of models;

- The inter-relationship between climate change and climate variability is complex, and there is scope to improve the awareness of differences and linkages between these risks in the farming sector;

- There is a greater need for integration of models, data collection/management and research across the climate and agricultural sciences. This includes efforts to extend beyond production risk analysis into the influences management can have, as well as social and economic impacts and feedbacks;

- There is a need for researchers to not only analyse climate change and drought risks but also quantify the uncertainties and examine the limitations—and initiate new research to reduce uncertainties;

- There are a number of agricultural systems which are vulnerable to climate change and drought in New Zealand, particularly those that lack diversity at the species, farm business and/or industry levels—there is need for bottom-up research with high levels of interaction between farmers and scientists that explores and better defines system resilience under climate and other stresses;

- Meteorological and hydrological drought is a risk that in principle can be reduced with application of research, monitoring, early warning and continual improvement of management. This differentiates it from other more abrupt natural hazards in agriculture where the risks are more difficult to anticipate and manage;

- There is a need for a strategic risk communication strategy to be developed, aimed at raising the awareness of drought and climate change risks across New Zealand agriculture, based on the most up to date science;

- It is important to maintain a balance between longer term climate change analysis while still pursuing analysis of shorter term risks such as seasonal forecasting and decadal scale climate variability. There is increasing recognition that building capacity to manage droughts in the short term also builds resilience to longer term climate change.

5. Opportunities to improve methodologies

5.1 Report recommendations

New Zealand has the opportunity to develop world class climate change risk analysis for its agricultural industries, using a risk management approach. Achieving this means harnessing capability that moves risk analysis from level one assessment of individual climate drivers, to levels two and three where the full production and economic costs and benefits of adaptive actions are explored.

Based on the workshop outcomes, it is clear that New Zealand has the research capability to achieve this goal. There has been considerable progress within specialised fields in terms of: climate data collection and management; climate modelling and downscaling; and impact modelling. However there is room for improvement in terms of streamlining integration across the agricultural and climate sciences and communication of risks with the agricultural sector. The challenge is to capture and use existing capabilities in a more integrated way, while continuing to innovate and undertake enabling research for the future. Based on these observations this report makes two recommendations:

Recommendation 1 – establish a program of applied adaptation and impacts research that focuses on using current capabilities and methods to analyse actual problems relevant to farming at the local and national levels. This program should have a clear integration imperative that calls teams of researches from different disciplines and institutions to focus on tangible problems facing stakeholders (the farming sector). It should take a 'no regrets' approach to the application of existing methods, but also clearly communicate uncertainties.

Recommendation 2 – establish a program of enabling science research that aims to continue to improve methodologies, reduce uncertainties and build new knowledge over time. This is more innovative research where new methodologies are tested. This program has a science imperative with the aim of focusing on problems that will enable New Zealand to improve its understanding of climate change in the future. Research may be carried out within or across different specialities and institutions depending upon the nature of problems.

To implement these recommendations a draft research program, including project level specifications is outlined below. The proposed research program is structured around three interrelated themes:

1. Trends, projections and impacts research.

2. Applied adaptation and resilience research.

3. Enabling science research.

It is important to stress at this stage that the projects within the research framework are presented as a draft for consideration and review. They have been presented in good faith to provide an overall view of the work required to improve on current practice. NIWA recognises that a number of the project ideas are not within its core expertise. Further expertise may need to be drawn upon to further shape the research projects, particularly in specialised areas of impact science.

5.2 Theme 1: Trends, projections and impacts

Project 1.1 Climate risk for New Zealand agriculture—trends and projections

The workshop identified that there is scope to improve understanding of the complex interactions between climate variability, drought, climate change and agricultural impact. The ***rationale*** of this project is to capture this opportunity by producing an analysis that informs the agricultural sector of both past trends in climate risk and also updated climate change projections. The core tasks of this project are to:

- update the drought risk analysis of Mullan et al. (2005) given the most recent set of climate change projections, and also build on new developments in data availability such as NIWA's virtual station data;

- include trend and projection analysis for more climate forcing variables, such as evapotrapsiration and radiation, in addition to rainfall and temperature;

- expand the range of impact indices to include not only Potential Evapotraspiration Deficit, but also production indicators such as trends and projections for mean regional pasture growth and animal metabolism.

This project has strong linkages to the enabling research project 3.1 climate downscaling, and project 3.2 establishing a regional monitoring network. The ***benefits*** of this project are to provide New Zealand agriculture with a compressive and well founded information source on past and future climate risks to agriculture, thereby significantly improving the industry's risk awareness. Ideally the project would clearly identify uncertainties, and be repeated at a time when new methods and future projections emerge.

Project 1.2 National and regional level economic impact assessment of climate change on New Zealand Agriculture

The need for understanding the economic impact of climate change was not clearly identified in the workshop. However, it is a fundamental component of understanding where New Zealand agriculture is likely to stand in the future international market place—an issue that was raised strongly in the workshop. In addition section 3.2.1 describes an overall change in international modelling practice, to move climate change risk analysis beyond examining climate and production drivers towards ascertaining economic costs.

The ***rationale*** of this project is to address these issues by providing New Zealand with a summary dollar cost of the impact of climate change on the agricultural sector. The main tasks are to:

- build on the methodologies and reporting framework developed in Project 1.1;
- use macroeconomic modelling, for example a total factor productivity approach and/or general equlibrium model, to ascertain the impact of climate change on New Zealand agricultural sector and economy; and
- provide insight into how climate change might impact of on farm businesses using microeconomic (bio-economic) models.

The progression of this project is dependant upon model development carried out in project 3.4, as well as leveraging off the methodologies and monitoring framework developed in project 1.1. The ***benefits*** of this project are to provide New Zealand with an overall net economic cost of climate change on agriculture for use in macro-economic planning for the broader economy, as well as providing information that can be used to focus policies and programs.

5.3 Theme 2: Adaptation and resilience

Project 2.1. Fact sheets on adaptations that build climate change resilience in New Zealand's Agriculture

The workshop identified a very broad range of potential climate change adaptations, as well as highlighting the risk that current knowledge may not be adequately captured. A number of examples were showcased where existing industry knowledge had been captured, for instance an analysis of climate change adaptation in the Kiwifruit industry.

The ***rationale*** of this project is to address these issues by providing New Zealand agriculture with a series of fact sheets on climate change adaptation. The core task is to research and collate existing industry knowledge. Adaptation has a broad definition, encompassing social, technological, economic and other considerations. As a result the fact sheet series should be flexible and encompass a broad range of subjects, for example;

- Examining costs and benefits of making changes to on-farm management;
- Changing production systems in the dairy, beef and sheep pastoral sectors;
- The role of biotechnology in on farm climate change adaptation;
- Building resilience through farm education and training; and
- Using irrigation water to mitigate drought and climate change impacts.

This project has strong risk communication theme, and the fact sheet series should target producers and agricultural professionals. This project provides ***benefits*** to New Zealand agriculture by building a mechanism for capturing exiting knowledge and ensuring that decision makers are fully aware of current and emerging adaptations.

Project 2.2 Benchmarking agricultural resilience to climate change through drought risk management in New Zealand

The workshop identified that improving drought risk management as a key adaptation response. It is a means of building resilience to climate change with the dual benefit of mitigating the effects of shorter run climate variability. The ***rationale*** of this project is to ascertain the extent to which New Zealand's current range of drought risk management practices mitigate future climate change. The core tasks of this project are to:

- conduct a national survey of drought risk management practices;
- identify which practices constitute best and average drought risk management under current short run climate variability;
- and test the performance of best and average drought risk management practices under future projected climate change scenarios and potential decadal scale shifts in climate variability.

The project is to be focussed on the regionally representative farm business developed under project 3.2. It has linkages with projects 3.1 climate downscaling and 3.4 farm level impact model development. The project will provide significant ***benefits*** to New Zealand's agriculture by enhancing industry and policy understanding of current resilience to drought and climate change.

Project 2.3 Adaptation to climate change through on farm use of irrigation water in New Zealand

A strong theme in the workshop was that irrigation was a key adaptive response to climate change. A number of industry representatives noted that availability of irrigation water was going to be critical in the future to manage the impact of drought. There was concern that New Zealand had low levels of knowledge about the size of the resource and how it could be managed sustainably.

The ***rationale*** of this project is to develop a way forward for New Zealand's management of its irrigation resource. The scope of this project is braod and potential research activities include:

- conduct an audit of New Zealand's surface and groundwater resources, including the identification of where there is lack of knowledge and or base line data;
- undertake modelling to analyse the risk of irrigation water deficits under future climate change scenarios, focussing initially on the surface water resource and if possible groundwater;

- identify current and leading practices in irrigation water use efficiency;

- make recommendations to address lack of knowledge/baseline data limitations;

- develop a set of guidelines for sustainable regional water management.

This project has strong linkages to project 3.9, where it is proposed to develop capacity to model the groundwater system, most likely in a test catchment. Although the proposed project is broad, it has potential to bring significant ***benefits*** to New Zealand, and is seen by industry as critically important in the management of climate change and drought in agriculture.

Project 2.4 Evaluating the risk of mal-adaptation to climate change for New Zealand agriculture

The workshop identified a number of potential adaptation responses, but also highlighted the concept of ‘mal-adaptation’. This is an emerging perspective in climate change response, describing a failure in risk management where decisions to take action are made that do not reflect the actual risks. For example, incurring a sunk cost by investing in a proposed climate change adaptation, when the analysis of risk is not based on the full range of climate outcomes.

The ***rationale*** of this project is to assess the risk of mal-adaptation for a select number of case studies, based on a subset of the regional monitoring framework developed in project 3.2. Its core tasks are:

- develop alternative weighting regimes for climate models and scenarios within the current range of future climate outcomes for New Zealand;

- using uncertainty analysis methods test the interaction of the weighting systems and a number of example adaptations using a whole farm bio-economic model;

- use optimisation techniques to maximise probabilities of successful adaptation given the full range of scenarios and under alternative climate weightings.

This project has linkages to projects 3.1 and 3.4, where climate downscaling methods are tested and model development work is undertaken. This project ***benefits*** New

Zealand agriculture by prototyping a method for focussing the selection of adaptation responses using quantified risk analysis. This will bring substantial savings to the development and implementation of adaptation programs for agriculture.

5.4 Theme 3: Enabling research

The enabling research projects proposed constitute the fundamental science aspects of the applied research in themes one and two. While a number of the applied research projects can be implemented in the short term with existing methods and a 'no-regrets' approach, there is recognition that there is need to continually improve the underlying science. The broad aims of this theme are:

- to ensure that methodologies underpinning the applied science themes have been subject to a high degree of rigour, through the validation, testing and peer review process;

- develop mechanisms to streamline the integration of climate and agricultural (impact) science;

- allow innovations to occur that ensure New Zealand continues to be well placed in the global research effort to understand climate change impacts and adaptations as well as drought response.

Project 3.1 Climate projection database and toolkit

A number of workshop participants identified the provision of observed climate data and projections as a fundamental, and sometimes limiting, factor in climate impact research and development. The review of methods also notes that choice of downscaling approach is critical for setting up different end uses and types of inference that can be made in a climate change risk analysis. Methodologies are also evolving and changing rapidly. The rationale is to improve the availability of climate change projections for a range of uses in agricultural science by developing a climate projection database and algorithm toolkit. As noted previously, an equivalent project in the United Kingdom known as EARWIG (Kilby et al. 2007) provides a useful benchmark. The core research activities include:

- fully update the current GCM model ensemble available to New Zealand scientists to reflect the IPCC fourth assessment report models;

- expand the variables available in the existing empirical downscaling methods to a comprehensive set for driving agricultural models, thereby including radiation, wind and potential evapotranspiration;

- develop methods that reduce errors in the current statistical downscaling procedures, particularly for rainfall;

- develop and implement improved stochastic weather generators for us in climate change impact analysis for agriculture that are suitable for application in transient analysis and improve the estimation of extremes;

- incorporate the full range of empirically downscaled climate change fields into operational climate data bases in a format suitable for implementation either with primary station data or virtual station data;

- incorporate the full range of climate change fields downscaled using the regional climate model into operational climate data bases in a format suitable for implementation either with primary station data or virtual station data;

- test and compare all downscaling methods by using them to drive the current suite of impact models (project 3.4);

- develop a simple web portal for accessing the climate databases and toolkit source code for impact researchers;

- publish a technical guideline report for use of the data and toolkit in impact studies.

Project 3.2 A regional monitoring network for climate change and drought risk analysis in New Zealand

A key observation of the workshop is the need to undertake more integrated and applied research addressing climate change impacts. The workshop also briefly described an important aspect of New Zealand agriculture, the diversity of climatic and land resources, and the difficulties in developing climate based research that is relevant for many farmers across the country. The ***rationale*** of this project is to develop a regional monitoring and analysis framework that can be used in both the applied and enabling research themes. The purpose is to:

- focus research on practical 'on-ground' problems of high relevance to the industry;

- foster integration across the impact and climate sciences that underpin climate risk analysis;

- streamline the integration of the applied and enabling research themes;

- provide a permanent network so that results can be updated in the future and compared with previous risk analysis;

- provide a focal point for the communication of research; and

- allow the extrapolation of the research results to any farm and micro-climate across New Zealand.

The core tasks of the proposed project are to:

- undertake a data mining exercise, aimed at collating, quality control and use of existing data sets to build on existing farm monitor and experimental projects (for instance Dairy NZ Research Farms, MAF monitor farms, Landcorp farms);

- select around 200–300 candidate sites, then rationalise the network by matching it with available data, as well as assessing the industry and resource representation of proposed sites;

- propose around 30 tier one sites, where there is a high level of data quality and availability, suitable for methodological testing and enabling research;

- propose around 80–100 additional tier two sites, suitable for carrying out further applied risk analysis, thereby increasing the industry and resource base representation of the network;

- produce regional scale maps that enhance the extrapolation of results to other locations.

This project is a practical strategic investment that will significantly improve the quality, availability and timeliness of integrated research and development for New

Zealand agriculture. It is a fundamental component of focussing climate change and drought research into the future.

Project 3.3 Improved understanding of forcing processes—evapotranspiration

Technical discussion at the workshop highlighted the ongoing scientific uncertainty in the monitoring and projection of potential and actual evapotranspiration. This is a fundamental process of the water balance, influencing the availability of both soil moisture and surface water resources. There are ongoing uncertainties regarding the process and function of 'global dimming' in New Zealand, where it is hypothesised that the radiation balance has been declining in response to mean increases in atmospheric aerosols, thereby reducing potential evapotransiration. There are also uncertainties in modelling the process, where there is debate concerning the usefulness of simple climate driven approaches compared with more complex approaches that consider the dynamics of vegetation.

This project aims to provide more definitive guidance on these issues for New Zealand agriculture by initiating two targeted studies:

- national to regional trend and attribution study of potential evaporation using available data from class A pans and other meteorological variables;

- in parallel, investigate the modelling of actual and potential evapotranspiration by comparing models of both intermediate and high complexity.

Project 3.4 Impact model application and development

Discussions and presentations at the workshop re-enforced the view developed in section 3 that New Zealand has developed considerable agricultural modelling capacity. This project proposes that a range of impact model application initiatives be implemented that draw on the climate change data and methods proposed in project 3.1. Broadly this includes activities that would:

- set up and validate the suite of conceptual and mechanistic whole farm pastoral and crop system models on the tier one sites proposed in project 3.2;

- run the validated models on the tier two sites;

- use the model runs and validation data at the tier one and two sites to develop a simplified national scale pastoral and crop production model, and use this to asses geographic shifts in New Zealand's agricultural climatology (an element of project 1.1);

- use the simplified model to develop appropriate total factor productivity metrics suitable for integration with a macroeconomic models of broad acre production. This could then be used in project 1.2.

There is also scope to improve the simulation of processes in the models themselves. The importance of this activity to the validity and quality of climate-agricultural risk analysis should not be under emphasised. Key areas include the simulation of carbon and nutrient dynamics, animal intake and species composition and the upper and lower environmental limits of animal metabolism. However, outlining the details of projects pursuing these goals is beyond the scope of this project, and best left to agencies with relevant expertise such as AgResearch, Dairy New Zealand, Crop and Food New Zealand, HortResearch and GNS Science.

5.5 Risk communication

A common theme in the workshop was the need to be more strategic about the communication of drought and climate change risk. There was recognition that often there was poor or patchy penetration of available information, the perception of risk may not be heavily informed by the science, and a need in general to improve the risk awareness of the New Zealand agriculture sector. It is proposed that a risk communication strategy be developed, focussed on developing a workshop program that would bring key scientists in the climate and agricultural impact fields together with the farming community.

5.6 Summary and timeframes

Table 6 provides a summary of the draft research framework and projects, including nominal timeframes for the work.

Table 6. Summary of proposed research framework and projects including nominal timing

Project	Nominal timeframe
Theme 1: Trends, projections and impacts	
Project 1.1 Climate risk for New Zealand agriculture—trends and projections	Twelve months
Project 1.2 Economic impact assessment of climate change on New Zealand Agriculture	Two years
Theme 2: Adaptation and resilience	
Project 2.1. Adaptations that build climate change resilience— fact sheets on for New Zealand's Agriculture.	Ongoing. Number of three to twelve month projects
Project 2.2 Benchmarking agricultural resilience to climate change through drought risk management in New Zealand	Twelve months
Project 2.3 Adaptation to climate change through on farm use of irrigation water in New Zealand	Two years
Project 2.4 Evaluating the risk of mal-adaptation to climate change for New Zealand agriculture	Twelve months
Theme 3: Enabling science	
Project 3.1 Climate projection database and toolkit	Two years
Project 3.2 A regional monitoring network for climate change and drought risk analysis in New Zealand	Six months
Project 3.3 Improved understanding of forcing processes—evapotranspiration	One year
Project 3.4 Impact model application and development	Ongoing, multi-year multi agency. Two to four years

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