Adaptation of New Zealand dairy farms to climate change: An integrated, farm-level analysis

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Abstract

The dairy sector is a cornerstone of the New Zealand economy and as such, it is important to understand the ways in which it is likely to be affected by climate change, whether it will need to adapt and if so, how this can best be achieved. The overall goal of this research was to analyse potential strategies for New Zealand dairy farms to adapt to projected climate change. For this purpose, an integrated biophysical and socio-economic research framework was developed. Drawing on recognised frameworks for the analysis of climate change adaptation, together with systems analysis methodologies, the framework sets out an integrated process for analysing potential adaptation strategies at farm level.

Six case study farms were selected for the analysis, representing major dairying regions in New Zealand and covering a range of climatic zones and management approaches. The farmers selected were experienced and respected operators, in order to draw on their knowledge of farming systems resilience. Qualitative social research provided insights into the way the farmers saw their farming systems and how climate change issues were placed in the context of other challenges facing the farmers. It also provided a farmer perspective on some of the driving forces that influence the current trajectories of New Zealand dairy systems, in particular their concerns around the effects of environmental regulation and changes in farm structure, which may affect the future adaptive capacity of their farming systems.

The next step in the analysis was to model the farms in the DairyNZ Whole Farm Model (WFM) under dynamically downscaled climate change scenarios provided by the National Institute of Water and Atmospheric Research (NIWA). This showed significant potential for some adaptations to mitigate the projected impacts of climate change. For example, making and feeding out more silage, and changing the pasture species modelled, showed benefits for nearly all farming systems. However, there were limitations in the capacity of the model to accurately represent the on-farm challenges of implementing such adaptations. Feedback from the farmers highlighted the limitations, as well as the potential value of such modelling work, emphasising the importance of assessing such research in context.

A second round of modelling work was carried out based on the suggestions of individual farmers for their own farms. The suggestions made by farmers were predominantly incremental, rather than transformational adaptations, reflecting the farmer's positive assessment of the current level of resilience in their farming systems, but also reflecting their operational and personal constraints. Modelling under present conditions and future climate showed that many of the adaptations did mitigate the impacts of climate change. However, there was still a largely negative impact compared to the same adaptations carried out under the baseline (current) climate. This implies that ongoing work, innovation and technological adjustments will be required to optimise these farming systems under future climate conditions.

For both incremental and transformational adaptations, there are two key factors in finding resilient pathways when challenged with the uncertainty surrounding climate change and other pressures. The first is the maintenance of flexibility and the avoidance of path dependence, to ensure ongoing adaptive capacity. Secondly, it needs to be recognised that resilience occurs at different scales. In some cases, adaptation measures that increase resilience at farm level, such as importing feed, may reduce resilience at a broader scale, which may in turn come under pressure from climate change.

The combined methodological approach meant that it was possible to reach beyond the limitations of each and form a more holistic picture of potential adaptation strategies. Some strategies lent themselves easily to testing in a model, while others were well beyond its scope. Conversely, the modelling work enabled a more objective and quantified assessment of farmer perceptions about the resilience of their systems.

Every adaptation decision involves a set of trade-offs. In conclusion, some of the trade-offs identified as part of this study are summarised for the range of adaptation strategies as originally identified from the literature. Conscious articulation of these trade-offs, in terms of the factors important for ongoing system resilience, is the first step in better informed choices that may lead to more sustainable development of future farming systems.

Acknowledgements

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Prologue

When I first started this thesis in 2010, climate change research in New Zealand stood on much rockier ground than it does now. The National Institute of Water and Atmospheric Research (NIWA) was at the time being dragged through the courts, at great expense, to prove that the science they had been carrying out in this area would stand up to intense scrutiny. Climate 'sceptics' had a strong voice in universities as well as in the media. I was often asked whether I 'believed' in climate change and given books to read by colleagues and friends presenting the view that climate change was not related to human activity.

In a few short years the political climate and language has changed. Climate 'sceptics' are now referred to more frequently as 'deniers'. However, my aim for this research was always to move beyond the political debate about climate change; and use it as a window through which to view the future development of our food systems, using New Zealand dairy farms as an example. There is a tendency for human beings to unite in the face of a looming threat and despite the controversy, to me it represented a way to look forward and move beyond the limited and polarised discussion about whether environmental or economic goals are more important.

As a classic 'messy problem' that cuts across biophysical and social spheres, climate change adaptation also represents an entry point into exploring different ways to understand complex socio-ecological systems. There was considerable debate with supervisors initially about the viability of taking the research beyond the modelling of whole farm systems, which already represents a high level of biophysical and economic complexity without adding the complication of social perspectives. However, it is a personal belief that if we are to move towards genuinely sustainable future farming systems, we will increasingly need to cross disciplinary boundaries and integrate the different forms of knowledge we acquire in doing so. This thesis represents my attempt at embracing this complexity.

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1 Introduction

Climate change is likely to have a significant impact on agriculture globally, depending on factors such as scale, location and the vulnerability of the people and activities concerned (IPCC, 2014). There is widespread concern over the potentially negative impact of climate change on food security in tropical regions, particularly Africa (IPCC, 2014, 2007; Schmidhuber and Tubiello, 2007; Sirohi and Michaelowa, 2007; Thornton et al., 2014). Under climate change scenarios, changes in temperatures and rainfall are expected to alter the suitability of different areas for agriculture globally, which may have an impact on the stability of food availability and access (Porter et al., 2014). There is less certainty around changes in extreme weather events, and yet these may ultimately have a greater impact on agriculture than changes in climate averages (Linnenluecke et al., 2014; Thornton et al., 2014).

In temperate regions, impacts are expected to be less severe than in tropical regions (IPCC, 2013; Porter et al., 2014). There may be both positive and negative effects on agricultural production. Negative impacts may result from increases in temperature, increases in both drought and heavy precipitation events, and increases in tropical cyclones. These changes may decrease yields and negatively impact soil quality, and increase pest and disease outbreaks. Potentially positive climate change impacts on temperate production systems include increases in crop yields and pasture growth as a result of higher levels of carbon dioxide (CO_2) in the atmosphere (Schmidhuber and Tubiello, 2007; Walker and Schulze, 2008); and in some regions, a longer growing season. In Northern Europe, for example, it has been suggested that under climate change, crop yields will increase and possibilities for new crops and varieties will emerge (Ewert et al., 2005; Reidsma, 2007).

In addition to these biophysical impacts, climate change is likely to generate economic and social changes. For example, increases in crop prices (Lobell and Tebaldi, 2014; Porter et al., 2014) may affect the viability of intensive animal farming strategies. Changes in water flows (Jiménez Cisneros et al., 2014) may have an impact on water quality and hence influence environmental regulations.

Socio-economic effects may be far-reaching and difficult to predict – for example, indirect impacts from climate change such as potentially increasing migration, may affect the way labour is structured on farms.

Climate is a defining feature of any agricultural production system, and in New Zealand, as in the rest of the world, the impacts of climate change are already becoming apparent in the form of rising average temperatures, and increased recurrence and intensity of extreme climate events (Clark and Tait, 2008; Porteous and Mullan, 2013; Reisinger et al., 2014). The dairy farming sector is a major contributor to New Zealand's economy and export trade, and therefore it is important to examine ways in which the sector will be able to maintain or increase productivity in the face of climate change.

Farms are complex socio-economic systems (Bryant and Snow, 2008) and analysis of climate change adaptation options can best be approached at farm level, where the combined effects of these changes will be felt and must be responded to (Newton et al., 2008). This thesis takes an integrated, farm level approach to understanding how best to support successful adaptation to climate change within a complex system. To illustrate this, several New Zealand dairy farms were studied to determine the current situation and project future viable adaptations.

1.1 Adaptation to climate change

Adaptation has been defined by the Intergovernmental Panel on Climate Change (Parry et al., 2007) in the context of climate change, as:

> The adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

The impact of a changing climate on a given system will depend to a large degree on its vulnerability – factors that will increase the severity of the impact within biophysical and human systems. The IPCC (Parry et al., 2007) has defined vulnerability in a climate change context as:

> The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climatic variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system.

There are a range of factors that contribute to the uncertainty in measuring the potential impact of climate change on the biophysical aspects of dairy systems. First, there is the uncertainty surrounding the projected climate changes themselves. Many of the effects of a warming climate are unpredictable and/or depend on complex feedback cycles that are still poorly understood (IPCC 2014, Parry et al., 2007; Solomon et al., 2007; Swart et al., 2009).

Secondly, particular aspects of climate change may be relevant to different aspects of the system. For example, heat and humidity are key issues in cattle welfare (Berman 2005, Kurihara and Shioya, 2003). However, increased rainfall can potentially have a negative impact on cattle reproduction due to an increase in parasite-induced abortions, e.g. from *Neospora caninum* (López-Gatius et al., 2005). Pasture growth and seed production may be enhanced by increasing atmospheric CO_2 concentrations (Edwards et al., 2001; Zhou et al., 2008) but limited by factors such as increases in temperature and precipitation changes (Ciais et al., 2005; Zhou et al., 2008).

Such uncertainties and system complexities, overlaid on the uncertainties inherent in the socio-economic spheres, increase the risk of maladaptation, or adaptations that actually increase vulnerability to climate change in the longer term (Barnett and O'Neil, 2010). In the context of dairy systems, examples of maladaptation might include measures that increase reliance on fossil-fuel based and water-intensive solutions, which are likely to reduce the overall resilience of the industry to energy and water shocks, and may lead to increased greenhouse gas emissions from farming systems. In order to effectively evaluate potential adaptations, it is important to consider these from a whole systems perspective (Stokes and Howden, 2010).

The scientific uncertainties present in both how climate change will be manifested at local and regional levels, as well as the uncertainties in how complex agro-ecosystems will respond to such changes, highlight the need for a more systematic and risk-based approach to the development of agricultural systems.

In particular, there is a need to better understand the trade-offs between different adaptations at a strategic level – for example, the trade-off between production intensity and agro-ecosystem resilience. Most of the proposed adaptation options described in the literature address only short-term tactical decisions for incremental change (e.g. Stokes and Howden, 2010). However, there is an ongoing debate about whether autonomous and/or incremental adjustments will be able to deal adequately with climate change (Dovers, 2013; Kennedy et al., 2010; Park et al., 2012; Preston et al., 2011; Stafford-Smith, 2013).

Specialisation implies higher productivity under a given set of circumstances, whereas diversification strategies increase resilience. For example, it has been noted in a European context that farms better adapted to prevailing conditions, with higher yields and incomes, appear to be less resilient to climate change and climate variability (Reidsma, 2007).

The identification of appropriate adaptation strategies depends on an integrated understanding of vulnerabilities, potential impacts and the feasibility of different adaptation options. There are still many gaps in our understanding of these factors. In particular, biophysical modelling studies are often carried out at a high level and based on averages, so that the full range of impacts and variability at farm level remains unexplored (Kalaugher et al., 2013[1]). In addition, the values underpinning the social, cultural and economic dimensions of vulnerability and adaptive capacity are currently poorly integrated with biophysical studies (Reisinger et al., 2014).

The present research combined biophysical-economic modelling and social research approaches to examine the potential for different adaptation strategies.

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[1] This paper sets out the methodological approach for this study and is included in this thesis as Chapter 3.

1.2 Goals and research questions

1.2.1 Goal and objectives

The overall goal of this research was to identify and analyse potential strategies for New Zealand dairy farms to adapt to projected climate change within a complex framework of interlinking socio-economic and biophysical variables.

To address this broad goal, three objectives have guided the research:

1. Review the vulnerability of New Zealand dairy farms to climate change, the likely impacts of climate change and potential adaptation options.
2. Develop a framework for evaluating potential adaptation strategies.
3. Carry out an integrated analysis of adaptation strategies in a farming systems context.

1.2.2 Research questions and approach

The objectives listed above form the basis for three research questions that were used to develop an operational framework:

1. *How can climate change impacts and potential adaptation options be assessed in a way that will adequately reflect their implications for the whole farming system?*

This question guided the development of a systems analysis framework for enabling the integration of both modelling and social research.

2. Will New Zealand dairy farms need to adapt to a changing climate?

Biophysical modelling was carried out on six case study farms in different regions of New Zealand (see Fig. 1) and complemented with social research on the same farms in order to gain an holistic understanding of the impacts of climate change at farm level.

3. *Which adaptation strategies have the potential to enhance both the productivity and resilience of dairy farming systems under future climate change scenarios?*

Based on the systems analysis (question 1), adaptation strategies were identified for their contribution to maintaining or improving the competitiveness (production efficiency), sustainability (resource use efficiency) and profitability (economic efficiency) of New Zealand dairy farms under anticipated future climate scenarios. Trade-offs between different management objectives at farm level were considered.

1.3 Selection of the case study farms

Six case study farms were selected to include the major dairying regions in New Zealand and cover a range of climatic zones with different anticipated responses to climate change. Farms were identified by asking consulting officers and scientists from an industry organisation (DairyNZ) and a Crown Research Institute (AgResearch) to nominate suitable farms. These industry representatives were asked to identify ‘high-end operators’. This choice was made both in order to capture the farmers’ knowledge on adaptation, and to give the best chance at satisfying the intensive data requirements of the DairyNZ Whole Farm Model (WFM) used for the modelling analyses. Selection was also based as far as possible on the following criteria:

Regional coverage: The case study farms were selected to cover the main dairying regions of Northland, Waikato, and the Bay of Plenty. Because of the expansion of dairy in the South Island and in order to consider the implications of potential shifts in agro-ecological zones, Canterbury and Otago were also included in the study. In order to further broaden the range of climatic zones covered, a farm from the Taranaki was added.

Representativeness: Case study farms were selected to be as physically average and representative as possible for their respective regions, based on data obtained from DairyNZ. For example, they should be close to average size and close to average numbers of cows, farm at an average level of intensity for the region and preferably have a common soil type.

Working farms: The primary goal of the farm should be commercial milk production (rather than a research farm).

Farmer interest: Each of the case studies involved working closely with farmers and relied heavily on cooperation and interest from the farmer's side. Farmer interest was therefore a prerequisite.

Owner operated: Where possible, preference was given to owner-operated farms, based on the assumption that owner operators have both a strategic and hands-on perspective.

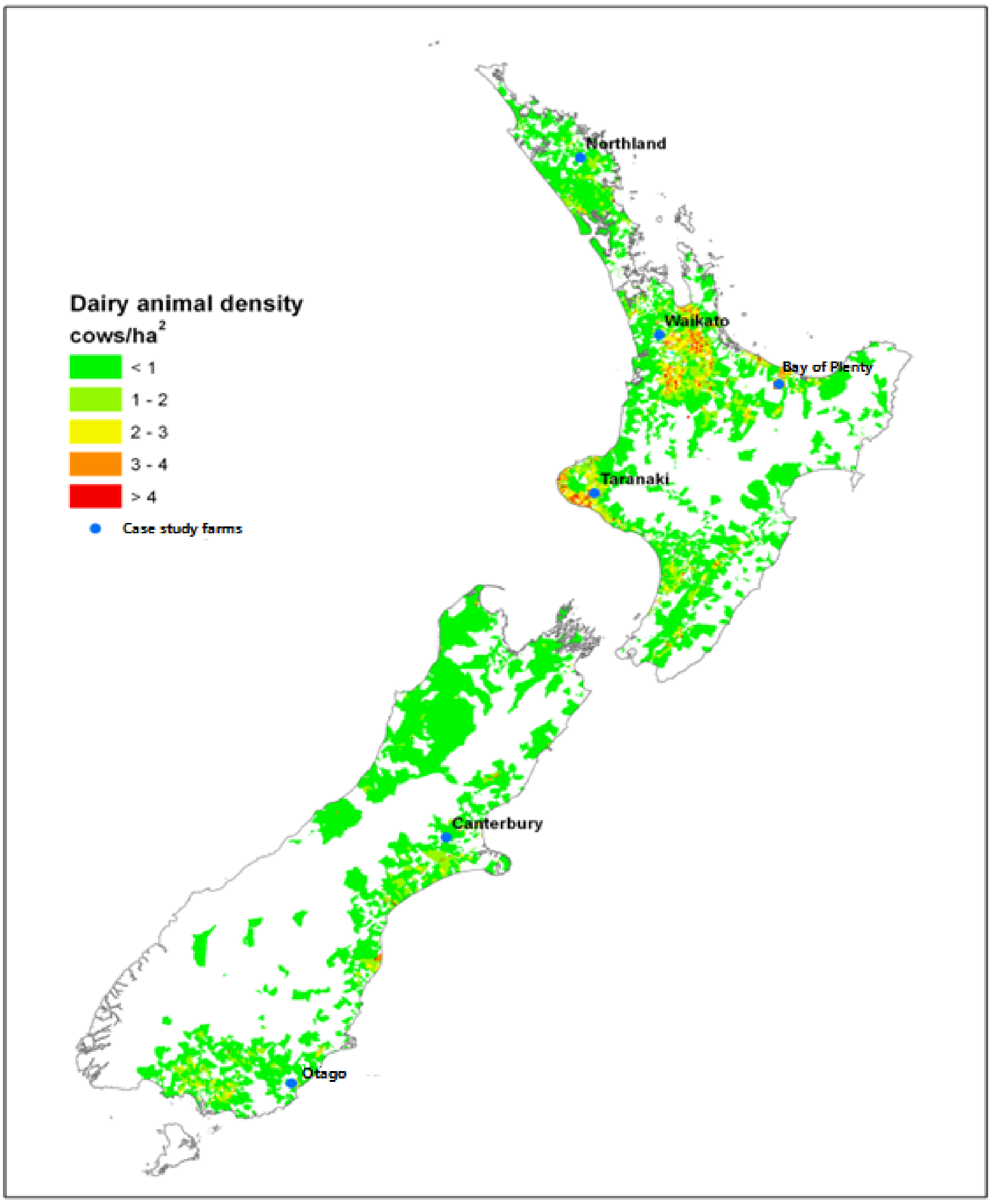

Figure 1: Case study farm locations in relation to dairying intensity in New Zealand. (After Clark et al., 2012). Data on stock density is sourced from the 2007 Agricultural Census.

1.4 Thesis structure

Following this introductory Chapter, the rest of the thesis is presented in six chapters. Chapter 2 presents a general literature review on the broad topic of adaptation of New Zealand dairy farms to climate change. In Chapter 3, approaches to analysing adaptation options are considered through a review of relevant methodological literature and description of the interdisciplinary Mixed Methods Framework that forms the basis for this research. This chapter has been published in Environmental Modelling and Software as:

> Kalaugher, E., Bornman J.F., Clark, A., Beukes, P. 2013. An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system. Environmental Modelling & Software 39:176-187.

This is followed in Chapter 4 with a general farmer perspective, based on interviews with farmers from the six case study farms, exploring their mental models, strategies for resilient farming systems and perspective on climate change.

In Chapter 5, an initial modelling analysis of the case study farms is carried out, utilising the DairyNZ Whole Farm Model (WFM) to assess potential impacts and four researcher-defined tactical and strategic adaptation options for the six case study farms. Modelling for this chapter contributed to Chapter 3 of the Ministry of Agriculture and Forestry (MAF, now a part of Ministry for Primary Industries) technical report:

> Clark, A.J., Nottage, R.A.C., Wilcocks, L., Lee, J.M., Burke, C., Kalaugher, E., Roche, J., Beukes, P., Lieffering, M., Newton, P.C.D., Li, F.Y., Vibart, R., Teixeira, E.I., Brown, H.E., Fletcher, A.L., Hernandez-Ramirez, G., Soltani, A., Viljanen-Rollinson, S., Horrocks, A., Johnstone, P., Clothier, B., Hall, A., Green, S., Dunningham, A., Kirschbaum, M.U.F., Meason, D., Payn, T., Collins, D.B.G., Woods, R.A., Rouse, H., Duncan, M., Snelder, T., Cowie, B., 2012. *Impacts of Climate Change on Land-based Sectors and Adaptation Options*. Clark, A.J.; Nottage, R.A.C. (eds.). Technical Report to the Sustainable Land Management and Climate Change Adaptation Technical Working Group, Ministry for Primary Industries, New Zealand.

Parts of this chapter have also been published as:

> Kalaugher, E., Beukes,P., Clark, A., Bornman, J.F. 2012. Adaptation Strategies for New Zealand Dairy Farms under Climate Change Scenarios. International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.) http://www.iemss.org/society/index.php/iemss-2012-proceedings.

In addition to these previously published results, this chapter includes an exploration of the farmer's reactions to the modelled results for their farms, in order to provide an integrated perspective.

The suggestions made by farmers are then taken up and explored further in a second round of modelling (Chapter 6) under an updated set of climate change projections. By modelling the incremental adaptations proposed by farmers for their own farms, this chapter addresses one of the key questions around climate change in temperate regions – whether the ongoing adaptations that experienced farmers are continuously carrying out will be enough to cope with the impacts of climate change, or whether more strategic or transformational changes will be required.

In Chapter 7 the results of the thesis are reviewed in the context of the original research questions. Conclusions are drawn on the impacts and adaptation strategies analysed in this research and the implications of the findings for the adaptation of New Zealand dairy sector to climate change. In addition, the integrated methodology is appraised, and conclusions drawn on the potential contribution of the lessons learned during this research to the broader study of adaptation in agriculture.

2 Background literature

Adaptation of New Zealand dairy farming systems to climate change is a broad topic, covering biophysical, social, economic and cultural dimensions. One of the initial challenges of integrated research is to explore these dimensions adequately, while still maintaining a defined and workable scope.

This chapter reviews a range of relevant literature on impacts and potential adaptation options for New Zealand dairy systems under climate change. It does not attempt a full review of all relevant dimensions, but is rather intended to provide enough background information to set the scene for the integrated analysis of factors that will be important for dairy farmers in adapting to climate change at the farm scale.

2.1 Global climate change projections

The most comprehensive reviews of the current state of scientific knowledge relevant to climate change are carried out by the Intergovernmental Panel on Climate Change (IPCC). This scientific body under the auspices of the United Nations brings together and reviews the work of thousands of scientists at five-yearly intervals, providing the most rigorous scientific assessment available of the physical basis of climate science (Working Group 1); impacts, adaptation and vulnerability (Working Group 2); and the mitigation of climate change (Working Group 3), as well as numerous special reports on particular topics of relevance to climate change.

The fact that climate change is occurring on a global scale is now considered unequivocal by the IPCC, based on observed increases in air and ocean temperature, sea level rise and widespread melting of snow and ice (IPCC, 2013; Solomon et al., 2007). Global average temperatures have increased measurably over the instrumental record (since 1850), and this increase has accelerated since 1950, with each of the last three decades successively warmer than any preceding decade since 1850 (IPCC, 2013; Solomon et al., 2007).

There are a range of natural phenomenon that contribute to the Earth's long term warming and cooling cycles, including factors such as glacial-interglacial variability on scales of 100,000 years or more, internal variability driving cool and warm periods on 50- to 100-year timescales and volcanic activity which can affect global temperatures for two to three years after a major eruption. Anthropogenic or human-induced 'Radiative Forcing (RF)[2]' has increased almost continuously since 1750, and at a much greater rate since 1960 than during the earlier industrial periods (IPCC, 2013). Anthropogenic radiative forcing occurs due to increases in concentrations of the 'greenhouse gases' carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), ozone (O_3) and halocarbons. Increased concentrations of these gases reduce the amount of radiation escaping the Earth's atmosphere. This initial warming triggers processes which lead to increases in water vapour in the atmosphere, and as this is the most effective greenhouse gas more warming occurs at a global scale. Concentrations of carbon dioxide, methane, and nitrous oxide have now increased to levels that are unprecedented in at least the last 800,000 years (IPCC, 2013).

Carbon dioxide increases are attributed to fossil fuels and land use change; methane and nitrous oxide emissions are mainly attributed to agriculture (Solomon et al., 2007). It is also *likely* (medium confidence, >66%) that anthropogenic influences have affected the global water cycle since 1960, by contributing to increases in atmospheric moisture content, changes in precipitation patterns over land, and intensification of heavy precipitation over land regions on a global scale (IPCC, 2013).

Future climate change is projected by using a hierarchy of climate models, at different scales and levels of complexity, for different purposes. The high degree of anthropogenic influence on concentrations of greenhouse gases means that future climate change will be largely dependent on human behaviour and technology development, which adds a great deal of uncertainty to any projections. The first four sets of global assessment reports produced by the IPCC (in 1990, 1995, 2001, 2007) addressed this problem by utilising a range of

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[2] 'radiative forcing' is a concept used to quantify comparisons of the strength of the different human and natural agents in causing climate change (Forster et al., 2007); it indicates a change in the balance of incoming and outgoing energy from the Earth's atmosphere.

storylines or ‘Special Report on Emission Scenarios (SRES)’ to simulate potential future climate changes, depending on trajectories of socio-economic development and including factors such as population changes, regionalisation, energy production and use, technology, agriculture, forestry and land use (IPCC 2013, 2000).

The climate change projections discussed in the Fourth Assessment Report (AR4, Solomon et al., 2007) were based primarily on the SRES A2, A1B and B1 scenarios (IPCC, 2000). The A2 scenario describes a very heterogeneous world where global population increases continuously. Per capita economic growth and technological change are more fragmented and slower than in other storylines. The A1B scenario assumes very rapid economic growth with more balanced and diverse energy sources, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The B1 scenario has the same population dynamics as the A1B scenario, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

The most recent IPCC Fifth Assessment Reports (IPCC, 2013; 2014) used a different approach, focussing on Representative Concentration Pathways (RCPs) (Moss et al., 2010). These new scenarios specify atmospheric CO_2 concentrations and corresponding emissions, rather than being directly based on socio-economic storylines that prescribe the radiative forcing, like the SRES scenarios (Cubasch et al., 2013). The four RCP scenarios used in the most recent assessment report cover a wider range of radiative forcing values than the three SRES scenarios used in the previous assessment. RCP4.5 is considered to be close to SRES B1, RCP6 is similar to SRES A1B and RCP8.5 is between the SRES A2 and A1FI scenarios. RCP2.6 is lower than any of the SRES scenarios (Cubasch et al., 2013).

Although different approaches and climate models have improved in a number of ways with the latest Fifth Assessment (AR5), the projected climate changes are similar in both patterns and magnitude to those presented in the Fourth Assessment Report (AR4), after accounting for differences between the RCP and SRES scenarios (see Fig. 2, IPCC 2013). However, the overall spread of projections for the high RCPs is narrower than for comparable scenarios used in AR4. This is because defining the RCPs as concentration pathways rather than socio-economic pathways means that many carbon cycle uncertainties are not considered (Cubasch et al., 2013). There is little divergence between or within the projected radiative forcing for the SRES and RCPs trajectories until around 2050, when the RCP 2.6 trajectory diverges clearly from the others.

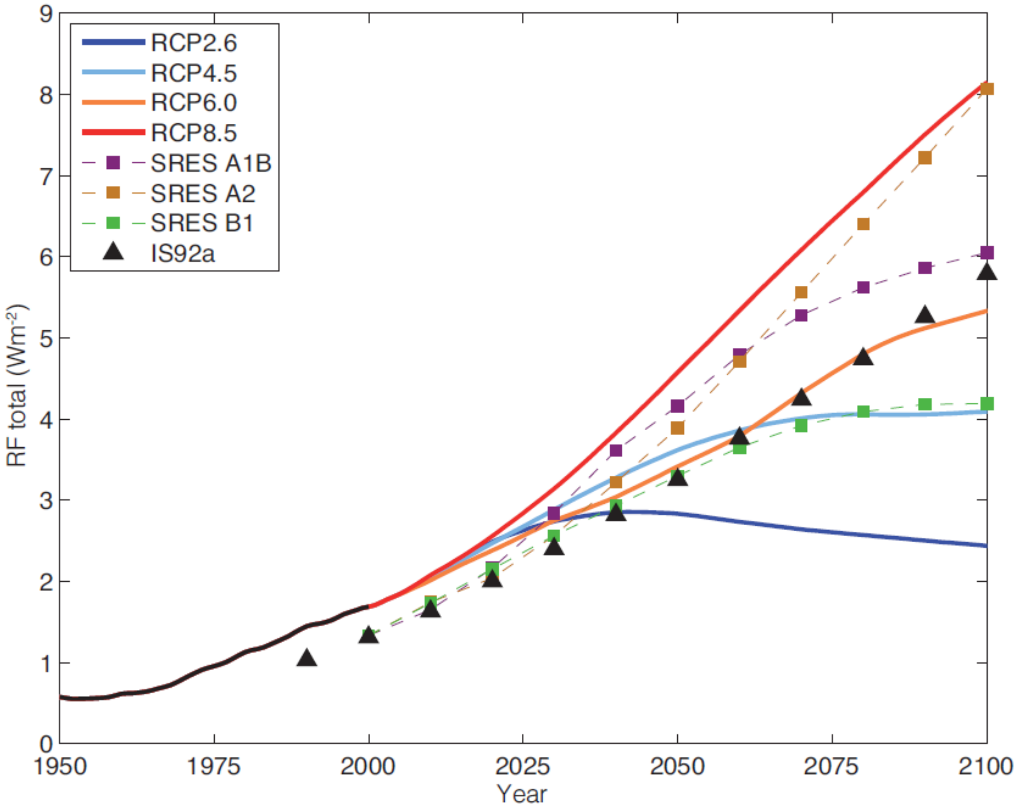

Figure 2: Historical and projected radiative forcing (RF) (W m^{-2}) relative to preindustrial (about 1765) between 1950 and 2100 (Source: Cubasch et al. 2013, page 146.). Previous IPCC assessments are compared with representative concentration pathway (RCP) scenarios. (IS92a was used in the Third Assessment Report (TAR)). Differences in the total RF of the three families of scenarios, IS92, SRES and RCP occur, e.g., for the year 2000, because of assumptions made on changes in emissions since the third (TAR) and fourth (AR4) assessment reports.

We are now essentially committed to a warming world. The AR5 report (IPCC, 2013) states that much of the projected climate change is now largely irreversible on human time scales unless there were to be a very strong and sustained reduction in anthropogenic CO_2 emissions. If radiative forcing effects were stabilized now, a global temperature equilibrium would still only be reached after centuries to millennia.

For the four RCP scenarios, assuming no major volcanic eruptions, global temperatures are projected to increase between 0.3 to 0.7°C (medium confidence) for the period 2016–2035, and likely between 0.3°C to 4.8°C for 2081–2100, relative to the reference period 1986–2005. There is high confidence that global temperatures for 2081– 2100 will exceed 1.5°C above 1850-1900 for three of the four RCP scenarios and 2°C higher for two of the RCP's. For RCP 8.5, warming over 4°C is projected with medium confidence. The projected temperature changes are not expected to be regionally uniform, but will likely be higher over land by a factor of 1.4 to 1.7. Temperature increases are also expected to be larger in the tropics and subtropics than in mid-latitudes (IPCC, 2013).

Precipitation changes are more difficult to project and future estimates are recognised as less skilful than projections of temperature changes (Bader et al., 2008; Fowler et al., 2007; IPCC, 2013). Continental-scale projections have improved since AR4 and it is considered virtually certain that, in the long term, an increase in global mean surface temperature will lead to an increase in global scale precipitation (Collins et al., 2013). However, changes in precipitation will be spatially highly variable between different regions, and projections at regional scales are less certain. In addition, under climate change, contrasts between regions and seasons will intensify (Collins et al., 2013). On a global scale, there will be changes in the distribution of short-term precipitation events, with more intense individual storms and fewer weak storms. Surface evaporation is also projected to increase, leading to decreases in runoff and soil moisture in many regions. Changes in the intensity and frequency of tropical cyclones are also difficult to predict (Collins et al., 2013). These observations are consistent with discussion on likely precipitation change found in numerous high level evaluations (for example Melillo et al., 2014; Steffen and Hughes, 2013; WBGU, 2009).

Many of the effects of climate change may be nonlinear or depend on complex feedback processes that are still poorly understood (Fowler et al., 2007; Parry et al., 2007; Solomon et al., 2007; Swart et al., 2009). While it is possible to model the main components of these systems - atmosphere, ocean, land surface, and sea ice - in practice the outputs of different models vary in the way they simulate different processes and in their accuracy compared with observed data.

Examples of nonlinear components and phenomena include arctic sea ice, the Greenland ice sheet, the Amazon forest and monsoonal circulations. For these effects there is little consensus and low confidence in any projections (IPCC, 2013). There is also a recognised and consistent tendency in downscaled hydrological models to underestimate climatic extremes such as droughts, storms and floods (Fowler et al., 2007). However, despite this uncertainty, future climate variability will have a significant effect and not taking it into account may mean that many negative and positive impacts of climate change are severely underestimated (Thornton et al., 2014).

2.2 New Zealand climate change projections

Overviews of the effects of climate change in New Zealand have been completed by Mullan et al. (2008) and Clark (2012) with an updated concise summary provided by Reisinger et al. (2014) as part of the IPCC Fifth Assessment report process. An overview of this work is provided here with emphasis on important factors for adaptation planning.

In New Zealand, a long-term warming trend of 1.1ºC has been observed between 1900 and 2009, with a 95% confidence interval of ±0.3ºC (Renwick et al., 2010; Reisinger et al., 2014). Long-term trends include higher temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns (Reisinger et al., 2014). It is considered virtually certain that warming and other climate changes will continue (Reisinger et al., 2014).

Located in the Southwest Pacific between 34° to 47° S, New Zealand has a complex maritime climate where a combination of latitude and topography dominate climate variability (Clark et al., 2012). Because of its position in the mid-latitude westerly wind belt, the main climate influences come from changes in wind flow (Renwick et al., 2010), particularly related to the phase of the El Niño/La Niña Southern Oscillation (ENSO, Mullan, 1996), as well as the subtropical high pressure belt that moves north and south with the seasons. The New Zealand climate is dominated in all seasons by these features interacting with steep mountain barriers along the west coast, aligned almost directly perpendicular to the flow of the westerly winds. Much of the country's weather is influenced by the alternating fronts and lows carried by the westerly winds, which cross New Zealand longitudes every four to five days at all times of the year (Sturman and Tapper, 2006).

New Zealand's rugged and mountainous terrain gives rise to considerable regional variability, as well as localised micro-climatic variability in some parts of the country (Sturman and Tapper, 2006). The complex interactions between the large-scale atmospheric circulation and the steep mountains on the western side of the country results in wetter conditions on the west coast, and drier conditions in eastern parts of the country.

Projections consistently indicate an increase in the westerly wind circulation over New Zealand, especially in winter and spring (Mullan at al., 2001; Mullan et al., 2008; Mullan et al., 2011). There may also be a tendency for westerly winds to lessen over New Zealand in the summer, but this is less certain (Mullan et al., 2008). These changes in wind flow mean that there is likely to be an increase in annual mean precipitation in the western parts of New Zealand, and a decrease in rainfall in the north-eastern South Island and eastern and northern North Island (Reisinger et al., 2014; Mullan et al., 2008).

Projections also suggest a more marked seasonality in rainfall and wind patterns (Mullan et al., 2008). It is anticipated that the increasing westerly winds in winter and spring will bring increased rainfall in the west of New Zealand and less in the east and north. In summer and autumn, projections suggest less westerly's, with drier conditions in the west and potentially more rainfall in the eastern parts of the North Island. Other climate changes may include decreased risk of frost, decreased average snow cover, increased frequency of extreme daily rainfall and potentially an increase in strong winds (Mullan et al., 2008). A summary of projected changes to the New Zealand climate system, and estimated confidence in these changes is provided in Table 1, after Clark et al. (2012).

Table 1: Main features of New Zealand's climate change projections (After Clark et al., 2012. Source: Mullan et al., 2008). The degree of confidence placed by the authors of the source report in the projections is indicated by the number of stars in brackets (**** indicates "very confident" and * indicates low confidence).

Climate variable	Direction of change	Magnitude of change	Spatial and seasonal variation
Mean temperature	Increase (****)	All-scenario average 0.9°C by 2040, 2.1°C by 2090 (**)	Least warming in spring season (*)
Daily temperature extremes (frosts, hot days)	Fewer cold temperatures and frosts (****), more high temperature episodes (****)	Whole frequency distribution moves right	
Mean rainfall	Varies around country and with season. Increases in annual mean expected for Tasman, West Coast, Otago, Southland and Chathams; decreases in annual mean for Northland, Auckland, Gisborne and Hawke's Bay (**)	Substantial variation around the country and with season	Tendency to increase in south and west in the winter and spring (**). Tendency to decrease in the western North Island, and increase in Gisborne and Hawke's Bay, in summer and autumn (*)
Extreme rainfall	Heavier and/or more frequent extreme rainfalls (**), especially where mean rainfall increase predicted (***)	No change through to halving of heavy rainfall return period by 2040; no change through to fourfold reduction in return period by 2090 (**)	Increases in heavy rainfall most likely in areas where mean rainfall is projected to increase (***)
Snow	Shortened duration of snow season (***), Rise in snowline (**), Decrease in snowfall events (*)		
Wind (average)	Increase in the annual mean westerly component of windflow across New Zealand (**)	Approximately 10% increase in annual mean westerly component of flow by 2040 and beyond (*)	By 2090, increased mean westerly in winter (>50%) and spring (20%), and decreased westerly in summer and autumn (20%) (*)
Strong winds	Increase in severe wind risk possible (**)	Up to a 10% increase in the strong winds (>10m/s, top 1 percentile) by 2090 (*)	
Storms	More storminess possible, but little information available for New Zealand (*)		
Sea level	Increase (****)	At least 18–59 cm rise (New Zealand average) between 1990 and 2100 (****)	
Storm surge	Assume storm tide elevation will rise at the same rate as mean sea-level rise (**)		

While the climate is naturally variable, extreme weather events still have a significant impact, particularly droughts and floods (Renwick et al., 2010). It is anticipated that these natural variations, superimposed on a long-term warming trend, will create more extreme events (Reisinger et al., 2014; Renwick et al., 2010).

There is uncertainty surrounding many aspects of the climate change projections, in particular projected rainfall changes (Clark et al., 2012; Reisinger et al., 2014; Mullan et al., 2008). It has been suggested that under mid-range climate scenarios it is very likely that the duration and intensity of droughts will increase, particularly in currently drought-prone areas (Mullan et al., 2005). However, rainfall projections are not consistent between climate models (Clark et al., 2011; Meehl et al., 2007; Mullan et al., 2008; Reisinger et al., 2014).

2.3 The New Zealand dairy sector

Worldwide, the dairy sector has undergone considerable growth in recent years and is now facing pressure on several fronts. Steady growth in the global demand for milk products (Kashtanova, 2010) has added pressure on dairy farmers to increase production. However, price instability over the past decade (DairyNZ 2014, Kashtanova, 2010) has also increased the volatility of dairy farmers' incomes.

The dairy industry forms the cornerstone of New Zealand's agriculture-based economy, with approximately 5 million cows and heifers as of 1 July 2014 (MPI, 2014). Approximately 95% of New Zealand's dairy products are exported (SNZ, 2012), accounting for 46 % of the total primary industries export value of NZ$17.6 billion, in the year ending June 2014 (MPI, 2014). The dairy sector has developed over the past 50 years from small scale, extensive dairy farms to modern operations with higher stocking rates, improved genetics and brought in feed. Milksolids production has increased over the past 25 years at a rate of about 8-9% per annum, reflecting growth in per cow production and in cow numbers (DairyNZ, 2014). The last 25 years has seen a steady growth in milk payout and operating profit per hectare, but also in operating expenses, and both have become more volatile. In addition, average debt levels have increased faster than the growth in milksolids in recent years (DairyNZ, 2014).

Growth in the number of dairy cows, as well as in milk yield per cow, is expected to continue (DairyNZ, 2014; MPI, 2014). Future growth is expected to occur mainly through increases in production per cow due to productivity gains from technology and genetics, although expansion of dairy farming is also expected to continue, especially in the South Island, despite pressure from increasingly stringent environmental regulations.

In New Zealand, dairy farming has expanded into more marginal lands in recent years (KPMG, 2010) which will, by definition, be less productive and be subject to greater environmental constraints. Dairy expansion has also resulted in the conversion of forested areas. During this time, farming practices have intensified, but have not necessarily become more efficient, particularly with regard to their environmental impact (Basset-Mens et al., 2009). There is significant public concern about the increasing environmental impacts of dairy production, particularly on freshwater ecosystems (Jay, 2007; MacLeod and Moller, 2006). Dairy farming is also a major source of methane, and in the context of New Zealand's commitment to the Kyoto Protocol, there is pressure for these emissions to be reduced (Beukes et al., 2010a). Heavy dependence on an export market with volatile exchange rates is also a source of vulnerability, with no market price support to provide a buffer to farmers (New Zealand Government, 2010).

Pressure on water resources is increasing as a result of agricultural intensification and environmental restrictions (KPMG, 2010). While temperate regions do not encounter the same water limitations as drylands, there is increasing competition for and regulation of water resources, which are increasingly viewed as 'liquid gold' (KPMG, 2010). Under climate change scenarios, effective management of this resource is likely to be a key issue. Trends in other resources, such as pesticides and fertilizers, which are energy-intensive to produce, may also become limiting to agricultural production in future (Jiang, 2011).

At the farm level, volatility in milk prices further adds to the uncertainty experienced by New Zealand dairy farmers. After a record payout in the 2013/14 season of over \$8.50 per kilogram of milk solids, the stated outlook for the farm gate milk price in 2014/15 was \$7.20 per kilogram, reflecting declining international dairy prices (MPI, 2014). However, this is now expected to fall below \$5.00 per kilogram of milk solids. In the context of increasing debt levels (DairyNZ, 2014), this level of payout means that many farmers will experience economic hardship even in a favourable climate year.

Considering increasing demand and the significant contribution made by the dairy sector to New Zealand's economy, continued expansion is very positive from a short term economic perspective. However, it raises serious questions on the longer term sustainability of dairy systems, particularly those in more marginal areas. The most recent New Zealand Situation and Outlook for Primary Industries (SOPI; MPI, 2014) highlights the fact that over the long term, an important challenge for the dairy industry will be finding innovative ways to cope with environmental concerns arising from dairy intensification.

2.4 Potential impacts on New Zealand dairy systems

New Zealand dairy farms are predominantly pasture based, and may therefore be more directly vulnerable to climate fluctuations than Northern Hemisphere systems where animals are housed and fed largely on concentrates (Clark et al., 2012; New Zealand Government, 2010). Modelling studies on potential impacts of climate change on dairy farms in New Zealand and in temperate areas of Australia have focused largely on pasture productivity, because of the close relationship in pasture-based dairy systems between the amount of dry matter consumed per hectare per year and farm profit (Chapman et al., 2009).

Pasture growth will be affected by factors such as changes in temperature, water availability and atmospheric CO_2 concentrations. Interactions between these factors can be highly complex, significantly increasing the uncertainty surrounding predictions of changes in pasture growth, pasture species composition and pasture quality (Clark et al., 2012; Lee et al., 2013).

There have been a number of studies modelling projections of climate change impacts for New Zealand (Baisden et al., 2010; Wratt et al., 2008; Zhang et al., 2007), but these were initially very broad scale and presented as averages to the middle and end of the century. There are some consistent patterns in anticipated climate change impacts: following the climate change projections described in section 2.2, negative impacts on pasture growth are expected in autumn and for parts of the east coast during summer, while winter and spring growth is likely to increase due to increasing temperatures and CO_2 fertilisation effects (Clark et al., 2012). However, some of these studies suggest a positive overall effect of climate change on pasture growth (e.g. Baisden et al., 2010), while others have indicated it will be negative (e.g. Zhang et al., 2007), depending on the variables included in the modelled scenarios, in particular CO_2 fertilisation.

More recently, modelling studies in comparable dairying areas in Australia (Cullen and Eckard, 2011; Phelan et al., 2014) and in New Zealand (Clark 2012; Kalaugher 2012[3]) have shown that impacts can be very location-specific, with negative climate change effects in some areas suggesting that system changes may be required. Such studies have indicated that while average changes in pasture productivity are often small under climate change scenarios, there may be a large variability and regional variation in impacts (Clark et al., 2001; Cullen and Eckard, 2011; Phelan et al., 2014; Wratt et al., 2008; Zhang et al., 2007). Also, studies modelling seasonal changes show greater sensitivity to climate change impacts than those using annual production as a measure (Reisinger et al., 2014). Rainfall is a key determinant of pasture production, and yet it is the least certain aspect of climate projections, adding another layer of uncertainty (Reisinger et al., 2014).

Increases in atmospheric CO_2 concentrations have been shown to increase pasture productivity through what is described as the 'CO_2 fertilisation effect', where higher levels of photosynthesis and reduced canopy transpiration lead to reduced fluxes of surface latent heat and increased water use efficiency (Cullen et al., 2009; Reisinger et al., 2014; Schmidhuber and Tubiello, 2007; Walker and Schulze, 2008). However, despite extensive study, the magnitude of this effect remains uncertain and it does not always translate into production benefits (Kamman et al., 2005; Lee et al., 2013; McKeon et al., 2009; Stokes et al., 2008;

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[3] The dairy farm modelling work presented in these two references (Kalaugher et al.,2012 and Clark et al., 2012) forms part of Chapter 5 of this thesis.

Wan et al., 2007). The key uncertainties relate to interactions between elevated CO_2 concentrations and water availability, as well as effects on species composition and nitrogen fixation (Newton et al., 2013; Wall et al., 2006; Watanabe et al., 2013). In addition, the positive yield response to increased levels of CO_2 may not be uniform across a range of temperatures (Casella et al., 1996; Clark et al., 2012; Newton et al., 1994). Based on an overview of published New Zealand and international work, Lee et al. (2013) estimated a range of 4 to 14 % increase in production biomass under enriched CO_2 in New Zealand dairy pastures that are not limited by water or nitrogen availability.

Plant responses to elevated CO_2 under variable environmental and management conditions have been identified as a source of uncertainty in our understanding of how global change processes will be manifested at farm level (Li et al., 2014; Rötter et al., 2011; Soussana et al., 2010). Because of the challenges inherent in capturing the likely impacts on ecosystem processes, some studies have omitted these impacts (e.g. Wratt et al., 2008; Zhang et al., 2007) while others have addressed the issue by applying blanket fertility increases to their data (e.g. Baisen et al., 2010; Fitzgerald et al., 2009). Some studies have gone further and developed models capable of integrating likely CO_2 effects on a seasonal basis, such as the work of Stokes et al. (2012), which incorporated known responses from the literature of likely CO_2 effects on different aspects of pasture growth into the model GRASP. Cullen et al., (2009) also incorporated anticipated production responses to elevated CO_2 into the Australian dairy model DairyMod (Cullen et al., 2009), which was further utilised in the study by Phelan et al. (2014). Although based on a robust selection of literature, these modelled CO_2 effects were not limited by nutrient or water availability and the results are untested against field data. Recently, a study by Li et al. (2014) compared responses derived from the ecosystem model APSIM/AgPasture with free air carbon dioxide enrichment (FACE) data from a site in the central North Island of New Zealand. They found that the model over predicted CO_2 fertilisation responses, largely due to poor prediction of years with small or negative responses. Their data also show a distinct seasonal response in CO_2 fertilisation effects, with the highest growth rate increases occurring in spring (Li et al., 2014).

Less direct impacts, or those that affect production through initialisation of other ecosystem processes, such as the distribution and abundance of pests and diseases, may also affect the productivity and sustainability of farming systems. For example, it has been suggested that some vector-borne diseases may increase under climate change scenarios (Rogers and Randolph, 2006). Increased rainfall may increase the incidence of parasites (López-Gatius et al., 2005) and disease and parasite spread following flooding (Brunsdon, 1962; Vermunt et al., 1994). There is also concern that weedy species may be in a more competitive position relative to pasture plants as a result of climate change (White 2001; Zand et al., 2006).

Climate change may alter the balance of species in the pastoral ecosystem at a number of different levels. Pasture species with a C4 photosynthetic pathway, and hence increased water use efficiency, may develop a competitive advantage over C3 pasture species such as ryegrass (Edwards and Still, 2008). Changes may also alter the distribution and/or abundance of existing invasive and pathogenic species weed and pest species (Bourdôt et al., 2012, Harris and Barker, 2007, Yeates and Newton, 2009); altering the effectiveness of management strategies such as biocontrol (Gerard et al. 2012) and currently effective plant resistance mechanisms (Chakraborty et al., 2011; Melloy et al., 2010). For example, many invertebrate populations are sensitive to temperature, which can have an impact on both pests and beneficial organisms such as soil biota and pest predators. Some microorganisms and fungi are also sensitive to increased UV-B radiation (Caldwell et al., 2007; Callaghan et al., 2004). Elevated atmospheric CO_2 has been shown to alter the structure of microbial populations in a pasture ecosystem (Montealegre et al., 2000).

For cows, heat and humidity are key welfare and productivity issues (Berman, 2005; Bryant et al., 2007; Kurihara and Shioya, 2003). Changes in feed quality and supply due to changes in pasture growth may also have a significant impact, as well as direct threats from extreme events such as flooding and drought (Clark et al., 2012).

There is concern over the risk of negative impacts on soil**.** Erosion, for example, is climate driven and may be exacerbated by increasing precipitation intensity. However, there is low certainty around these effects (Basher et al., 2012). The impact of climate change on freshwater resources will also depend largely on changes in precipitation. There is medium confidence that rivers originating in the northeast of the South Island and east and north of the North Island of New Zealand will be negatively affected (Reisinger et al., 2014), and this may affect the viability of potential adaptation options such as irrigation.

Projected increases in the frequency of extreme weather events (medium to high confidence, IPCC, 2013) may have a significant impact on New Zealand agriculture. Flooding in recent years has caused severe damage to infrastructure; and widespread drought in many parts of New Zealand during the 2007-08 and 2012-13 seasons resulted in substantial economic losses. For example, approximately NZ$3.6 billion were lost in direct and off-farm output in the 2007–2008 droughts (Reisinger et al., 2014). The 2012-13 drought was considered the “worst, second worst or third worst since 1972/73” for over half the country (SOPI, 2013). The impacts of such a drought go well beyond the direct biophysical and economic effects (MPI, 2013). There is an increasing body of research on the resilience of farming systems from a social perspective (e.g. Burton and Peoples, 2008; Craddock-Henry, 2011; Pyne and White, 2009, Kenny and Fisher; 2003; Kenny, 2010) and this is further discussed in Chapter 3.

Indirect climate change impacts are those which affect global markets and prices with corresponding flow-on to the New Zealand economy. As an internationally focussed industry the dairy sector may arguably be more exposed to these effects than the direct on-farm impacts (Tait et al., 2008). Internationally, economic forces may work in New Zealand’s favour, and it has been suggested that the higher food prices driven by climate change may have a favourable impact on the New Zealand economy (Reisinger et al., 2014). For example, Saunders et al., (2009) estimate an increase of 14.6% in agriculture and forestry producer returns in New Zealand under the A2 scenario by 2070. Climate change mitigation policies, such as those aimed at biofuel production, may also increase global commodity prices (Saunders et al., 2009; Stroombergen, 2010). However, future shifts in price signals of milk solids are difficult to anticipate, given the complex linkages between agricultural commodity and oil prices, especially considering emissions reduction pathways into the future as the world enters a period of greenhouse gas mitigation. With New Zealand’s export-based agricultural economy, these factors could potentially offset the domestic economic impact of climate change on agriculture (Tait et al., 2008).

2.5 Potential adaptation options

A wide range of potential options have been identified for dairy farms to adapt to climate change. Clark et al. (2012) provide a comprehensive review of climate change adaptation options for New Zealand dairy farms, and a summary of their results is provided in Table 2. A common approach to adaptation options is to group adaptations in terms of the degree of change that would be required in order to adapt (Clark et al., 2012; Stokes and Howden, 2010): 1) tactical adaptations, which comprise well-known responses that are currently part of day-to-day management options for farm operators. 2) strategic adaptations, which are system-wide changes, based on proven approaches from other districts or systems; and 3) transformational change, which involves innovation to develop completely new production systems or even industries.

Another way of conceptualising adaptation options is based on the kinds of investment required to adopt the adaptation, which can be considered at tactical, strategic or transformational levels. Strategies identified in the literature are discussed below.

2.5.1 Adopting species better adapted to the anticipated climate

This strategic focus encompasses selection of new plant and animal species. For example, new crop and pasture species with increased drought-tolerance and water use efficiency, heat tolerance, and new endophytes; and selection of cows for thermotolerance and thermoregulation capacity (Clark et al., 2012; Lee et al., 2013; Smit and Skinner, 2002; Stokes and Howden, 2010).

2.5.2 Reducing stocking rates

Reducing stocking rates has been suggested as a way to address the environmental variations and economic risks associated with climate change (Clark et al., 2012; Smit and Skinner (2002). Milk production per hectare decreases with decreasing stocking rates, but per cow production has been shown to increase (MacDonald et al., 2008) suggesting that efficiency gains and a reduction in variability may have the potential to offset production losses. Stocking rates have been the subject of research in the context of mitigation strategies (Beukes et al., 2011; Doole, 2014).

2.5.3 Imported resources

Importing resources from outside the farming system includes strategies such as the application of more imported fertiliser (for example, to ensure that growth is not limited under CO_2 fertilisation effects) and the use of more supplementary feed to fill feed deficits (Clark et al., 2012; Lee et al., 2013; Stokes and Howden, 2010).

2.5.4 Diversification

Diversification at all levels in the system provides a degree of redundancy and hence resilience. At the enterprise level, diversification in keeping with land class helps spread the risk (Kenny, 2010). For example, one study found that diversity in farm size and intensity, particularly high in Mediterranean regions, reduced the vulnerability of regional wheat yields to climate variability (Reidsma and Ewert, 2008). At farm level, the benefits of increasing pasture diversity may warrant consideration. Sanderson (2006) describes a number of ecological mechanisms through which plant diversity may contribute to increased stability and productivity in grazing systems. Adaptation options proposed include the use of both annual and perennial pasture species and/or diverse pasture mixes at species level, (Clark et al., 2012; Kenny, 2010; Stokes and Howden, 2010). Using crops in the system can provide supplementary feed in times of shortage Kenny (2010) and break pest cycles (Clark et al., 2012). Diversification of crop types and varieties, including crop substitution, and diversification of livestock can also help to address the environmental variations and economic risks associated with climate change (Reidsma and Ewert, 2008; Sanderson, 2006; Smit and Skinner, 2002).

2.5.5 Improving resource use efficiency

Many of the adaptations suggested in the literature are focussed on ways to improve the efficiency of resource use in the farming system. For example, conserving more fodder such as hay and silage (Clark et al., 2012; Stokes and Howden, 2010), careful grazing management (Kenny, 2010) or even agisting stock in unsuitable conditions (Stokes and Howden 2010). This can also include planning in time and space such as forward contracting supply of supplementary feedstock (Stokes and Howden 2010), and more efficient storage and use of water (Kenny 2010; Stokes and Howden 2010) and energy resources, as well as waste management (Kenny 2010), for example, irrigating effluent back onto paddocks.

2.5.6 Investment in infrastructure

Investing in new infrastructure such as shade, animal housing and feed pads, or irrigation infrastructure, can help regulate temperature, improve feed intake efficiency and compensate for changes in precipitation through irrigation (Clark et al., 2012; Kenny, 2010; Smit and Skinner, 2002; Stokes and Howden, 2010).

2.5.7 Natural microclimate management

Ecosystem management on a farm scale can contribute to the farm's resilience and provide other benefits. Trees on farm can provide shade and shelter as well as stabilising slopes (Stokes and Howden, 2010; Clark et al., 2012; Kenny, 2010). Revegetation and soil organic carbon management can help improve groundwater recharge and maintain soil moisture, as well at retaining more nitrogen in the soil (Clark et al., 2012; Kenny, 2010; Schipper et al., 2010; Smit and Skinner, 2002; Stokes and Howden, 2010). This might include, for example, alternative fallow and tillage practices. Changing the land topography to control water flow around the farm can help address the moisture deficiencies associated with climate change and also reduce the risk of farm land degradation (Smit and Skinner, 2002)

2.5.8 Timing adjustments

Changes to the timing of farm operations can help to address potential changes to the duration of growing seasons and associated changes in temperature and moisture (Smit and Skinner 2002). Seasonal changes might include alteration of calving patterns, lactation periods or grazing rotation lengths (Clark et al., 2012). On a daily scale, timing adjustments can help address animal welfare issues that may arise with temperature increases. For example, by minimising animal movement during the day (Clark et al., 2012; Stokes and Howden, 2010)

Table 2: Adaptation knowledge summary for the dairy sector (after Clark et al., 2012)

Driver	Impact	Tactical	Strategic	Transformational
Higher seasonal temperature	• Changes to seasonal herbage yield • Earlier reproductive development • Increased weed and subtropical C4 grass ingress into pastures • Reduced herbage quality • Increased geographical spread of pests and diseases	• Change stocking rates • Lengthen lactations • Produce more silage/hay • Alter calving patterns • Alter grazing rotation lengths • Improve pasture assessment and monitoring • Use alternative pasture/crop species that are more heat tolerant • Sow endophyte-containing species • Use crops to break pest cycles	• Use newly developed plants adapted to warmer temperatures	• Use newly developed plants adapted to warmer temperatures • Invest in research to genetically modify plants for increased heat-tolerance
Heat stress	• Reduced intake • Reduced production	• Alleviate by cooling during milking • Minimise animal movement during the day	• Outdoor shades • Cow selection for heat tolerance	• Move away from heat stress regions
Cold stress	• Improved cow welfare • Reduced feed efficiency	• Shelter	• Wintering systems for supplement feeding	• Winter housing in cold regions
Low water availability	• Reduced herbage yield • Reduced pasture persistence • Increased weed and subtropical C4 grass ingress into pastures • Reduced herbage quality	• Use irrigation where available • Use alternative pasture/crop species that are more drought-tolerant/ water use efficient • Reduce stocking rates • Improve pasture assessment and monitoring • Use supplementary feed to fill feed deficits • Conduct pasture renewal	• Use newly developed plants adapted to drought or that are more water use efficient • Invest in new irrigation infrastructure • Invest in infrastructure required to store and distribute supplementary feeds • Revegetation and soil organic carbon management to improve groundwater recharge and maintain soil moisture	• Use newly developed plants adapted to drought or that are more water use efficient • Invest in research to genetically modify plants for increased drought-tolerance and/or water use efficiency
Waterlogging and flooding	• Reduced herbage yield • Reduced pasture persistence • Increased weed and subtropical C4 grass ingress into pastures • Reduced herbage quality	• Reduce stocking rates in prone regions • Improve pasture assessment and monitoring • Use more supplementary feed to fill feed deficits • Conduct pasture renewal	• Invest in infrastructure required to store and distribute supplementary feeds	
Increased CO$_2$ concentrations	• Increased herbage yield (potential depends on N available to plants) • Increased legume content in pastures • Increased water use efficiency	• Increase stocking rates • Lengthen lactation period • Produce more silage/hay • Alter calving patterns • Increase pasture diversity • Increase fertiliser applied		

2.5.9 Planning tools and technologies

Another area of strategic investment for climate change adaptation is the development and use of decision-support tools and (weather-related) early warning systems (Clark and Tait, 2008; Smit and Skinner, 2002; Stokes and Howden, 2010). These can support both improved planning, and better day to day management through, for example, improved pasture assessment and monitoring (Clark et al., 2012)

At all levels of adaptation, most options involve trade-offs in the development of the system as a whole. The identification of appropriate adaptation strategies also requires consideration of the multiple management objectives confronting farmers, and an understanding of the trade-offs between these objectives. A pastoral agro-ecosystem is required to be productive, and it is also required to maintain public good ecosystem services, such as maintenance of water quality. The main focus of agricultural research is usually on the production side. However, the maintenance of productivity can also be considered on different scales (e.g. short term *vs* long term) and under different conditions (such as drought).

2.6 Approaches to assessing climate change impacts and adaptation options at farm level

A range of methodological approaches have been developed for the analysis of climate change impacts and adaptation options, and several of these are reviewed in the following chapter (Chapter 3). The focus of such approaches has developed over the years. Early approaches focussed on the development of climate change scenarios in order to assess their impacts from those scenarios (Dessai et al., 2005). This meant that the results of such assessments were highly sensitive to uncertainties in the climate models such as methodological choices around climate downscaling (Dessai and Hulme, 2007; Wilby and Dessai, 2010).

Bottom-up approaches that start with present vulnerability, rather than focussing on future scenarios, can offer insights into vulnerability and adaptive capacity that cannot be generated by scenario-based methods. In New Zealand, a range of social research has addressed the capacity of farmers to cope with climate change, particularly extreme events (Burton and Peoples, 2008; Payne and White, 2009; Kenny, 2010; Craddock-Henry, 2011). However, such approaches remain qualitative in nature, making them difficult to integrate with information from climate projections.

More integrated and adaptation-focussed assessment processes are now emerging which focus on engaging stakeholders and enhancing adaptive capacity, particularly for some high level assessments such as the Adaptation Policy Framework developed by the United Nations Development Programme (UNDP). However, there are still large uncertainties present in the way climate change will be manifested at finer scales. For the New Zealand dairy sector, such uncertainties make it difficult both to incorporate climate change into sectoral planning and to communicate climate change issues to farmers.

Reisinger et al. (2014) highlighted in the most recent IPCC assessment report that our understanding of future vulnerabilities and the feasibility and effectiveness of potential adaptation strategies is still limited by poor integration of economic and social dimensions with biophysical studies.

The following chapter reviews approaches to the assessment of climate change adaptation and proposes a Mixed Methods Framework that forms the basis for the approach taken in this thesis.

To understand the factors affecting farm level adaptive capacity, it is necessary to focus on the farm system itself, utilising a finer level of weather inputs that can be more easily related to the management challenges that farmers deal with on a daily basis (Newton et al., 2008). As described by Clark et al. (2012), a range of climate change projections are available for New Zealand that utilise different technical approaches, and the underlying science is continually improving. The approach taken here is to utilise the best available projections at a particular point in time. This allows the science of improving the accuracy and reliability of regional scale projections to evolve while simultaneously supporting adaptation.

3 An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system

Abstract

The development of effective climate change adaptation strategies for complex, adaptive socio-ecological systems such as farming systems, requires an in-depth understanding of both the dynamic nature of the systems themselves and the changing environment in which they operate.

To date, adaptation studies in the New Zealand dairy sector have been either bottom-up, qualitative social research with farmers and communities, or top-down, quantitative biophysical modelling. Each of these approaches has clear benefits as well as significant limitations. This review considers concepts and approaches that support the potential for different disciplines to complement each other in developing a more in-depth understanding of farming systems and their adaptive potential. For this purpose, a Mixed Methods Framework is presented, using examples from a pilot study of a New Zealand dairy farm to illustrate the complementarities between the two current approaches.

By presenting this methodology in a specific context, the review provides the theoretical basis for a practical way to integrate quantitative and qualitative research for climate change adaptation research. This chapter provides the methodological structure used throughout the thesis.

3.1 Introduction

Analysing the future sustainability of a complex system such as a dairy farm in the context of climate change presents significant challenges. The impact of climate change on agriculture will depend on factors such as scale, location and the vulnerability of the people and activities concerned (Adger, 2006; Aydinalp and Cresser, 2008). There are many uncertainties around the degree to which global and regional climate could change, and many of the effects are unpredictable and depend on complex feedback cycles that are still poorly understood (Fowler et al., 2007; Parry et al., 2007; Solomon et al., 2007; Swart et al., 2009). Uncertainty is further increased by the complexity of pastoral agro-ecosystems (Bryant and Snow, 2008) as specific effects of climate change, such as rising atmospheric CO_2 concentrations, may have an impact in different ways on different aspects of the farm system.

Traditionally, adaptation studies have focussed on the analysis of specific risks under climate change scenarios. There are two dominant approaches to climate risk assessment and adaptation studies: 'Top-down' approaches, which feed downscaled climate scenarios into impact models in order to calculate probable impacts and test potential adaptation measures; and 'bottom-up' approaches, which generally focus on ways to reduce the vulnerability of a community to climate events based on past experiences, often following an extreme event or disaster (Wilby and Dessai, 2010).

Integrated models, such as the DairyNZ Whole Farm Model (WFM) (Beukes et al., 2011; 2008) referred to in this review, provide a useful basis for assessment of climate change adaptation options, allowing the manipulation of management options under future climate scenarios and providing both biophysical and economic outputs. Although mostly characterised by a top-down methodology, such models provide an effective means to integrate key aspects of farm systems performance with estimates of climate variability.

Despite these advantages, the use of integrated models like the WFM in top-down studies has a number of limitations when applied to the analysis of adaptation. There are biophysical uncertainties, as currently no models are available that include a fully comprehensive range of biophysical processes important in the analysis of climate change adaptation options, such as pests and diseases, pasture species competition or soil carbon dynamics.

Models do not always include 'softer' elements in their system boundary, such as socio-economic factors, limiting their value for the practical evaluation of some climate change adaptation strategies (Dynes et al., 2010). In addition, such complex integrated models are not usually directly accessible to farmers, and in many cases these key farm decision-makers are excluded from the model development and application process. Thus implementing management decisions in practice necessitates collaboration between stakeholders and researchers. This aspect has also been emphasised by others, e.g., by Martin et al. (2011), whose scenario approach focused on encouraging participatory involvement of farmers in managing adaptation to climate variability, and which also connected the science with feasible farm applications.

A pivotal question is how to accommodate and synthesise different perceptions of the farming system and the 'soft' and 'hard' components of the system. Participatory bottom-up, qualitative research can provide a more direct reflection of the on-the-ground reality that farmers face in making management decisions. However, for any proposed adaptation measure, there are biophysical impacts that need to be evaluated, trade-offs to be made in present and future costs and benefits. Social research, by nature, is unable to adequately quantify these impacts and trade-offs.

This paper argues that in order to understand and address properly the available adaptation options and the context in which those options would be useful, an interlinked approach utilizing both qualitative and quantitative research methods is necessary. This is neither 'bottom-up' nor 'top-down', but an interdisciplinary process that develops plural and conditional assessments of the trade-offs inherent in different management strategies. This paper presents a conceptual framework using a New Zealand dairy farm system as a working example, with concepts from resilience approaches and soft systems methodology as one way to facilitate the working together or synergy of two different methodologies for achieving a dynamic and inclusive analysis of complex farming systems.

3.2 Approaches to climate change adaptation assessments

Since the early 1990s, there has been a rapid expansion of research on adaptation to environmental change (Nelson et al., 2007). One of the earliest frameworks for the assessment of impacts and adaptation was provided by the Intergovernmental

Panel on Climate Change (IPCC) (Dessai et al., 2005), which is also considered the standard approach (Burton et al., 2002). This approach defines seven steps: 1) Problem definition; 2) Selection of the method; 3) Testing of the method (e.g. sensitivity analysis); 4) Selection and application of climate change scenarios; 5) Assessment of biophysical and socio-economic impacts; 6) Assessment of autonomous adjustments; and 7) Evaluation of adaptation strategies. This framework provides for the systematic quantification of the severity of climate change impacts on a pre-defined biophysical or human system (Parry and Carter, 1998).

Many assessments still follow the broad IPCC framework. However, such assessments are heavily focussed on the development of climate change scenarios and the assessment of potential impacts from these scenarios (Dessai et al., 2005), rather than on current vulnerabilities or on adaptation options (Burton et al., 2002). Because of this, the results of such assessments can be highly sensitive to the uncertainties in the climate models (Dessai and Hulme, 2007), stimulating the development of increasingly sophisticated models for the purpose of adaptation assessments (Burton et al., 2002; Dessai et al., 2005).

More recently, risk management has become a central concept in many climate change assessments, particularly in light of the projected increases in extreme weather events. A core concept in risk assessment for climate change is the need to analyse not only average changes, but also the potential frequency of major losses (Yakushev, 2009). However, while there is broad agreement that the management of uncertainty and concepts of risk management are important, there are a wide range of approaches to risk assessment and each community of practitioners has adopted a different definition of the process (Dessai et al., 2005). The quantification of risks in the context of climate change adaptation research is particularly challenging due to the high level of uncertainty associated with climate change projections and difficulties in attaching probabilities to different development pathways, as well as the global nature of the problem (Dessai and Hulme, 2004). Stirling (2010) highlights the dangers of an overly narrow focus on specific, quantified risks, suggesting that it is an inadequate and oversimplified response to incomplete knowledge. He suggests that a more rigorous approach to incomplete knowledge is required, which takes into account less quantifiable aspects of uncertainty as well as “the deeper challenges of ambiguity and ignorance”.

A broad criticism levelled at adaptation studies to date is that they have a tendency to be rather prescriptive and normative about specific management practices. Particularly for top-down, scenario-based assessments of adaptation options, the options evaluated tend to focus on areas where immediate benefits can be gained. For this reason, there is often little progress in removing the more persistent and intractable vulnerabilities (Nelson et al., 2007). In addition, because adaptation is considered in relation to specific risks, the assessments are often static in nature, i.e., measuring the levels of risk before and after adjustments have taken place (Nelson, 2011; Nelson et al., 2007). In the context of agricultural systems, prescriptive recommendations about management practices may have limited usefulness. Because systems are not static entities, but dynamic in space and time, there will be ongoing changes in the sensitivity and adaptive capacity of systems (FAO, 2008). Risk management perspectives continue to evolve to take into account the surprise, uncertainty and the long-term nature of climate change adaptation, as well as the multiple sources of stress and risk (Nelson, 2011).

A parallel conceptual development in adaptation research has been a focus on more systems-oriented ‘resilience’ approaches (Folke et al., 2010; Nelson et al., 2007). Farms are considered as ‘complex socio-ecological systems’. Such systems do not change in a linear fashion but rather incrementally as they reach particular thresholds (Briske et al., 2010), often to the (negative or positive) surprise of those trying to manage them (Nelson et al., 2007). This is closely aligned with the emerging ‘non-equilibrium’ perspective (Scoones, 2004), which embraces the complexity of systems and encourages more flexible and dynamic adaptive responses to climate change. In the case of New Zealand farming systems, it has been noted that “equilibrium is not an option and, if achieved, is short-lived” (Beijeman et al., 2009).

Given the uncertainties surrounding the assessment of adaptation measures, it has been suggested that it is now timely to allow the appraisal of adaptation options to take centre stage, rather than the climate change scenarios themselves (Wilby and Dessai, 2010). The safest approach to adaptation is to aim for flexible and diverse systems that are resilient to shocks (FAO, 2008). This approach focuses on ways to build a system's ability to cope with adverse effects rather than on the effects themselves, which remain highly uncertain. By concentrating on the system, rather than on the problem, and assessing adaptation options in the context of their contribution to the overall resilience of the system, the outcomes have a much stronger chance of being 'no-regrets' (Wilby and Dessai, 2010). However, the level of flexibility or diversity required for sustained adaptation so far has been difficult to ascertain.

Definitions of resilience vary and abound, particularly in the social literature (Windle, 2011), where the concept has long been applied to human response to adversity. In the context of adaptation to climate change, resilience has been defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity" (Folke et al., 2010). Walker et al. (2002) adopted a broader definition, suggesting that resilience comprises either the ability of a system to maintain its function when perturbed, or the "elements needed to renew or reorganise if a large perturbation radically alters structure and function".

While resilience is clearly important, achieving greater resilience may come at the cost of (short-term) productivity. The identification of the appropriate adaptation strategies requires consideration of the multiple management objectives facing farmers, and an understanding of the trade-offs among these objectives under different system arrangements (Nelson, 2011; Stoorvogel et al., 2004).

3.3 The need for an integrated approach

3.3.1 Current methodology

Much of the recent literature has focussed on the concept of complex, adaptive socio-ecological systems, and the failure of disciplinary approaches to address adequately the complexities of these systems. The consequences of this inadequacy have been described as a "profound failure of knowledge" (Cornell et al., 2010) and there is an urgent need for greater inter-disciplinarity and depth of perception in assessments of such systems.

There have been a number of pleas for a more integrated approach, highlighting the need for a ‘suite of tools’ together with field experimentation (Dynes et al., 2010) and integrated research methodologies (Mastrandrea et al., 2010; Norgaard and Baer, 2009; Patwardhan et al., 2009; Pearson et al., 2011) to effectively address the uncertainty and complexity of climate change processes. Mastrandrea and Schneider (2010) pointed to the need for a bottom-up/top-down vulnerability assessment and emphasised the necessity for direct partnerships between stakeholders and scientists e social scientists and climate scientists in this context.

Calls for interdisciplinary methodologies to complex problems are not new - the potential power of combining different approaches to gain new insights has been recognised since at least the early 1940s (Miller et al., 2008). This also has been explored by numerous authors (Mansilla, 2010) in concepts such as ‘consilience’ and the ‘jumping together’ of ideas across scientific disciplines (Wilson, 1998) and theories of ‘conceptual blending’ (Fauconnier and Turner, 1998). Despite this recognition, in practice there are many challenges and barriers to the adoption of interdisciplinary methodologies and most studies still follow disciplinary lines (Nelson et al., 2007). Adaptation work in the New Zealand dairy sector provides an example of such dichotomy. Studies to date have been either bottom-up, qualitative social research with farmers, such as the work of Kenny (2010) and Burton and Peoples (2008), or top-down, quantitative biophysical modelling work such as that of Zhang et al. (2007) and Dynes et al. (2010). Modelling systems, such as SimCLIM and Climpacts (Warrick et al., 2001) and the Ecoclimate work (Wratt et al., 2008) reflect the science and availability of downscaled climate change projections in New Zealand, with several of the main drivers of variability in climate/pastoral systems being captured in the Ecoclimate model. However, these biophysical models do not integrate the inherent complexities of farming systems, such as pests, diseases, animal health effects, farmer coping ability or farm management (Newton et al., 2008). A recent study (Dynes et al., 2010) took one step further to compare a selection of adaptation management strategies under mid-range climate scenarios, in a case study setting. However, the study was still limited by the scope of the model and uncertainty in the climate change projections available.

Top-down, modelling based approaches generally reflect a mechanistic view of agricultural systems where the knowledge generated is objective and replicable, acquired via the scientific method; and seeks to demonstrate causality and allows for prediction. On the other hand, bottom-up, social science methodology provides an example of a 'constructed' view of nature where knowledge is viewed as a narrative e interpretive and critical. The knowledge obtained in this way is embedded in a particular context and recognises the values associated with such knowledge (Miller et al., 2008). For example, qualitative social studies that examined the resilience of dairy farmers to extreme events such as droughts (Burton and Peoples, 2008; Kenny, 2010; Payne and White, 2009), have shown the flow of ideas from farmers to researchers, highlighting the importance of context and engagement in understanding principles of resilience. This aspect is dealt with in more depth under Section 3.3.3.

3.3.2 Divergent perceptions

Researchers and farmers may have quite different perceptions of a farming system and different approaches to solving a particular problem. One issue is a difference in temporal perceptions and planning horizons between scientists and farmers. Strategic planning horizons for farmers rarely extend beyond 10 years (Gray, 2001). However, planning for adaptation to climate change is necessarily a long-term strategic process and climate change scenarios are usually analysed for a point in the future beyond the longest planning horizon of most farmers. Qualitative social studies, in contrast, tend to incorporate longer perspectives in the context of human involvement, resulting in a better match with the farmer's planning horizons.

Scale is another factor that influences a difference in perception between farmers and researchers. Top-down research utilizing models often operates from a global to farm level, usually following disciplinary boundaries. Again, social research tends to resemble more closely the scales on which farmers are operating for the simple reason that it involves engaging with farmers around their management systems and planning. The issue of bridging the scale gap represents a particular challenge to any research approach: it is difficult to gain an in-depth perspective of a system and apply the knowledge gained through research without understanding the linkages between different scales (Patwardhan et al., 2009).

3.3.3 Addressing resilience

The social research carried out to date (e.g. Kenny and Fisher, 2003; Burton and Peoples, 2008; Payne and White, 2009; Kenny, 2010) has resulted in significant insights into farmer decision making and the resilience of New Zealand farming systems by asking about farmer experience of past climate events and their perceptions on climate change. Such social research can further provide a broad perspective that includes less tangible and quantifiable components of the system. However, it is often limited by reliance on subjective personal experience and a lack of hard quantitative data. There are also limitations in focussing on past and current events, as these are increasingly a limited guide to a future under climate change.

Models can have a more valuable role in improving the resilience of farming systems if development and use is embedded in the adaptation process itself through high levels of participation by farmers (McCown and Parton, 2006; Voinov and Bousquet, 2010). If the farmers or managers of an agricultural system are viewed as ‘clients’ (Woodward et al., 2008), it is important that they are involved throughout the innovation process, from problem definition and model design and testing through to the policy planning and evaluation phases of any model-based research process. In the case of climate change adaptation in dairy systems, allowing for experimentation with adaptation options in a virtual, modelling world reduces the substantial risk involved in premature physical implementation and trials. It also allows adaptation options to be explored within the bounds created by climate change projections.

Participatory modelling, which incorporates both technical and social elements, is now recognised as a powerful tool that can contribute to collaborative learning and quantification of the impact of proposed solutions to a given problem (Cabrera et al., 2008; Voinov and Bousquet, 2010; Woodward et al., 2008; Martin et al., 2011). By jointly defining the ‘virtual world’ to be modelled, this virtual world is likely to more accurately resemble the real world. Comparing the jointly defined virtual world to the real world creates learning opportunities. Such a participatory modelling approach requires the establishment of a common epistemology or way of understanding the knowledge generated. However, the establishment of a joint epistemology often ends with one epistemology winning over the other (Miller et al., 2008).

Another limitation to participatory modelling is presented by the technical challenges of the models themselves. For example, the scope of the study may be limited by the capacity of the model; and the more integrated and complex the model, the less accessible it is likely to be to end-users such as farmers, unless the process of modelling development expands the system boundary and viability of the model for specific uses. The boundary extensions of the model may include socio-economic factors in their structure for the practical evaluation of some climate change adaptation strategies (Dynes et al., 2010). However, softer elements of the system, such as the personal resilience and adaptive capacity of a particular farmer, can have a significant influence on the response to the severity of climate impacts (Darnhofer et al., 2010a) but may prove extremely difficult to model. While there is significant value in the inclusion of farmer perspectives in the overall analysis, the issues raised are still reduced to descriptive ‘factors’ in an otherwise objective and context-free research method, thereby losing part of the value that might be gained by a more balanced combination of epistemologies.

3.4 Methodological approaches to facilitate integration: towards a mixed models framework

3.4.1 Systems approaches

Systems approaches have been particularly designed to support studies that integrate different disciplines (Kropff et al., 2001). They have been applied to farm management since at least the 1970’s. The integrated nature of these approaches contrasts strongly with the highly reductionist approach taken by early agricultural scientists (see Beijeman et al., 2009). Early systems work took the form of ‘hard’ systems analyses that integrated physical aspects of the system (see Beijeman et al., 2009). As systems concepts continued to develop, the need to incorporate ‘soft’ systems components (such as social practices, economics, politics and culture) became apparent.

Increasingly, businesses such as farms are viewed as complex, self-adapting systems capable of learning, synergy, and innovation (Beijeman et al., 2009).

Systems approaches have a number of common elements: First, they work to avoid the traps of reductionist, linear thinking by focussing on the interconnectedness of variables in the system. They also work to incorporate multiple perspectives into the analysis in order to understand the dynamics of the system and the processes through which beneficial change can occur (Reynolds and Holwell, 2010).

The term 'transdisciplinary' has evolved to describe approaches that effectively transcend the boundaries between different scientific disciplines and non-scientific sources of knowledge, and a number of frameworks have been developed to enable integration of different kinds of knowledge (Pereira and Funtowicz, 2006). However, such frameworks are usually focussed at the regional level. Analysis of management strategies at farm level offers greater potential for the effective integration of stakeholder (i.e. in this context, farmer) perspectives.

3.4.2 Communicating and harnessing knowledge

The challenge of adapting to climate change is fraught with uncertainties. In order to address such a challenge effectively, strategies should be based not only on the explicit knowledge of researchers but also on the tacit, contextual knowledge that farmers have gained from experience. The knowledge developed by farmers is often different in nature to that developed by formal researchers. It is embedded in the context of their farming system, and based on the day-to-day experience that contributes to a tacit understanding of the system, without necessarily understanding the underlying mechanisms (Hoffmann et al., 2007). Hoffmann et al. highlight the importance of externalising the tacit knowledge of expert farmers so that it can be integrated into the research process. This can be facilitated by the creation of conceptual models, which externalise or make explicit a particular view of a system. Tacit knowledge may be used to address less quantifiable aspects of a system through the intuitive understanding that is based on seeing similarities with previous experiences (Hoffmann et al., 2007). For this reason, the harnessing of such knowledge is a valuable asset in the development of climate change adaptation strategies and in other areas of research where there is a high level of uncertainty.

The question of how to harness the different knowledge and experience of researchers and farmers for the generation of new knowledge has been the subject of much debate (Hoffmann et al., 2007). A wide range of participatory methodologies has been developed to facilitate communication, and yet arguably the most important element in the effectiveness of participatory research is the attitude of the researcher (Barreteau et al., 2010; Neef and Neubert, 2011). A key element in the effectiveness of any integrated, participatory research is the recognition of the validity of different epistemologies or conceptualisations of knowledge (Miller et al., 2008).

3.4.3 Soft systems methodology

The technique of conceptual modelling for externalising a particular view of a system has been utilised in the Soft Systems Methodology (SSM) developed by Peter Checkland in the 1980s for the analysis of "problematical, messy situations" in an organised way. This approach has facilitated the development of the framework presented in this paper, because it is a well-established and broadly applicable methodology (Checkland and Poulter, 2010) for analysing complex situations such as those occurring in the adaptation of dairy systems to climate change. SSM is based on two key ideas: The concept of "learning your way through" problematical situations; and the organisation of this learning through using conceptual systems models of purposeful activity as a source of questions to ask in real situations (Checkland and Poulter, 2010).

A key strength of SSM is that it explicitly identifies the worldviews of key actors in a system (Checkland and Poulter, 2010). In doing so, it has real potential to cross-reference different ways of perceiving knowledge. This addresses one of the main weaknesses of much interdisciplinary research (Miller et al., 2008). The SSM approach was developed in the context of business management; however, variations of the methodology have been used in the life sciences context as well. For example, Wixon and Balser (2009) applied a version of SSM to the analysis of soil respiration responses to global climate change. The framework presented in Section 3.5 includes components from both the Wixon and Balser version and the original SSM as described in Checkland and Poulter (2010). In particular, the SSM framework that explicitly describes the components of a soft system (see Section 3.5.2) is useful in this context. This methodology does not represent hard categories, but rather a flexible tool for describing a system, as a starting point for discussion and analysis (Checkland and Poulter, 2010).

3.4.4 Conceptual and quantitative models

Resilience thinking and techniques, using e.g., SSM, draw on conceptual models as tools for learning about systems. In this context a ‘model’ can be defined as “any representation of a system that is stable enough to serve as the basis for discussion about the system it represents” (Barreteau et al., 2010). When employing such methods together with quantitative computer models, such as the Whole Farm Model, it is therefore important to consider how they fit together conceptually. Fig. 3 provides a representation of the place of the Whole Farm Model, which serves to quantify and test specific quantifiable aspects of the system, in a conceptual model that includes some of the broader social and biophysical components of a dairy farming system.

Fig. 3 aims to highlight the progression between ‘softer’ and ‘harder’ system elements. Less tangible, softer elements of the system are represented on the left hand side, progressing to more readily quantifiable (but often very complex) system elements on the right. Many of these elements may also potentially be incorporated into quantitative models.

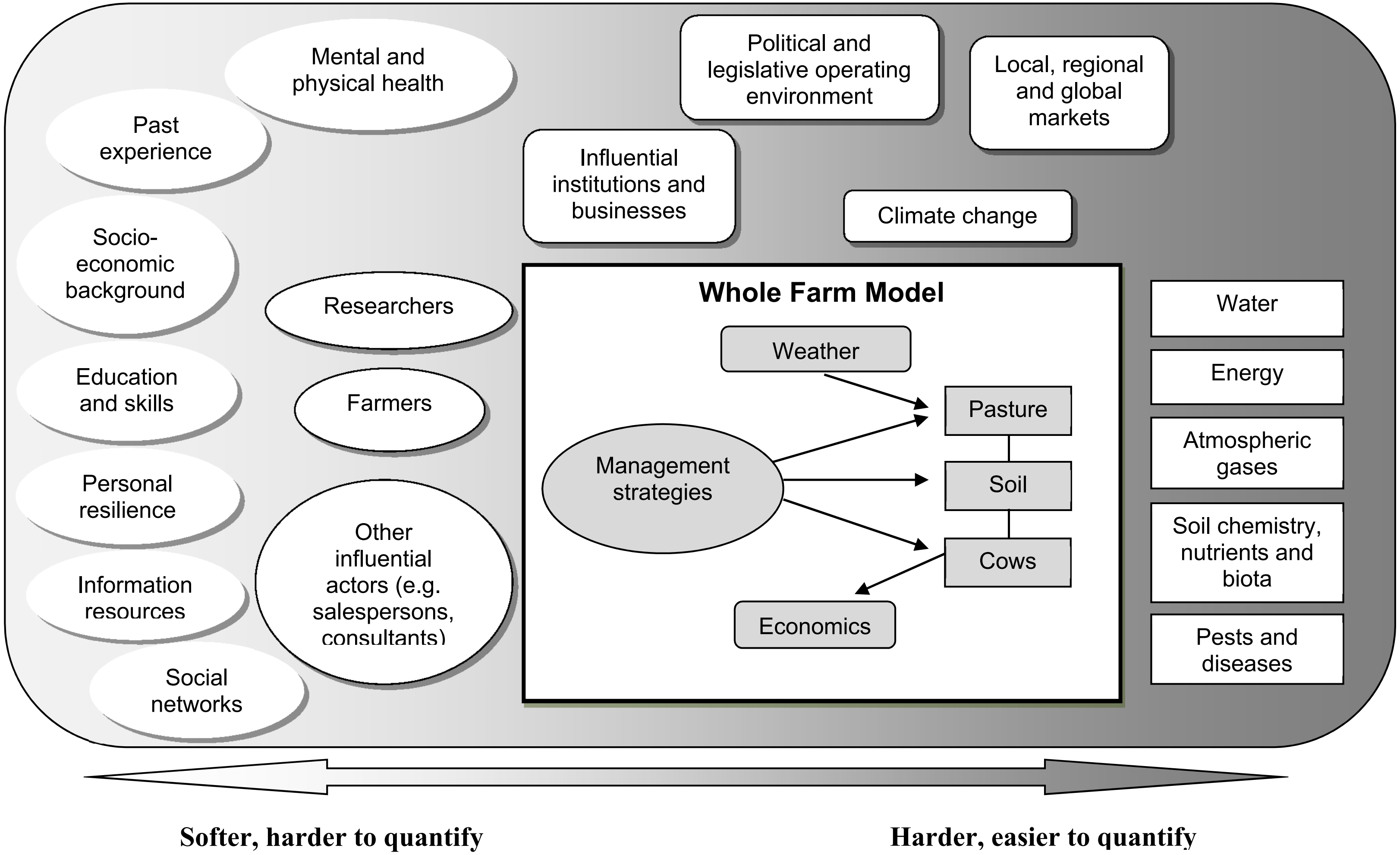

Figure 3: Conceptualisation of the positioning of the Whole Farm Model in relation to softer and harder elements of a farming system.

3.5 A framework for analysing adaptation strategies for a New Zealand dairy system

This section presents a framework for the integrated analysis of adaptation strategies for a dairy system. By presenting this methodology in a specific context, the aim is to contribute further to the development of practical ways to integrate quantitative and qualitative research.

3.5.1 Methodology

The framework has been developed against the background of relevant literature on climate change and risk management frameworks, as well as systems and resilience thinking. It also draws on a pilot case study carried out on a New Zealand dairy farm in the Waikato region, North Island.

The pilot study farm is pasture-based with ca. 160 ha and around 500 cows. The owner/operator of the pilot study farm provided management and production information from his farm for input and validation in the Whole Farm Model, a semi-structured interview and further communications. While the pilot study did not test the complete framework, it provided initial insights into the processes, which were valuable in the development of the approach.

3.5.2 A Mixed Methods Framework

This framework is focused at farm level and is suitable for implementation in a case study or series of case studies of actual working farms. The focus of the framework is on ways to combine quantitative and qualitative inputs and actively promote the cross-fertilisation potential of such integration.

The analysis starts with two scoping exercises; one by the researcher; followed by a researcher-facilitated scoping exercise with the farmers (see Fig. 4). This is carried out in order to allow for the independent definition of researcher and farmer perspectives on the system, effectively creating two conceptual models of the farming system for analysis and integration. Through this process, researchers gain an understanding of their own and the farmers' perspective, the differences between them and why these differences exist.

The development of future scenarios and modelling of their impact on the farm system using current management practices (step 3), provides a quantitative input into the assessment of risks and adaptation options. Together with the historical context and systems perspectives provided in the scoping exercises this information forms the basis for a joint assessment (step 4) of the current adaptive capacity of the farming system; risks to the system under future scenarios; types of uncertainty inherent in the analysis; and proposed adaptation options. Relevant quantifiable adaptation options are analysed by the researcher in step 5. The results of these analyses are then validated with the farmer (step 6). If necessary, the process can be repeated until both researcher and farmer are satisfied that the outputs of this quantitative analysis give an accurate enough reflection of the trade-offs inherent in different strategies to provide a useful basis for the next step.

The final phase of the analysis consists of the evaluation of the adaptation options identified and the logical steps towards feasible implementation. In this process, the trade-offs identified in the modelling assessment are evaluated in the context of the ‘rich picture’ painted of the system through previous steps in the assessment.

3.5.2.1 Scope (researcher)

The first step in the scoping exercise is to consider the development of a system over time. A historical profile of influences and changes in the system (in this case, the New Zealand dairy industry), particularly how it has coped with past shocks, reveals much about its adaptive mechanisms (Walker et al., 2002).

As a technical term, the word ‘mess’ is used by soft systems researchers to express the complexity and diversity of perspectives present in a problem situation (Checkland and Poulter, 2010).

Recognition of a range of perspectives and potentially conflicting interests can facilitate a richer appreciation of the problem situation. In the case of adaptation needs for a New Zealand dairy farm, the point of view of the farmer may be quite different from that of the researcher, and industry representatives such as milk processors may have a different perspective again. These differences can be quite clearly expressed if they are solicited. For example, the New Zealand (Waikato) dairy farmer in the pilot study highlighted the emphasis of researchers on reducing stocking rates and improving per-cow productivity, particularly in the context of climate change mitigation. He considered the idea of focussing on higher per-cow production to be a “luxury” after three years of drought had left the family struggling financially.

Actively defining the farming system from the researcher perspective enables a direct comparison in the next step with the farmer perspective, as a basis for understanding the differences. For this purpose, this section draws on the SSM tool for generating ‘root definitions’ that identify core components of the system (Checkland and Poulter, 2010).

Two of the key root definitions expressed in SSM are the concepts of ‘worldview’ and the perception of the ‘transformation process’ occurring in the system that is being analysed. Researcher perceptions of the system are strongly influenced by their worldview including norms, values and approach to understanding knowledge. The transformation process occurring in the farming system can be represented in different ways: in its simplest form, a dairy farm is seen as a process of transforming grass into as much milk as possible, by keeping and milking cows. It might also be described as a process of transforming money into a lifestyle by running a complex farm. In essence, this is a process of clarifying the most important goals of the system and what contributes to their achievement.

In order to gain a comprehensive picture of the power dynamics at work in the system, the primary actors, with their particular roles, are then recognised. In identifying those directly affected by the functioning or non-functioning of the system (Checkland and Poulter (2010) refer to these as ‘customers’) and those with the power to stop or change the system (‘owners’), influences and consequences become clear. For example, in an owner-operated farm, the farmers are both the primary decision-makers and the most affected by the farm system processes. However, influential industry bodies such as farmer-owned cooperatives may also have the power to define aspects of the system through their role in providing access to the market.

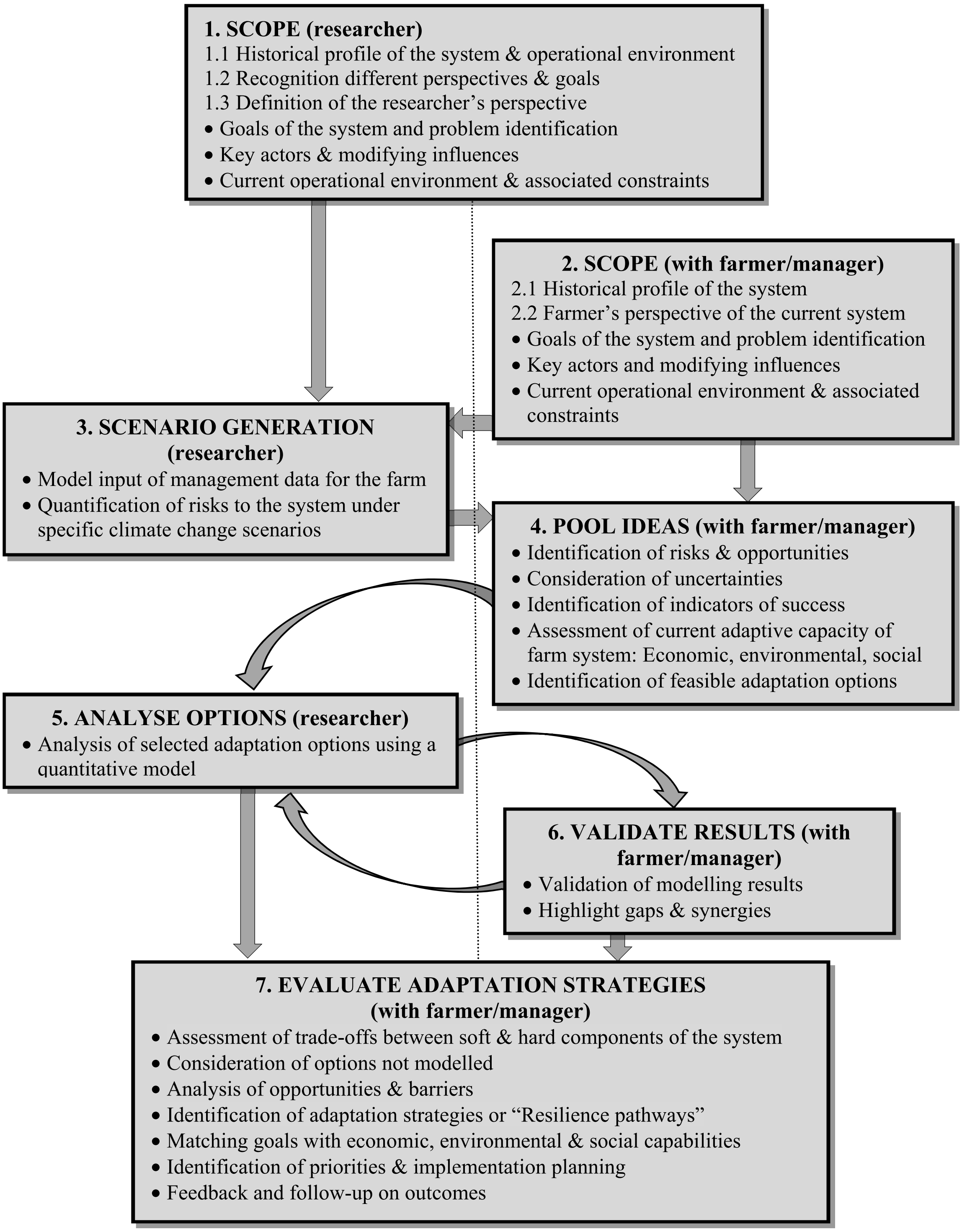

Figure 4: A Mixed Methods Framework for analysing adaptation strategies in a New Zealand dairy system.

Finally, the environment in which the system operates needs to be defined. This involves recognition of the challenges and risks facing the system in question, and also the uncertainties inherent in the identification of such risks (Stirling, 2010). Many of these challenges have the potential to interact and compound potential risks and uncertainties. For example, in New Zealand, the dairy industry is a cornerstone of the economy, with an export value of NZD 11,323 million (Ministry of Agriculture and Forestry, 2009). The competitive advantage of New Zealand's dairy industry is based on the efficiency of its low cost, pasture-based systems compared with more intensive systems reliant on feeding concentrates, such as most European dairy systems (Basset-Mens et al., 2009; Gray, 2001). However, pasture-based systems are also more vulnerable to climate fluctuations. Climate change projections indicate that the climate change process will increase not only average temperatures but also climatic variability and the frequency of extreme weather events such as droughts and floods (Renwick et al., 2010). Demand for water resources is increasing as a result of agricultural intensification and environmental restrictions (KPMG, 2010) as well as population demand in peri-urban areas. Demand trends for other resources, such as pesticides and fertilizers, which are energy-intensive to produce, may also become limiting. In addition, pressure on farmers to reduce their environmental footprint is increasing (Beukes et al., 2010a; Jay, 2007; MacLeod and Moller, 2006) as well as pressure to improve animal welfare practices. Global and regional markets will be affected both directly and indirectly by climate change, and dynamic market responses to global change are the subject of considerable uncertainty (Abler et al., 2000).

3.5.2.2 Scope (with farmer/manager)

The second step is to scope the study from the perspective of the (case study) farmer, facilitated but not influenced by the researcher. First, an historical perspective of the farm's development is a key mechanism for gaining an understanding of the farming system. Past studies (Burton and Peoples, 2008; Kenny, 2010; Kenny and Fisher, 2003; Payne and White, 2009) have gained significant insights into farmer decision-making and the resilience of New Zealand farming systems by asking about farmer experience of past climate events and their perceptions of climate change.

There are a range of participatory methodologies that can be used to gain insights in this step and in further collaboration with farmers. Semi-structured interviews may be the most effective tool for the scoping exercise. However, as a research method these rely heavily on the skill of the researcher (Kvale and Brinkman, 2009). Formulation of the questions should elicit response about the way farmers view the key components and processes occurring in the farming system, to enable articulation of the 'root definitions' as outlined in step 1. This will then form the basis for creating a richer picture of the system from the farmer's perspective.

A combination of methodologies may be appropriate, depending on the resources available for the study. For example, for the purpose of the scoping exercise, an informal farm walk may yield insights that do not arise in a more formal interview setting. Particularly for steps 4 and 7 (following), group activities, such as workshops, focus groups and group farm walks may be of considerable value in promoting the cross-fertilisation of ideas. In such settings it is also possible to incorporate the use of tools such as Venn diagrams (Lynam et al., 2007) or game scenarios (Martin et al., 2011) to gain an in-depth understanding of the relative influences of different actors and institutions. In practice, however, most studies are limited by resources. Whichever methodologies are selected, the focus of the research should be on understanding the farmer's worldview and perspective of the system, as well as accessing some of the tacit knowledge built up through experience.

As part of the scoping exercise, basic farm management data needs to be collected for input into the model for the next step, the modelling of future scenarios.

3.5.2.3 Scenario generation (researcher)

The development of future climate scenarios is an important basis for assessing future risks that may threaten a farming system. Farmers' learning is based primarily on past experience. However, in the case of issues such as climate change, the past may not provide a reliable basis for planning the future. The usefulness of modelling as a tool was recognised by the pilot study farmer: while noting the limitations of models in picking up the complexity of the farming system, he noted that they were useful in "narrowing down" and identifying key issues and important trade-offs.

The pilot study farmer considered climate change as an insidious process that would not have a significant impact in the time that he planned to be farming, and considered short-term climate variation to be more important. At the same time, he spoke at length about the difficulties of the past three drought years. Drawing the link between longer term climate change processes and likely increases in events such as droughts in the pilot study is likely to promote longer term strategic thinking and planning on the part of the farmer.

3.5.2.4 Pool ideas (with farmer/manager)

This step seeks to clarify the risks facing the farming system and its current capacity to cope with those risks, and to identify viable adaptation options. Based on the scenario modelled for the case study farm under analysis, a simple, context-specific risk management matrix for the region in which the farm is based will provide a basis for assessing the potential magnitude of risks to the system. Important parameters to identify in such a matrix include the key potential impacts, areas of greatest vulnerability, and priority areas of action (Cobon et al., 2009). Such an exercise should also consider the level of uncertainty associated with the risks identified and the reasons behind the uncertainty, in order to maintain a plural and conditional perspective on the quantified risks (Stirling, 2010).

The classical approach to climate change assessments considers as a baseline the 'autonomous adjustments' that may take place in response to climate change events without external intervention. However, because of the complex nature of a farming system and intensive, ongoing management, it is more useful here to analyse the basic state of the farming system using concepts of resilience and in the context of the adaptive cycle of the system.

In the pilot study, the farmer initially noted three main sources of risk to the farming system: the payout for milksolids, climate, and his personal resilience. He emphasised the importance of the human element in resilience, for example physical and mental health, and noted the role of past health issues in his goal to maintain a system that is less management intensive.

The farmer identified two main aspects of system resilience. First, he stated that the physical components of his farm were not resilient to weather extremes, particularly drought, but that they had tried to set the farm up to be resilient by having a moderate stocking rate, using mainly home conserved feed, and buying in small amounts of supplementary feed. The farmer considered flexibility in management to be a key source of resilience. For example, he had a very flexible drying off policy and had modified his stocking rate and bought in feed to manage the droughts over the past three years. After three difficult drought years in a row, the farmer expressed a cautious approach to innovation, noting that he would look carefully at strategies being modelled and demonstrated by research before changing a practice. The impact of these three difficult years had clearly reduced the resources available to the farming system, and had a compounding effect: financial stress had increased the pressure to produce more milk. Combined with the drought, the pressure to produce had intensified both management requirements and stress on the biophysical resources of the system, including the need to re-grass approximately a quarter of the farm in the past year. This in turn increased pressure on the farmer and had a detrimental effect on his personal resilience and capacity to innovate.

Resilience in complex adaptive systems is by nature exceedingly difficult to measure, as the future of a complex adaptive system is considered unknowable (Darnhofer et al., 2010b). The ‘resilience thinking’ school of thought conceptualises the development of a complex adaptive system over time as moving through four successive phases of an ‘adaptive cycle’ (Allen and Holling, 2010; Darnhofer et al., 2010b). The first phase is exploitation, in which the young system capitalises on the resources available in a phase of rapid growth. This is followed by a stable conservation phase, in which the interconnectedness of the system increases and it specialises in order to capitalise efficiently on the resources available. The increasing specialisation and rigidity in this phase then leads to decreased resilience and a ‘release’ phase in which the system collapses due to stress. This is then followed by a phase of ‘reorganisation’, in which there is potential for the system to exit the current cycle and take on a new state (Allen and Holling, 2010; Darnhofer et al., 2010b).

Based on the farmer's description of his system, the past three years had significantly reduced the resources available on farm, and the system had suffered from the external shock of three successive years of drought. This suggests that the farm is nearing a period of release after which reorganisation will be necessary. Questions which provide further insights in this context include:
- How interconnected, 'closed' or open is the system?
- How much buffering does the system have in terms of the resources available?
- How dependent is the system on external resources?
- At what stage in the adaptive cycle is the system currently?

As noted under step 2, there are different approaches to gain farmer input: Semi-structured interviews are one option, but group-based activities such as workshops of focus groups might allow for greater cross-fertilisation of ideas. It may be useful to compare adaptation options proposed by the farmer(s) with those drawn from the literature. Some farm level adaptation options identified in the literature include (based on Stokes and Howden, 2010; Kenny, 2010; Smit and Skinner, 2002; Gueringer et al., 2009; Reidsma and Ewert, 2008):
- Selection and management of pasture and animal species, diversification to increase resilience
- Infrastructure adjustments or tree planting to provide shade and shelter
- Spatial and temporal adjustment of management practices, for example, adjustments to the layout of the farm, changes to the timing of farm operations, fodder conservation and use strategies and a flexible stocking policy
- Reducing the intensity of production
- Measures to reduce soil moisture loss such as changes to the land topography, re-vegetation and soil organic carbon management, for example, through alternative fallow and tillage practices
- Measures to improve irrigation efficiency and store water more efficiently.

The options then can be categorised and an initial assessment made on which of the options can be analysed using the model, and which will need to be considered separately. With regard to the options listed above, for example, it is possible to model most of the adjustments in management practices listed in the DairyNZ Whole Farm Model (WFM) (Beukes et al., 2005). However, it will not be possible to simulate options such as changes in land topography, infrastructure adjustments or tree planting.

In order to identify feasible adaptation options in the next step, it is necessary to agree on a joint set of indicators of success to refer to in the modelling analysis. These should be relevant to both the farmer and researcher and ideally include economic, social and biophysical indicators.

3.5.2.5 Analyse options (researcher)

Whole farm simulation models such as the WFM provide a complex 'virtual world' in which to model the effects of different management strategies on interactions between climate, management, and cow and pasture production in a farming system (Beukes et al., 2005; Bryant and Snow, 2008; Woodward et al., 2008). The WFM uses flexible decision rules and provides outputs for pasture growth and animal production on a daily time step, and economic results on an annual basis.

There are a number of approaches to integrating climate information into farmer-guided modelling experiments (Clark and Tait, 2008), ranging from: analogue studies where a period from the past is selected to represent change, thereby examining known natural climate variability; sensitivity studies where a range of possible climate changes are considered and the response of the system examined; and scenario studies where projections of future climate change from climate systems models are used, isolating the probabilities of change attributable to anthropogenic influences. Each of these methods has trade-offs between levels of certainty, and their ability to isolate the human influences on climate change. In the integrated framework, choice between these methods is guided by farmers concerning which climate stimuli should be the focus of adaptation. The case study presented here is an example of an analogue study, but high quality climate change projections suitable for farm systems analysis have been developed for New Zealand using the physical regional climate model PRECIS, and are available for future evaluations (http://www.metoffice.gov.uk/precis/).

Three different ‘weather years’ were modelled in our pilot study as a climate analogue: 2009-2010: the most recent year for which management data were available. Precipitation was below average at 1,068 mm; 2007-2008: a drought year, with 914 mm precipitation; and 1995-1996: considered a very favourable climate year with a total precipitation of 1508 mm (see Table 3). However, as they are based on past weather, analogue studies have the limitation that they are unable to account for projected increases in climatic variability. Where regionally downscaled climate projections are available, these may provide a more accurate picture of potential future variability.

For the pilot study farm, one adaptation strategy was analysed as an example, i.e. a reduction in stocking rate. For each of the model runs, economic parameters were kept the same to enable a simple comparison between the years. Economic data from the year 2008e2009 were used, as this was the most recent year for which it was available in the WFM.

The stocking rates modelled were based on the farmer’s comments on his management decisions. The farm in question had recently survived three difficult years, and the farmer had dropped his stocking rate from 3.7 cows/ha to 3.2 cows/ha. He noted that he was maintaining the system at this rate by buying in extra feed, in anticipation of a return to more normal weather conditions. For this reason, an additional model run was carried out for the original stocking rate of 3.7 cows/ha for the high yield year (1995-96).

Table 3 shows that in the ‘virtual,’ modelling world, a further reduction in stocking rate would be more profitable even in a high yield year.

3.5.2.6 Validate results (with farmer/manager)

This step involves comparison of the modelling exercise with the insights provided by the social research. First, the results are considered against what is already known of the system, and key questions formulated. It is then useful to revisit the results of the exercise together with the farmer. Tools for this might include further interviews, a written survey or a discussion workshop.

Table 3: Modelled impact of reduction in stocking rate for the pilot study farm (2008-2009 economic inputs).

Weather year	**1995-1996 (high yield year)**			**2007-2008 (drought year)**		**2009-2010 (last year)**	
Stocking rate (cows/ha)	3.7	3.2	2.7	3.2	2.7	3.2	2.7
Milksolids (kg/cow/year)	266	287	313	279	313	296	324
Milksolids (kg/ha/year)	983	933	861	907	878	960	892
Pasture production (kg dry matter/ha/year)	12,345	12,245	11,946	9,672	9,679	11,600	11,508
Change in cow liveweight (kg/year)	-5	6	17	-46	-43	-34	-1
Dairy operating profit/ (NZ$/ha)	130	512	799	-374	-32	246	484

In the case of the stocking rate question, there is a clear difference in perception between the top-down modelling exercise and the farmer who is in charge of managing this system. The farmer is unhappy with the current situation but feels the need to maintain a higher stocking rate and even underfeed his cows in order to pay the mortgage. However, the model suggests that even in a good year, he would be financially better off with a lower stocking rate.

The simple answer from a researcher perspective might be to suggest to the farmer that he would be better off dropping his stocking rate. However, exploring the reasons behind the difference in perception may provide more useful insights into solving the problem. In this case, the farmer noted that the results confirmed his own observations that he was overstocked. His solution was not to destock, but to buy in more feed for the next year.

From the farmer perspective, the complexity of the system means there are many issues that the model addresses in a simplified way, for example the quality of pasture and supplementary feed. The value of the farmer perspective is that it is embedded in the actual context in which the decision must be made. To gain a deeper understanding of the reasons behind the differences in perception, the following questions can be asked:

- How accurate is the modelling work from the standpoint of the farmer? Are there important gaps in the model's representation of reality?
- What other factors influence the decision to maintain or reduce stocking rate? (for example, cashflow issues, adjustment costs, or even other less obvious

disincentives such as the fact that culled stock would be sold at a lower rate than the average value shown in the farm accounts, giving the appearance of lost profit.)

The validation and modelling steps can be iterative until researcher and farmer are satisfied with the adaptation options identified. For example, it would be useful in this case to model the farm once more for the climate analogue years, with different levels of bought in feed.

3.5.2.7 Evaluate adaptation strategies (with farmer/manager)

In the final step, adaptation strategies are evaluated based on both the qualitative understanding gained of the system and it's functioning, and the modelling analysis performed to quantify specific trade-offs. Quantification of specific biophysical and economic trade-offs in a model and then re-examination of these trade-offs in the context of the complex socio-economic system in which they take place will highlight the interactions between the biophysical, economic and social aspects of the system. For example, in the pilot study farm there was a clear synergy between the results of the modelling exercise and the needs of the farmer, who had drawn attention to the cost of knowing his cows were underfed to his own morale and personal resilience, as well as to the desire to reduce the management intensity of his farm. The validation of this limited modelling exercise has paved the way for an open dialogue on both the way in which the model operates and other interactions operating within the system, such as social and economic factors. In addition, it has opened a constructive debate on climate change from the perspective of adaptation. Like most Waikato farmers (Smith et al., 2008), the farmer in this pilot study was not convinced that climate change is responsible for increasing adverse weather events.

In order to identify 'resilience pathways', a starting point is to consider in reverse the types of adaptation that are undesirable. Barnett and O'Neill (2010) define five main kinds of 'maladaptation': actions that 1) increase emissions of greenhouse gases; 2) disproportionately burden the most vulnerable; 3) have high opportunity costs (high social, environmental, or environmental costs relative to their alternatives); 4) reduce the incentive to adapt (for example by encouraging unnecessary dependence on others, stimulating rent-seeking behaviour, or penalising early actors); and 5) create path dependency by investing in trajectories that are difficult to change in the future, reducing the flexibility and hence adaptive capacity of the system in question. To this can be added the maladaptation of increasing dependency on resources which may become scarcer in future, such as water or fossil fuels (Stokes and Howden, 2010). To reverse these maladaptive paths, assessment of adaptation options should need to be based on 1) synergies with mitigation; 2) equity; 3) low opportunity costs; 4) increasing the incentive to adapt; 5) flexibility, path independence and 6) reducing dependence on external resources. These goals need to be understood in terms of the management trade-offs underlying the activity. In particular, it may be useful to consider the trade-offs between production intensity, management intensity and diversification of the system at different levels.

The final product of higher level adaptation studies has been primarily either yes or no answers on whether the system has the potential to adapt successfully or not (Fitzgerald et al., 2009); or broad principles for supporting resilience and adaptive capacity and unquantified lists of adaptation options (Kenny, 2010; Smit and Skinner, 2002; Stokes and Howden, 2010; Reidsma and Ewert, 2008). Evaluation of these principles at farm level allows for the quantification of costs and benefits and makes it possible to answer key questions from a practical perspective, in particular:

- What are the interactions and interdependencies across the social, economic and biophysical dimensions of the system?
- Which adaptation strategies demonstrate synergies across the different dimensions?
- Which adaptation strategies contribute clearly to the resilience of the overall system in the face of perturbations?

In order to evaluate the adaptation strategies in a way that will highlight the different trade-offs, one technique which may be useful is multi-criteria mapping, proposed by Stirling (2010) and others as a way of providing plural, conditional advice in the face of uncertainty. Criteria for such a mapping exercise should be defined, along with indicators of ‘success’, together with the farmer(s) whose farm is under analysis. Multi-criteria mapping would allow for matching the farmer's goals with the economic, environmental and social capabilities of the farm, and help to identify priorities for implementation.

As noted above, adaptation of a farming system to climate change is a continuous and dynamic learning process. The evaluation step should be followed up with a mechanism for providing feedback to the researcher on the assessment process, as well as on the usefulness and implementation of the outcomes of the assessment.

3.6 Discussion and conclusions

This paper has briefly reviewed some of the key methodologies commonly used in assessment of adaptation to climate change to date, and their main advantages and disadvantages. The strongly disciplinary nature of current research into adaptation options for New Zealand dairy farms represents a constraint to understanding complex socio-ecological systems. The present dichotomy in research and discussions on the subject of whether top-down, quantitative or bottom-up, qualitative approaches are more useful should be replaced by the question: what can each approach contribute to understanding the farming system? This review has highlighted the need for an integrated methodological framework to capture a richer systems perspective by embracing both the qualitative, social science approaches and the quantitative, biophysical approaches to the analysis of adaptation strategies. Based on the gaps and needs identified, a Mixed Models Framework has been proposed (Fig. 4), supported by information obtained from a pilot case study farm which allowed for concrete examples to be presented. This framework represents a starting point for the integration of the two dominant kinds of research currently being undertaken.

Adaptation of farming systems to climate change is a continuous, dynamic process, starting with present needs and the current operational environment. In order to ensure that the adaptation research carried out supports farmers and other stakeholders, and keeps policy development relevant, quantitative research such as biophysical and economic modelling needs to be embedded in the context of the realities facing decision-makers. Successful adaptation of agriculture to climate change will depend ultimately on the actions of individual farmers (Stokes and Howden, 2010) and their flexibility in applying new management strategies.

As an example, the VERDI simulation model by Ripoche et al. (2011), using a 'mixed' strategy approach to a vineyard study, showed that high flexibility offset potential effects of climate variability on vineyard performance. Farmer perspectives and perceptions, and the context in which adaptation decisions are made need to take a central role in adaptation studies.

Because of the inherent uncertainty in predicting the future of complex systems, the most important way that researchers can contribute to farmer adaptive capacity in the context of climate change is not by providing prescriptive answers or lists of options. Rather, a dialogue is required for both researchers and farmers to fully benefit from one another's perspectives and knowledge, thereby gaining an in-depth understanding of the range of adaptation options, the barriers to implementing these options, and the specific trade-offs involved in different management choices.

The need to build the 'adaptive capacity' of system managers is now also reflected in a range of literature on adaptation to climate change (Dessai et al., 2005; Adger, 2006; Folke et al., 2010), as well as business management and farm management (Beijeman et al., 2009). Managers need to understand and articulate their own particular context (Allan and Stankey, 2009). Research aimed at understanding and challenging how farm managers perceive the farm system will afford insights into the way in which farmers establish strategies. Important in this context is taking into account farmers' tacit knowledge, built up from current and past experience within the operational environment of the farm and the external factors that perturb the farm system.

Approaches to climate change adaptation, like many other complex issues, can be significantly enhanced if quantitative modelling is valued as a tool in the context of a broader assessment. For this purpose, it is important to clarify the role of integrated, quantitative models in the broader conceptual models utilised by farmers and researchers. Since the challenge of adapting to climate change is subject to a great deal of uncertainty, quantitative modelling is a key tool in the development of future scenarios and in the analysis of trade-offs between different adaptation strategies. Ongoing work is continuously expanding the horizons of quantitative computer modelling. However, in utilising such models, it is important to maintain a perspective on their relationship to elements in the system that are not included in a quantitative model. Positioning the quantitative model in the context of a wider system that includes both soft and hard elements (Fig. 3) means that the quantifiable aspects of the system can be measured without losing sight of the softer aspects, which can then be analysed using social science research methodologies.

The integration of qualitative and quantitative research approaches can contribute to effectively analysing the most important interactions and feedbacks at work in agricultural systems at farm scale. While challenging in practice, efforts towards such integrated approaches will generate much more grounded and realistic information about potential adaptation responses and improve the flexibility in response to climate change variables and associated impacts of society.

By incorporating systems thinking concepts and multiple (interdisciplinary) methods, the proposed Mixed Methods Framework has the potential to provide a more integrated 'rich' picture of the farming system, obtained through a participatory approach. A key strength of this approach to interdisciplinary research is the process of actively defining the system independently from different perspectives, and then through a participatory exercise, bringing the two perspectives together. This has the effect of providing two windows through which to observe the system, facilitating a greater depth of perception. It is vital that the differences in perspective between farmers and researchers are communicated, recognised, respected, valued, and integrated for analysis and evaluation.

Finally, as with all interdisciplinary research, there are likely to be significant challenges in the actual implementation of such a mixed models framework, including the availability of expertise and resources. However, the potential benefits are significant. In particular, embedding the research in a joint learning and co-development process involving researchers and farmers, based on an open recognition of the validity of both perspectives, is likely to improve the credibility and legitimacy of the research in farmer perceptions. In doing so, it will facilitate a dialogue for increasing the understanding on climate change adaptation issues by both farmers and researchers and contribute to the implementation of adaptation practices based on accommodating the ‘soft’ and ‘hard’ methodological approaches. A successful outcome will be an increased overall resilience of the farming system both in the present and future.

The working example presented in this article is a single case study farm. However, the methodology could well be applied to a series of farms. Each additional example would add depth to the analysis as farms will differ considerably both in the environment in which they operate and in the preferences, goals and management practices of the farmers.

The analysis of multiple farms could be approached in two ways: either by analysing each farm separately and comparing the results at the end, or by creating opportunities for the cross-fertilisation of ideas during the analysis. Steps 4 and/or 7 of the MMF would lend themselves well to such cross-fertilisation, for example, in the form of workshops and participatory exercises with researchers and farmers. Such an approach would help to identify cross-cutting principles and areas of difference earlier in the analysis and potentially provide useful insights to a range of end-users, from farmers to policy makers.

3.7 Application of the Mixed Methods Framework to this thesis

This chapter has provided the theoretical background and framework underpinning the methodology applied to this study. For the most part the logic and steps of this framework were followed. However, there have been some minor points of divergence from the original conceptual framework (Fig. 4) in the practical application of the research.

Chapter 2, a literature review, describes the system and climate change problem from a researcher perspective (step 1). Chapter 4 represents step 2 in the framework, scoping the system from a farmer perspective. In Chapter 5, a modelled analysis of climate scenarios for each specific farm was carried out (step 3), together with a set of researcher-defined adaptation options. These results were then validated with farmers during the interviews (section 5.3.6, relating to step 6).

The original framework proposed an iterative process where validation of adaptations suggested by the farmers, as well as the final evaluation (step 7) was carried out together with the farmers. However, for this research it was only possible to validate the first set of (researcher-defined) modelled results together with the farmers. The final evaluation of strategies (step 7, Chapter 7) was carried out by the researcher.

4 Climate change in context: Farmer perspectives on adaptation

Abstract

Dairy farms are dynamic systems, constantly adapting to the biophysical, social and economic environments in which they operate. This chapter represents the second step in an integrated assessment of adaptation options for six temperate, pasture based dairy farms under different climate change scenarios. Based on interviews with the decision-makers on six farms from different regions of New Zealand, it provides farmer perspectives on how climatic risks are positioned within the broader context of continuous change and development.

The chapter highlights the interconnectedness of different pressures facing farmers, the diversity of strategies that can contribute to resilient farming systems, and the importance of flexibility in maintaining adaptive capacity. It concludes that the practical knowledge and innovative ideas of experienced, adaptive farmers is an under-utilised resource in the search for a more in-depth understanding of climate change adaptation strategies.

4.1 Introduction

While New Zealand farmers are generally aware of the climate change debate, there is still limited understanding of what these changes will mean at farm level. As described in Chapter 3, the impact of climate change on New Zealand's pastoral farming systems is still subject to a high level of uncertainty. In addition, past policy experiences have been identified as a strong predictor of climate change attitudes in farmers (Niles et al., 2013) and the highly politicized nature of the early debates around climate change, including the proposal for the infamous 'fart tax' on methane emissions (Kenny 2011) may have influenced perceptions.

The last 25 years has seen a steady growth in milk payout and operating profit per hectare, but also in operating expenses, with both becoming more volatile. In addition, average debt levels have increased faster than the growth in milksolids in recent years (DairyNZ, 2014). New Zealand dairy farmers have adapted to increasing market volatility by developing new skills and management practices to mitigate risks and capture opportunities (DairyNZ, 2014). This adaptive capacity may mean they are also well equipped to cope with increasing climatic volatility. However, incremental adaptation has limits (Park et al., 2012) and there are concerns that it may reduce the incentive to carry out more costly but more beneficial transformational changes to the system (Reisinger et al., 2014).

Researchers, policy makers, and rural professionals are faced with the challenge of how to support farmers to adapt their systems to climate changes in a way that enhances their resilience to other pressures (Adger, 2006; Beijeman et al., 2009; Dessai et al., 2005; Folke et al., 2010). Farmers are managers of their own systems and ultimately, any decisions on adaptation strategies will be made with reference to their own particular context. To support them effectively, an understanding of the context in which such decisions will be made needs to be built (Reisinger et al., 2014; Verdon-Kidd, 2012; Yuen et al., 2012). There is a need for improved communication of climate change science to farmers and engagement with experienced farmers for a more comprehensive understanding of the potential costs and benefits of the different adaptation pathways (Kenny 2011; Niles et al., 2013).

The tacit knowledge built up over time by experienced farmers is an invaluable asset in coping and adapting to ongoing change (Burton and Peoples, 2008; Craddock-Henry, 2011; Kenny, 2011; Payne and White, 2009). Such knowledge can contribute to our understanding of how to support the development of farmers' adaptive capacity, where prescriptive recommendations about specific management practices have limited success in removing the more persistent and intractable vulnerabilities in a system (Nelson et al., 2007).

As part of a broader mixed-methods analysis of six case study farms based on the methodology outlined in Chapter 3 (Kalaugher et al., 2013), this chapter aims to profile the adaptive capacity of a selected group of experienced farmers. This provides valuable information, not only regarding the general principles of what makes a farm resilient, but the ways in which climate change impacts are likely to be important to farmers, the basis for making decisions on adaptation. In doing so it also examines potential limiting factors to adaptation, considering the wider contextual environment in which farmers operate.

The aim of this study was to access the knowledge of experienced farmers to contextualise the potential threat of climate change, and to better understand which aspects of farm management contribute to making their farming systems more resilient and capable of adapting to a changing climate.

4.2 Methods

The social research presented here is part of a broader integrated analysis of the six case study farms, based on the framework articulated in Chapter 3 (Kalaugher et al., 2013). This study uses a combination of research methods including textual analysis and semi-structured interviews with farmers, supported by participant observation, to build a profile of adaptive capacity from six case study farms. These were selected from major dairying regions in New Zealand: Northland, Waikato, BOP and Taranaki in the North Island, and Canterbury and Otago in the South Island (refer Fig. 1, Chapter 1). The farms cover a range of climatic zones and management approaches and are average in size for their regions, with average or above-average stocking rates (see Chapter 5 for more details of the biophysical aspects of the farming systems).

Commercial, owner-operated farms are the focus for this study, based on the assumption that owner operators have both a strategic and hands-on perspective of their farming systems. Of the case study farms, five of the six farms are owner-operated, and the other is a research/education farm. The farmers were identified as experienced and respected, high-end operators in the region by either the DairyNZ regional consultants for that area or by researchers from AgResearch (one of New Zealand's largest Crown Research Institutes) who were carrying out research on their farms. A choice was made to purposefully sample this category of well-connected and experienced farmers as they are considered a good source of context-specific, expert knowledge about coping with and adapting to ongoing changes in their farming systems (Gray, 2001; Nuthall, 2009).

4.2.1 Textual analysis and participant observations

A range of textual analyses were undertaken to understand the context in which the individual farms operated. The first part of the integrated analysis involved setting up and running the DairyNZ Whole Farm Model (WFM) under downscaled climate projections for each of the six dairy farms (Chapter 5). This involved a structured questionnaire and then follow-up conversations by email and phone to understand the set-up and management of each farming system, between October 2010 and May 2011. This provided considerable insight into the physical management of the farm and the biophysical resources available to it. In addition, farmers were questioned about their thresholds for adaptive management responses to changes in climate from year to year with regard to practices such as culling, importing more feed and drying off. This enabled the set-up of the Whole Farm Model to incorporate a range of standard management responses, adequate to deal with the baseline climate (1980-2000). While farmers were aware that the focus of the study was climate change adaptation, this structured information gathering did not address climate change *per se*.

In order to embed the researcher in the day to day operation of the farms and better understand the context for the farm management strategies under discussion, an offer was made to assist with farm work for a day, and on four of the six farms this offer was accepted. This was an unstructured process, with the researcher joining in regular activities like milking, stock movement and feeding calves but observing key decisions and processes. For the two remaining farms, a farm tour was undertaken. For the Otago farm it was not possible to visit the case study farm itself as the manager had very recently changed jobs and moved cities, so interviews relating to this farm were instead conducted with the (ex) manager in Christchurch. At no point did the researcher actively participate in the decision-making process, and any interaction was focused on prompting the farmer to reflect on how a decision was made, rather than providing guidance or information that could influence that decision. Observations made during the on-farm participation were recorded in note form.

4.2.2 Semi-structured interviews

Two semi-structured interviews were conducted for each farm between November 2011 and September 2012. The interviews were conducted face to face on the farm, with the exception of the Otago farm, as noted above. The decision of who would take part in the interview was left to the farmers themselves. In total, nine people were interviewed including two male farmers, one male manager, two couples and one father-daughter team.

The first interview was intended to gain a broad understanding of the farmer's mental model of their farming system. As outlined in Chapter 3 (Kalaugher et al. 2013), part of the conceptual basis for the approach taken to this study stems from Soft Systems Methodology (SSM), originally developed by Peter Checkland in the 1980s as a technique to develop a conceptual model in order to externalise a particular view of a complex system (Checkland and Poulter, 2010). The interview questions (Annex 1) were structured around the 'root definitions' in the SSM tool for identifying core components of the system (Checkland and Poulter, 2010). These include concepts of 'worldview' and perceptions of the 'transformation process' occurring in the system, as well as the primary actors, with their particular roles and power structures, and the external operating environment.

The gap between the two interviews varied from one day to a few months, but in all cases, the second interview was conducted after the unstructured time on farm, to ensure that the researcher had a general understanding of the farm context before asking questions about specific farm practices.

In the second interview, results from the modelling study (Chapter 5) were presented to the farmers and their perspective sought on the potential and practical limitations to the adaptation options presented. These results are presented in Chapter 6.

Two questions asked during the first interview incorporated a rating exercise: The first was on risk, asking "what could make your systems fall over?" and rating the risks identified out of 10. The second was to rate the system's overall resilience, out of five. Both of these exercises provided a basis for further discussion on these topics. It is important to note that other risks were also identified and discussed outside of the formal rating exercise.

Each interview was recorded and transcribed *ad verbatim* and the results were analysed on a thematic basis using the qualitative analysis software package: NVIVO © to help identify emerging themes.

4.3 Results and discussion

Together, the nine farmers interviewed for this study represent well over 200 years' of adult experience managing dairy farms. In addition to this, seven of the farmers who took part in the interviews had grown up on a farm.

While only two of the farmers mentioned a formal university education, all were well embedded in industry networks and were involved with research and/or industry leadership in some way through close connections with and work at a university, participation in research, mentoring other farmers, or involvement in more formal industry leadership.

4.3.1 Mental models of the farming system

The concept of 'mental models' has been used to conceptualise the cognitive filter through which individuals interpret the external environment (Halbrendt, 2014; Jones et al., 2011). Farmer's 'mental models' of their farming system have been shown to strongly influence their decision making (Eckert and Bell, 2005) and as such, are likely to form the basis for adapting the farming system to future changes.

Despite the fact that the farmers interviewed were a purposeful sample selected based on a set of specific criteria, there was considerable variation in their approaches to dairy farming, based on their own worldview, personal goals and environmental differences. Their farm management choices were also variable, from once-a-day milking, to having a very large part of the farm under a maize crop, to consciously choosing not to carry out cropping on the farm (Table 4). Profit and productivity were common goals across all of the farming systems (Table 4) but there was obvious divergence between the farmers in the other goals and priorities. Environmental stewardship was of core importance to some of the farmers. Animal welfare was also of central importance to some, to the point of going against what was considered standard industry advice on practices such as inducing cows to give birth early. This spread out calving regime had been followed for many years despite past advice from industry that it would negatively affect production (it should be noted that the practice of inductions is now being phased out). Another farmer saw his animals from a much more functional perspective, describing the cows as a 'factory'.

Another farmer's approach to farm management was more academic, using a consultant and starting with a theoretical analysis of the system using models to optimise efficiency. The farmers also expressed in different ways the importance of enjoying the farming lifestyle, because its all-consuming nature means there are few opportunities to leave it behind at the end of the day:

> It's quite a lot of hard work and its 24/7 … so there needs to be lots of rewards … I'm not prepared to do this if it's not really worthwhile…

A common thread across all of the interviews was an inherent flexibility in the way these farmers thought about their systems, and descriptions of ways in which their farms and management practices had changed over the years. There was a recurring theme in the interviews that the future is unknowable, and in the hands of the next generation. Variability and change was considered to be a part of daily life – something they were good at dealing with:

> the farm's always in a stage of being developed, it's never constant …it's not… static.

As noted in Chapter 3, research approaches to climate change adaptation have often been considered in a static sense, in relation to specific risks (Nelson, 2011; Nelson et al., 2007). The dynamic perspective that farmers have of their systems further reinforces the need to ensure that risk management research can take into account the surprise and uncertainty (Nelson, 2011). One farmer expressed this by describing his strategic approach as reactive:

> Regarding the strategic things I think when we look back we're more reactive than proactive. … we don't go out looking for - we should buy another farm … if the opportunity is there we think about it…and if you buy a block next door … we'll have to upgrade the cow shed.. So we just adapt.

Table 4: Comparison of farming operations and farmer's goals and indicators of success for the six case study farms

	Northland	**Bay of Plenty**	**Waikato**	**Taranaki**	**Canterbury**	**Otago**
People on the farm	Farming couple (occasional relief milker).	Farming couple Son is lower order sharemilker, who employs two other staff. Lower order sharemilker on another block.	Married farmer but wife works off farm 4-7 staff including manager, herd manager and herd assistant.	Father and daughter, who is lower order sharemilker, and employs assistant.	Married farmer, wife partly involved Lower order sharemilkers, students.	Manager of research and education farm, governed by a board with dairy advisory group and management staff.
Farming system *(based on the five DairyNZ 'production systems' as defined in section 5.2.2)*	System 3, OAD with jersey cows. Large support block run with beef cattle as a separate operation (and wintering off), a turnip crop in winter and PK and silage as required.	System 2, lower stocking rate, grows some maize and makes grass silage. Palm kernel, silage fed as required. Effluent irrigated	System 4 dairy, part of a large and diverse operation including a large area growing maize silage. Palm kernel, straw, maize silage fed as required. Effluent irrigated	System 4, currently in the process of changing from a jersey to kiwicross cows. No crop, contract maize silage. Palm kernel, maize silage, molasses, hay, silage as required. Effluent irrigated	System 4 (due to low pasture growth) Palm kernel, silage fed as required. Large irrigated dairy, one of two dairy operations run side by side.	System 3 dairy farm. Grass silage made Turnips, swedes grown. Effluent irrigated. Silage and maize fed as required.
Specific challenges	Kikuyu incursion.	Dry summers.	Pugging on flats in winter.	Long shape of farm.	Water regulation.	Wet winters, flooding, public image.
Goals	To maximise what we can get out of the grass without using capital Herd improvement.	Very strong focus on animal health and welfare.	Business efficiency Low debt Expansion, intensification.	Production and financial.	Science based approach to improving performance including modelling to look for potential areas of improvement.	Best practice Example for community Training students.
Measures of success	Production goals profitability, sustainability no other staff. cow BCS.	Economic bottom line, but animal welfare and environment more important.	Production efficiency Tidy, forward planned farm	Economic indicators, also role in industry and community.	Sustainable farming system that meets financial objectives.	KPIs around per hectare, per cow production
Long term vision	Balance between financial goals and lifestyle.	Children take over the farm, enjoy retirement.	Further intensification and investment in capital structure, including standoff area and potentially water harvesting infrastructure	Get out of cowshed Children take over the farm.	Depends on whether children want to take over the farm Also on environmental regulation.	Plan to intensify, in shed feeding and bigger herd homes.
Non-negotiables	Stay once a day Always apply some fertiliser Always AI Minimum 40 day round.	No inductions.	Not milking cows No higher debt Not much land use change.	No wintering barn, unwilling to intensify.	Not milking cows Not system 5 (but may be forced to).	No winter milk No winding back productivity.

This perspective on flexible and adaptive management came through strongly as a theme. However, this flexibility was coupled with a broadly strategic approach to the future, for example by taking opportunities as they arose, where they might improve future options:

> I put in a water system but I run them to the boundary fences… not knowing that the farm will come on the market, but I always do it just to be cheeky, out of the four I've done I've bought the three neighbours. Generally the longest I've gone… is 15 years…I can do it because I know I'm going to be here long term…

In economic terms, the value of increasing the number of choices available in the future is now being recognised in the concept of 'real options' (Anda et al., 2009; Dobes, 2008). As with choices in the present, there is a trade-off in investment – the greater the investment in a particular option, the more viable that option will be relative to other choices.

Most of the farmers expressed a sense of being 'ahead of the game' and exhibited the confidence to make choices that did not always follow mainstream thinking, but suited their own worldview and/or farming environment - for example, the choice to milk once a day, or the choice to not carry out inductions. This supports the observation by Dowd et al. (2014) that farmers undertaking transformational change tend to be those with more far-reaching knowledge and social networks, but that their ties to family, friends and colleagues tended to be less strong, enabling them to diverge from established social norms.

Aside from the selection criteria, the characteristics these farmers had in common were related to the flexibility of their mental models, their confidence, their connectedness with both research and the farming community, and their openness to change. These tie in closely with the attributes listed by other authors in successful 'adaptors' (Boxelaar et al., 2006; Niles et al., 2013; Nuthall, 2009; Payne and White, 2009), in particular their willingness to face "reality of uncertainty and ambiguity" and strong sense of self-efficacy.

4.3.2 Strategies for resilience

Resilience is defined by the IPCC (2014) as the "capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation".

In order to understand what makes a farm resilient in practice, it is necessary to encompass both biophysical and social components of the system. The farmer's perspective as a system manager provides a window through which to analyse resilience and gain valuable insights into how these different aspects of the system combine in practice.

The farmers all rated their farming systems quite highly in terms of their overall resilience (between 3/5 and 5/5) and experience played a large role in their confidence, particularly in coping with extreme weather events such as drought:

> We don't find it as bad as what we used to because we've been through it time and time again… It just comes with experience.

All of these farmers have been through hard times and exhibit pride in their self-reliance. These may be characteristics particular to this group of experienced farmers. However, other studies have also noted a high level of self-reliance as well as confidence among farmers in their ability to adapt to potential climate change risks (Aldunce et al., 2015; Niles et al., 2013).

While farmers were not specifically asked to define resilience as part of this study, the following section outlines the components they considered important in achieving it. In most cases, they focussed on farm management practices as a way to reduce risk. The most important strategies they identified related to 1) buffering – ensuring the system is not stretched to its limits; 2) ensuring there is a high enough level of diversity and flexibility in the system to cope with variability; 3) careful planning in time and space; and 4) building social capital.

The strategies identified by the farmers in this study relate directly to those identified in previous qualitative studies looking at farmers' experience in dealing with extreme weather events in order to better understand the principles of farming system resilience (e.g. Burton and Peoples, 2008; Craddock-Henry 2011; Kenny and Fisher, 2003; Kenny, 2011; Payne and White, 2009). However, a notable gap in the strategies identified compared with other literature is the use of vegetation and shelterbelts. Some farms, in particular the Northland farm, clearly made use of this strategy, as every steep slope was planted in trees. However, it was not mentioned in the context of adaptation to climate change or farm resilience generally. There are two possible reasons for this omission: 1) the modelling focus of the study may have influenced the adaptations discussed; or 2) as the other studies on resilience were on a mixed group of drystock, cropping and dairy farms, it may be that descriptions of the use of vegetation as a strategy originated primarily from drystock farms. It should be investigated whether this represents a more general extension gap in the dairy sector.

4.3.2.1 Buffering in the system

One of the main strategies evident over all the farms was simply efforts to minimise risk by not pushing the system to its production limits, but rather maintaining buffers. The buffering principle was evident in financial management, in feed supply management, and in animal health.

Being experienced long-term farmers with a family history in farming, the farmers interviewed had relatively low debt levels and large scale operations which provided security in hard times. As such, they are likely to be in a more robust financial situation than many New Zealand farmers, as debt levels have been increasing significantly in recent years (DairyNZ, 2014).

Other forms of financial buffer included use of the "farm income equalisation account" available through the Inland Revenue Department (IRD), which allowed a degree of tax equalization over good and bad years. One farmer also commented on an observed relationship between level of equity and climate risks:

> Over in Australia, they've got 90% equity in a lot of their properties, whereas we're 30 to 50, far higher [debt]. Their weather, climatic risk is a bit higher but they can't understand how we sleep at night…

In relation to feed supply, keeping extra feed on hand was considered an important insurance policy. One farmer observed a feedback cycle relating to the changing strategic use of supplementary feed: The fact that farmers were keeping more feed in reserve as insurance for a bad year was meaning more feed was on hand and leading to better feeding of the animals even in a good year, resulting in more milk production. As a buffer was still required, this was having the effect of steadily increasing the demand for supplementary feed. He went on to describe the likely positive flow-on effects for the rest of the system, including fertility improvements that would contribute to industry goals of reducing induction rates.

The wider trend towards increasing use of supplementary feed was seen as driving a trend towards more and more crops grown on farm. Concerns were expressed over the potential implications of this trend, in particular the potential economic implications of moving away from pasture-based systems, both from an environmental and from a financial perspective. The farmers were aware of examples from other countries, particularly Australia, where farming systems based on large, highly productive cows and a high level of imported feed were simply not profitable.

The buffering principle was evident also in the careful management of animal health on farm. For example, the choice to milk once-a-day was based partially on the fact that the cows had a long way to walk to the milking shed. Another emphasized that the end of the milking season should be timed to ensure optimal cow condition and fertility for next season, even at the cost of extra production in the current year.

Finally, all of the farmers interviewed had in some way built time and mental space into the system to plan strategically, for example, by employing staff or milking once a day. Minimising stress and risk in the system was an important component of this. This is true at different management scales, from the overall, long-term strategic design of the farming system.

> People tend to think that you do once-a-day because you want to go fishing and go to the beach … that's all very nice but that wasn't why. When we looked at our business way back, then we saw that first of all it was quite stressful for the cows and for us and for the family and that we could actually just do a whole lot of other things as well as going to the beach…all the development on the farm…

4.3.2.2 Planning in time and space

Strategic planning was seen as a key element of managing a resilient system. There were differences in the farmers' perceptions of the degree to which they planned. At the seasonal level, strategies included buying in extra feed when prices were low, pre-contracting feed at a fixed rate, and as noted above, careful planning to ensure longer term animal health was prioritised over short-term productivity gains.

There was a high level of awareness of the impact of global markets on local feed supply:

> Like right at the moment America's having a big drought so our PK prices…are going up and soon it will be uneconomic for them to buy, so it might come down and then we'll have to decide do we contract for the next year…

Keeping on top of things enough to be responsive in the short term (weeks) was also an important element, for example having plans in place to deal with drought at least two weeks before it hit.

Examples of very long-term planning were based on expanding potential future options such as planning for and implementing very extensive water systems.

4.3.2.3 Diversity and flexibility

Having a range of tools and options was of key importance. Diversification, by definition, provides a buffer against climatic and other sources of variability (Allan and Holling, 2010; Martin and Magne, 2015; Reisinger et al., 2014), including backup sources for important resources:

> I'd say my system is actually just about five out of five. Primarily because of our diversification and with the different feedstuff that I can bring in…
>
> Part of my system now is to have back-ups for water. Both farms…can get water from two different sources. And we've put systems in place so we can feed palm kernel any time we need to. We do have lots of bailage and we're quite careful about the quality of the bailage – we do more testing of it when we buy it. Then the one farm has got grain so we can just crank up the grain if we need to.

Greater diversity promotes redundancy and therefore increases adaptive capacity (Darnhofer et al., 2010a; Martin and Magne, 2015). For farming systems, this concept has also been described in terms of the degree of plasticity in the system as a way of describing the tactical and strategic flexibility of farm systems and hence their sensitivity to the variability of critical inputs (Cowan et al., 2013; Rodriguez et al., 2011).

Many of the concerns that farmers voiced in the course of the interviews can be related to the concept of path dependency. Path dependency is a term referring to investment in trajectories that are difficult to change in the future, reducing the flexibility and hence adaptive capacity of the system in question (Barnett and O'Neill, 2010). Particular examples described by farmers included the vulnerability of over-dependence on only ryegrass (see Chapter 5), and the pressure to intensify.

4.3.2.4 Social capital

A strong link has been identified in the literature between social and ecological resilience (Adger, 2003). Particularly in times of hardship strong social connections within the farming community, and between farmers and industry are of critical importance (Burton and Peoples, 2008). This was also emphasised by the farmers in this study. They highlighted the importance of investing in strong relationships built on mutual trust and loyalty, with staff and family, and also with contractors and industry. In particular, the importance of the relationship with the bank manager was highlighted.

As noted earlier, the farmers who took part in this study by definition had strong networks and often leadership roles in their communities. Common threads across all of the interviews included the expression of a strong sense of community, and in most cases a sense of responsibility to the community as a role model, whether it was in the context of coaching children's rugby or in mentoring other farmers. From the interviews it was also clear that they felt well connected and had the personal skills required to build and maintain strong social networks.

However, some also noted the limiting influence that peer pressure could have on other farmers. For example, knowing farmers who refused to go to discussion groups because they would have to put their per cow production on a board with local farmers. Peer pressure could also strongly influence larger choices in farming system design.

> He said to me you know I'd quite like to be once-a-day but all the neighbours would give me such a hard time and they completely ostracized someone because they went once-a-day and I don't want that to happen…

4.3.3 Risks to the farming system

To place climate change in the context of other challenges and drivers of change in the farming system, farmers were asked in an open way to identify risks to their farming system. The exercise was based on the question "what are the risks to your system – what could make it fall over?" This question was asked without preparation time and intended to access the farmer's intuitive response to what they felt to be the biggest risks they were facing. The process of rating these responses then allowed for a more in depth discussion of the risks identified. Fig.5 shows the cumulative rating for the main groups of risks identified by the farmers in the rating exercise.

The key groups of risks identified by these farmers are discussed below. It should be recognised that the farmers interviewed as part of this study represent a very small subset of New Zealand dairy farmers. They are more experienced and likely have lower debt levels than most New Zealand farmers, which may have significantly biased their perceptions of risk. The results presented here should be understood in that context.

Counterintuitively, financial risks were not among the greatest risks to the system identified by these farmers. This may be a reflection of their experience and time in farming, implying relatively low debt levels and confidence in their ability to navigate payout fluctuations successfully. Pests and diseases, fertility problems and animal health were also seen as moderate, but manageable risks. Pasture performance was rated 7 (on a scale of 1-10) on the Waikato farm. Although this was not mentioned in the rating exercise by the other farmers, it was discussed in depth in the context of the adaptations. Succession was identified as risk by only two of the farms, as in most cases where it was relevant, plans were already in place to pass the farm on to the next generation. Other risks were also identified and discussed outside of the formal rating exercise.

Weather, not climate per se, was identified as a significant risk. However, two groups of risks were emphatically rated the most potentially dangerous: Those relating to impending environmental regulations, and people-related risks such as management and staffing issues.

4.3.3.1 Environmental regulations and the perceptions of ‘Greenies’

Environmental regulations and the perceptions of ‘Greenies’ were rated the highest overall risk to the farming system. These farmers are aware that change is looming, and that we are undergoing a change from the productivist regime of the past (Jay, 2007; MacKay et al., 2009). However, the shape, and especially the cost of such changes are hard to judge.

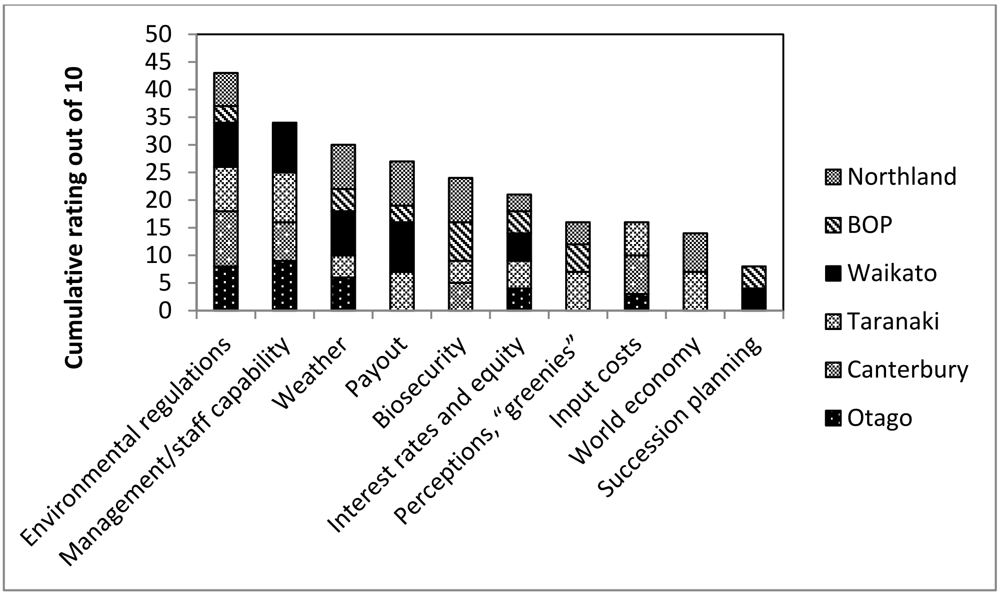

Figure 5: Relative risks to the farming system, as rated out of 10 by farmers from the Northland, Bay of Plenty, Waikato, Taranaki, Canterbury and Otago farms.

In New Zealand, a number of Regional Councils are currently developing and implementing new regulations, particularly around water quality and quantity. Some of these changes, for example, the introduction of nutrient limits around Lake Taupō in the central North Island, have required significant changes to farming systems and involved highly emotional responses from farmers who felt their livelihood was threatened (Botha et al., 2013). There was a keen awareness among the farmers interviewed of the fact that regulations were likely to increase, and were already much stricter overseas.

Most of the farmers interviewed expressed fear and uncertainty about the potential future of regulations for environmental issues such as water quality and quantity, as well as greenhouse gas emissions. In New Zealand, the Resource Management Act (1991) is interpreted at a regional level by Regional Councils, resulting in a range of different approaches to regulating farming practices. The farmers were very conscious of regulatory changes occurring in different parts of the country and had discussed the impact of new regulations with farmers from different regions:

> …you hear these odd quotes about 'most problems in life are caused by fear.' And I think that those who are part of the process or close to the process are getting very, very scared. And that's going to lead to a lot of problems. And I can't get over that comment I saw the other day – of the guys in the Waikato; every time they hear a helicopter their stomach drops. So, I think the rest of society needs to think about that just a bit …

The fear directly relates to the viability of their livelihood, and whether the impending environmental regulations will limit their ability to continue to grow and develop the farm. There was a strong perception of powerlessness in the face of the rules and a sense that they are driven by the perceptions of 'Greenies' who don't understand the practicalities of farming or the huge investment required for changes to the farming system.

This perceived powerlessness may be related to an increasing marginalisation of farmers from an increasingly urban society, which has been observed in studies from other countries (Källström and Ljung, 2005). It is likely to have been exacerbated by a high profile media campaign that was started in 2002 by the Fish and Game Council in New Zealand, focussed on the impact of dairy farming intensification on New Zealand's freshwater ecosystems under the slogan 'dirty dairying'. The campaign led directly to the development of the 2003 Dairying and Clean Streams Accord between industry and government bodies, which has now evolved into the broader 2013 Sustainable Dairying: Water Accord, highlighting the power of such campaigns to influence industry direction and policy. Uncertainty about the rules themselves was a source of stress, and also uncertainty about when they might be implemented.

> But you see (the Emissions Trading Scheme has) only been deferred until 2015 and we don't know what impact that's going to have. … We don't know what we're contributing; we don't know how we're contributing. And so I don't know where climate change comes into all that. Are we supposed to button off now, are we supposed to intensify? Or what are we supposed to do?

Despite the high level of connectedness and experience of this group of farmers, they highlighted the difficulties of being involved in or trying to influence policy processes:

> You've got to make a submission and… for a cocky that's just come out the cowshed to make a submission…And you ask; how do you make a submission? Oh, we'll send the form out to you. You've got to identify which area of the ten-year district plan you object to, or is it the draft annual plan you object to? And I say I don't know…

Changes to the farming system take time, money and planning. Some of the farmers were concerned about being pressured into capital-intensive measures, such as feed pads or housing to better capture dung and urine, where the capital costs involved will mean they have no choice but to intensify their operations.

> When you put a lot of inputs in with the feed pad it's like there's no real turning back and you've got to do it all the time, and we'd have to milk more cows to utilise it completely.

However, as mentioned above, the farmers were still realistic about the changing times, noting that a decade ago they couldn't have imagined their current level of intensity.

The level of fear and uncertainty among the farmers interviewed about changes in the regulatory environment highlights the importance of the policy environment in enabling or restricting adaptation. The fear may be excessive, as New Zealand farmers have in recent memory the difficult experiences of the economic reforms that took place in the 1980s, which brought an end to price subsidies and production subsidies in the economic sector (Wallace, 2014).

However, the high level of perceived risk and fear around future changes to environmental regulations may present a significant risk to farmers' capacity for positive adaptive responses to climate change and other pressures. Perceived risk is a strong driver of change, but does not determine whether the change will be adaptive or maladaptive. Studies in other fields have shown that a high threat perception may be positively correlated with maladaptive responses, including avoidance (Grothman and Patt, 2005), supporting the farmers' concerns that maladaptive choices may potentially be driven by fear of changes to environmental regulations.

Clear communication by regulatory authorities and organisations supporting farmers, and empowerment of farmers to become more involved in regulatory processes, may therefore be a key factor in increasing farmers adaptive capacity to climate change and avoiding uninformed and maladaptive efforts to second-guess future environmental regulations.

The importance of policy in facilitating adaptation to climate change is recognised (Amaru and Chhetri, 2013; Berry et al., 2006) but has not been thoroughly analysed in the New Zealand context. New environmental regulations to implement national legislation such as the National Statement on Freshwater

Management[4] is developed at regional level, with little guidance to regional councils on how this should be carried out except generally encouraging stakeholder involvement in the process. Further study is required to more explicitly analyse the effect of policy development arrangements on the adaptive capacity of New Zealand farmers in light of their importance to the economy of the country as a whole.

4.3.3.2 Management and labour risks

The quality of the people running the farm, both management and labour, were identified as an important risk by most of the farmers. Labour issues were integral to decision making and all four farms that relied on external staff considered this one of their biggest risks – summed up by one farmer as:

> If you haven't got the right people to run it, you've haven't got an enterprise.

Although not rated in the exercise as a risk by the Northland or BOP farms, it was clearly a key aspect of decisions made about the structure of the farm. For example, it was an important aspect of the choice made by the Northland farmers to milk only once a day, effectively eliminating the risks associated with employing staff.

> The limitation was always management, the timely decision-making and stock management, pasture management – they're just so critical. You can set whatever KPI's [key performance indicators] you like but it's really what happens on the farm that makes the biggest impact…

Changes in the culture of dairy farming and the attitudes of the next generation were of real concern to some of the farmers. A number of trends were identified, with potentially serious consequences for the adaptability of the farming systems. The first was the changing expectations of staff regarding labour conditions. There was a strong feeling that society was changing and agriculture was changing with it:

> Like one time you used to work 24 hours a day, seven days a week and most of the farm managers nowadays are probably averaging 40 to 50 hours a week…We've got to compete with the rest of the world…and they're talking about four day weeks and twelve weeks maternity leave, and all those sorts of things. And it all becomes a cost to the system – and whether we can accommodate those sorts of things or not, I'm not too sure. They're probably accommodating them right now by taking short-cuts and implementing technology that allows us to do those sorts of things.

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[4] http://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2014

Changes in staffing arrangements were also linked with the changing expectations and increasing risk-averseness of the next generation. Social culture is generally changing to become more risk averse. This does not really fit with the traditional farming culture of “taking the good with the bad” required for pasture based farming generally, and it can impact on the way labour contracts are arranged with younger staff. A related concern is the different staffing structures in place. A 50/50 sharemilking has a number of particular inefficiencies in terms of different drivers:

> And with all the animal welfare issues, it’s far better to control the cows yourself… Because as 50/50 sharemilkers, their wealth is based on cows so they wouldn’t cull cows, even though they had mastitis, which reduces production. …

The second trend identified was increasing farm size, with farm owners now doing less work on farm. This means that farming systems are increasingly dependent on unskilled labour with no ownership of the system, there to just 'do the job” so that operational systems had to be either very simple or automated:

> As it goes on, most farms will be corporate-owned before too long, or family-corporate sort of thing… the majority of the owners won’t be actually physically doing the work. That’s why you’ve got to have a simple system, – sometimes you get a good manager who is dead keen on feeding cows and grass and all that sort of thing. Then he goes and you get a manager that just wants to do the job…

A follow-on impact of increasing automation was less control by farmers over functional aspects of the system and greater reliance on external ‘experts’, for example to carry out repairs if a computerised system broke down.

4.3.3.3 Weather and climate risks

Weather-related risks are an important part of farming that have to be considered, and clearly played a significant part in the farmers’ management strategies. However, the farmers noted that they were used to planning for weather risks, and indicated confidence in their ability to cope with them.

> Well, the weather is a risk really…but that’s just farming, so then we can rank that at the lower end because we try to manipulate or plan for some of that…

The way questions were answered indicated that the terms climate and weather were often used interchangeably - and planning for climatic factors was primarily considered on a seasonal basis:

> We probably don't directly say we’ve done it because of the climate … but farming would be one of the industries where climate is (a) risky element of any decision….

The only farm where weather was not identified as a risk was the Canterbury farm, which is irrigated. However, for this farm, environmental regulation was rated 10 out of 10, and the farmer jokingly attempted to give it a rating of 15/10. In Canterbury a major focus of regulation is access to water, a key resource for the region where farms are mainly irrigated. Regulation, rather than the availability of water itself, is seen by the farmer as the main limiting factor in this context. This reinforces the view that adaptation to climate change is driven primarily by concerns for specific local limiting factors, in particular water availability (Haden et al., 2012; Niles et al., 2015).

O'Kane et al. (2009) drew a connection between Ulrich Beck's Risk Theory (Beck, 1996) and the way that farmers perceive risk in general – in particular, that farmers spend a great deal of time and energy assessing and attempting to plan for a wide range of highly uncertain risks (O'Kane et al., 2009). Beck theorised that this increasing complexity has led to "risk anxiety" and as a result, increasing isolation and individualisation of responses to risks. This individualisation has also led to increasing scepticism around traditional collective belief systems, including centralised scientific research (Fuller, 2007).

Vulnerability to risk can be considered as a function of three key elements (Adger, 2006; Craddock-Henry, 2011): 1) the shocks and stresses to which a system is exposed; 2) the sensitivity of the system: its ability to respond to the external stresses and 3) the capacity of the system to adapt to new states when necessary. If Beck's theory that complexity has led to an increasingly individualised approach to risk management is applied to these concepts, it makes sense that the risks identified in this study as being of most concern were not those related to external shocks and stresses, such as financial or climate risks, but rather the risks that could potentially limit the capacity of the system to respond to such risks in future. This also relates to the strong sense of self-reliance expressed by farmers in section 4.3.1.

All of the farmers saw climate change as part of the bigger picture of constant change in the world, which they were dealing with on a daily basis. The farmers talked around the issue of whether the climate was changing in terms of their own experience. Opinions varied, and some felt it was just natural variation, that "evens out". In general there was a high level of uncertainty about the subject:

> You know, there's so many experts on climate change and what's happening or where it's heading and it's hard to know what to believe or what it is.

Some made observations about changes in extremes, and indicated that these might be changing beyond their past experience:

> …And normally you'd say the autumn rains have come but we've had some years where they haven't and we've actually dried off or the season's finished earlier than we've expected. So we just expect it at some stage now. Global warming!

Extreme weather events often provided a stimulus to make transformational adaptations on the farm, but usually not in isolation (Berrang-Ford et al., 2011). Tipping points for change are reached when more than one event or factor compound.

> We did have a real bad drought in 2003 and 2004. I have to admit that I came as close to a nervous breakdown as I ever have because both our wells disappeared…when you get things over Christmas and New Zealand shuts down so you can get no help. And the nor 'west – just a whole series of, one of these perfect storms, a whole series of events happened and suddenly we didn't have enough water, it was hotter than hell and the wind was blowing every day and you just couldn't keep up and the cows were just dropping, and that was the year we'd sold the cows so getting in calf was really important and we're getting more cows getting back in heat in January and yeah, those sorts of things… when I started sleeping again it was because I'd figured out a way to get around it – I needed another well and some better systems…… so we dug the second well after that and it took care of a lot of problems.

The perceived severity of an extreme weather event is influenced by other factors that affected their capacity to cope with the event, and this is also context specific (Burton and Peoples, 2008; Wiid and Ziervogel, 2012)

Farmers adapt to extreme weather events based on clearly observed limitations in the current system. However, more subtle changes in weather patterns are more difficult to analyse robustly. Wiid and Ziervogel (2012) found in a study of commercial farmers in South Africa that farmer perceptions of changes to the weather in their location correlated well with observed weather data, but this may be difficult to translate into the management changes required. Gray (2001), in a case study of expert farmers, discussed how farmers make a distinction between long-term changes and short-term aberrations in climate, for planning purposes. He suggested that the expert farmers in his case study used repetition of experience to identify if a fundamental shift in climate had occurred: for example, after experiencing three cold, wet springs, the case farmers changed their plans for that period. However, he noted that farmers had observed this was not a very robust method, and farmers sometimes made system changes based on what they thought was a developing weather pattern, only to discover that it had changed again. This may indicate potential for decision-support tools to help farmers identify and analyse changes in the climate at their own specific location and relate these to broader projections.

4.3.4 Sources of knowledge

Adaptation to climate change is one aspect of the ongoing process of adapting a dairy farm to a constantly changing environment. It is important to recognise in this context that climate change is not likely to be the main driver of change in these farming systems, and that tipping points, where systems go through transformational changes, will likely be the result of a combination of different factors including both economic and environmental drivers. There is a recognised need to embed climate change adaptation in the broader context of resilience to multiple threats and stresses (Wilbanks and Kates, 2010)

Strong networks were considered especially important when considering a change to their systems. The farmers indicated that they get information from a wide range of sources, including internet, trade papers, agricultural field days, and reputable industry organisations like DairyNZ. However, the most important source of information was other farmers. This has the double advantage of an independent and trustworthy information source, and being able to see the change in context.

> Seeing it in the flesh is number one. Preferably in an environment that's as close …as we can, and then just general information gathering – so internet, brochures, Fieldays. Certainly independent farmers would be the number one port of call – everybody else is probably trying to sell you something…

Discussion groups, and in some cases even farm consultants, were appreciated mainly for the opportunities they presented to find out what other farmers were doing, and for making contacts with other farmers in order to go and visit and talk to them on-farm afterwards. This indicates that there may be scope for more direct stimulation of on farm innovation through farmer networks and exchange programmes for leading innovators, particularly to visit other areas which may provide climate analogues for changes to come.

While local examples were considered the most important, there was also a keen interest in understanding the full range of possibilities, including looking further afield to overseas examples.

As information from research sources is gathered in an eclectic fashion, along with other information as part of the farmer's quest for knowledge on a particular topic, it may not be clear to the farmer where the information originated. For example, research by DairyNZ (Gregorini et al. 2006) formed a part of one farmer's mental picture of how he saw his system developing, but was not identified as such by the farmer.

Some farmers also expressed frustration at the changing recommendations coming from research organisations, and most of these farmers also expressed a feeling of being ahead of research:

> Yes, so the biggest thing with research in NZ is keeping up with aggressive farmers that have got the equity to change…Science just can't keep up with them, because we do it so quickly and that's known worldwide…

However, research was still considered important, with DairyNZ an important source of information on current best practices. The farmers were generally positive about the value of scientific research, especially where it was presented in context:

> Keep the science coming… Put the scenarios in front of us and let us make our own decisions.

The capacity to adapt and the capacity to innovate are closely interconnected (Rodima-Taylor et al., 2012). For this reason, forward thinking farmers with the resources and confidence to experiment are an invaluable resource in driving the innovation that may be required to adapt to climate change. There is now much research evidence, frameworks and successful examples of farmers and scientists working together to determine viable adaptations and future directions for farming systems (Le Gal et al., 2011; Eastwood, 2012; Klerkx et al., 2012; McCown et al., 2012; McCown, 2002; Rodriguez et al., 2011; Sewell et al., 2014). Much of the value of such approaches lies in the contextualisation of scientific knowledge, allowing iterative, co-learning approaches that can incorporate the objectivity of the researcher with the context specific understanding of the farmer. Such partnerships will be essential for fostering a culture of innovation that can support successful adaptation to climate change and other forces of change.

A key challenge of such approaches for researchers will be to step out of their specific field of research and formulate research questions based on an in-depth understanding of the broader, context specific issues facing farmers.

4.4 Conclusions

Adaptation to climate change is an ongoing and highly context-specific process that cannot be carried out independently of other risks and driving forces. While climate is one of the risks on which these farmers base their decision-making, they generally consider it to be within the scope of their capacity to adapt. Adaptation of the farming system is therefore likely to be driven to a large degree by farmer perceptions of changes to more immediate risks, such as environmental regulation, management and staffing issues. Climate change may also directly influence these risks, for example, through new environmental regulations, or new pests and diseases. On the other hand, changes in the risks associated with labour and management capacity will directly impact on farmers' capacity to adapt to climate change. There is a danger that pressures presented by other forces, such as fear of environmental regulation, may negatively affect adaptive capacity or drive maladaptation.

The mental models of the farmers in this study, while distinctive, all exhibited a high degree of flexibility and were shown to evolve over time. They have adapted themselves and their farms to extreme climatic events in the past, are confident in the resilience of their system, and have a range of tools and strategies in place to cope with variability and change.

The ability to cope with variability is dependent on inbuilt flexibility and having multiple options. A range of management options are needed to enable appropriate choices to be made depending on the goals and worldview of the farmers, as well as on the resources available and limitations and challenges specific to their region.

Principles for resilient farming systems identified through the interviews included 1) ensuring a degree of buffering in aspects of the system as diverse as finances, feed and animal health, as well as the human capability of the system; 2) strategic planning; 3) diversity and flexibility in the system; and 4) social capital.

Regarding planning in time and space, this is a skill which is usually developed through experience, along with the accompanying "rules of thumb". These skills can either be shared through farmer to farmer extension, or more formally by analysing each particular situation on farm and developing decision making rules under different circumstances. This is a useful approach and many decision making rules have been developed. Combining both research and farmer experience can improve the robustness of such rules.

Of key importance for the maintenance of flexibility and diversity in the system is the avoidance of path dependence. This is an essential message to both researchers and policy makers: That no one solution will 'fix' the problem of climate change. The ability to cope with variability is dependent on inbuilt flexibility and having multiple options. A range of management options are needed, to enable appropriate choices to be made depending on the goals and worldview of the farmers, as well as on the resources available and limitations and challenges specific to their region. A key challenge for regulators will be to ensure that any changes brought into the regulatory environment are developed and implemented in such a way as to enhance, rather than inhibit farmers' adaptive capacity and flexibility.

The final principle, building social capital, is a well-recognized aspect of resilience and this was reinforced by farmers. There is scope for further research on how the cultural and social changes identified by farmers may impact on their ability to adapt to climate change.

Potential future climate change is seen as only one of a wide range of risks. The complexity and uncertainty associated with potential future stresses and shocks may explain the relative importance these farmers place on risks that may limit adaptive capacity, such as regulatory risks and those associated with management and staff capacity, rather than the risks posed by the potential stressors themselves.

There is a danger that pressures presented by other forces, such as fear of environmental regulation, may negatively affect adaptive capacity or drive maladaptation. Of key importance for the maintenance of flexibility and diversity in the system is the avoidance of path dependence. A key challenge for regulators will be to ensure that any changes brought into the regulatory environment are developed and implemented in such a way as to enhance, rather inhibit farmers' adaptive capacity and flexibility.

5 Scenarios of adaptation 1: modelling farm-level climate change impacts and researcher-defined adaptation options

Abstract: Projections indicate that climate change may exacerbate existing pressures on the productivity of New Zealand dairy farming systems. To assess the importance of these projections at farm level, detailed farm-scale model simulations of climate change impacts were undertaken and potential adaptation options explored for six representative pasture-based dairy farms located in the major dairying regions of New Zealand. The analysis suggested that without adaptation, the overall impact of climate change is likely to be negative in most locations of the case study farms. However, the level and type of impact depends to a large degree on regional climate variability as well as on the management practices of each farm. Response to projected climate changes under current management ranged from no change to an 18% decrease in average annual pasture production. This translated to a 1% to 69% decrease in operating profit, depending on the farm and climate scenario. The modelling work and farmer's responses indicated that the options modelled have the potential to provide both benefits and management challenges across the different regions and climate years. This study has particularly highlighted the need to contextualise agricultural systems modelling under climate change scenarios.

5.1 Introduction

For farmers, adaptation to climate change is part of a continuous, iterative process of adapting to a number of changing pressures that affect farm management (Stokes and Howden, 2010). Understanding how the impacts of climate change will be manifested in practice, and which adaptation options show the most promise for farmers, requires an understanding of the different environments and management strategies.

This chapter aims to assess the potential localised impacts of climate change on temperate dairy systems by modelling six dairy farms from different regions using a detailed farm systems model. Following the impact assessment, the effects of changes to current management practices will be examined with farms exposed to climate variability represented by different global climate change scenarios.

Detailed assessments at farm-scale allow the exploration of management responses to climate change. They are an important focus for climate change studies as it is the scale at which farmer decisions are made (Newton et al., 2008).

While pasture growth is arguably the most influential driver of profit in pasture-based dairy farms, in practice they are complex ecosystems (Bryant and Snow, 2008) with biophysical, management and financial components. Climate change impacts on pasture growth cannot be assumed to affect profitability in a directly linear fashion. The capacity of these systems to adapt to climate change will depend not only on changes in pasture growth but also on the way the different biophysical, management and financial components interact.

Over the past decade, improvements in farm systems models mean that many of the complex interactions between biophysical and management systems can be simulated with some confidence. Examples of such studies in the climate change context include the work of Fitzgerald et al. (2009) on Irish dairy farms, and Dynes et al. (2010) in the New Zealand context. Fitzgerald et al. (2009) carried out an integrated, whole farm study using the "Dairy_sim" model, based on a scenario of future dairying systems that would produce the greatest output of milk on a particular land area. They suggested that Irish dairy production should be able to readily adapt and remain viable under projected climate change scenarios (Fitzgerald et al., 2009). In New Zealand, Dynes et al. (2010) applied a whole-of-systems perspective to the potential flow-on effects of climate-driven changes in pasture growth. In this study, a separate model was used to simulate pasture growth response (EcoMod), which then fed into a farming systems model (Farmax Dairy Pro). The study compared a specific set of adaptation management strategies (cow numbers, calving date, supplementary feeding and grazing strategies) under a mid-range climate scenario for a dairy farm in the lower central North Island (Manawatu). It was suggested that these strategies had the potential to turn a negative climate change impact into a financially positive outcome for the modelled farm.

An important aspect of integrated, whole farm systems modelling is the capacity to examine responses at a finer temporal scale than would otherwise be possible. Whole farm dairy system studies of responses to climate variability have shown strong temporal patterns in the influence of weather on pasture growth and quality (Roche et al., 2009). However, these were shown to be mitigated in well-managed dairy systems through tactical grazing practices, highlighting the importance of farm management in modifying the influence of weather in complex agro-ecosystems.

Whole farm models are highly complex and detailed input is required for setting up farm scenarios. Significant investment is needed for site establishment; particularly if management effects (adaptations) are assessed (Clark et al., 2012). Consequently, previous studies have focussed on technically feasible but idealised modelled farms (Dynes et al., 2010; Fitzgerald et al., 2009) or paddock-scale modelling (Cullen et al., 2009).

A key challenge for studies that aim to integrate climate projections with detailed biophysical and management systems models is the establishment of an appropriate form of model and level of detail in order to provide meaningful results. This will depend on the specific objectives of the study (Bennett et al., 2013; Jakeman et al., 2006). In the case of climate change analysis for farming systems, the sheer complexity of interactions has meant that most studies have focussed on climatic averages, and it is recognised that modelling studies generally tend to underestimate variability (Fowler et al., 2007). However, in practice, uncertainty and climatic variability may be more important to farmers than changes in average temperature and precipitation.

While a number of studies have analysed potential impacts of climate change on New Zealand dairy farms in different ways and at different levels (e.g. Baisden et al., 2010; Dynes et al., 2010; Warrick et al., 2001; Wratt et al., 2008) to date, none of the assessments carried out have analysed actual working farms. In setting up modelled farms which mimic actual farming systems, this study enables a more realistic analysis of the potential for particular adaptations. It also allows for discussion about these options with the farmers in relation to their own farms, enabling a more in-depth understanding of the implications of different management adaptations.

5.2 Methods

5.2.1 Model selection

In order to better understand the implications of climate change, and potential adaptation options from a farm management perspective, a detailed farm systems model was required in order to allow a broader suite of management practices to be examined than has been attempted previously in the climate change context. Model selection was considered in an effort to balance the biophysical representation of the system against the need to explicitly model the effects of management for adaptation. In the New Zealand context, some of the most commonly used models for the analysis of climate change in farming systems included the DairyNZ Whole Farm Model (WFM), the AgPasture model for APSIM (Keating et al., 2003; Li et al., 2014) and the DairyMod system (Johnson et al., 2008; 2013).

AgPasture and DairyMod are examples of complex simulations that represent the underlying biophysical systems in considerable detail. However, these models do not incorporate the different management regimes that occur on working dairy farms in New Zealand, including the transfer of nutrients as part of effluent management, stock rotations and, in the case of AgPasture, milk solids production. They also do not incorporate economic data, which forms a key component of farmer decision-making.

The WFM is considered an appropriate system to study adaptation because it allows the representation of a large range of New Zealand farm system configurations and management options. It was selected for this study because flexible decision rules allow an analysis of the effects of different management strategies on interactions and feedbacks between climate, management, and cow and pasture production in a farming system (Beukes et al., 2011; Bryant and Snow, 2008).

The WFM provides outputs for pasture growth and animal production on a daily basis, and economic results on an annual basis. Daily weather inputs also allow for fine-scale simulation of climate effects. It is a continuously developing model that is utilised for a range of analyses of different farming systems (Beukes et al., 2005; 2010a; 2010b; 2011; Romera et al., 2009), and has been previously evaluated and reviewed (Beukes et al., 2008; Bryant and Snow, 2008). It is based on three fully integrated modules: a mechanistic model of cow metabolism (Molly, see Baldwin,1995); a weather-driven pasture module (McCall, see Romera et al., 2009), and a management/economic module (Beukes et al., 2005). New components are added as and when there is a defined need and sufficient supporting data. For example, some of the crops defined in this version of the model are weather-driven, such as the maize model that was provided by Plant and Food Research (described in Li et al., 2009). For other crops, such as chicory, the capacity of the model is still limited and crop yields must be defined by the user.

A limitation of the WFM in the context of a climate change study is that it does not simulate the effects of CO_2 fertilisation (see Chapter 2, section 2.6). This means that a modelling analysis that specifically includes CO_2 effects, such as those carried out by Cullen et al. (2009; 2011) and Phelan et al. (2014), was not possible in this study. In a review of published research Lee et al. (2013) estimated that when climate and nutrients are non-limiting, CO_2 fertilisation may lead to a positive growth response between 4-14% in the ryegrass-clover based swards that dominate New Zealand's dairy production systems. This response has been shown to exhibit strong seasonal patterns, with the highest growth rate increases occurring in spring (Li et al., 2014).

As noted in Chapter 2 (section 2.5), the modelling of plant responses to elevated CO_2 under variable environmental and management conditions has been identified as a major source of uncertainty in our understanding of how global change processes may be manifested at farm level (Li et al., 2014; Rötter et al., 2011; Soussana et al., 2010). Because of the challenges inherent in capturing the likely impacts on ecosystem processes, some studies have omitted these impacts (e.g. Wratt et al., 2008; Zhang et al., 2007) while others have addressed the issue by applying blanket fertility increases to their data (e.g. Fitzgerald et al., 2009;

Baisen et al., 2010).The recent study by Li et al. (2014), the only study to date to compare responses from FACE experiments with modelled data in New Zealand pastures, highlighted the potential for models, in this case AgPasture, to overestimate these effects due to poor representation of years with small or negative responses to CO_2 (Li et al., 2014).

In order to simulate management effects, which was the primary focus of this study, the WFM was preferred as the modelling environment. There is a possibility to adjust the pasture module to replicate CO_2 fertilisation by adjusting the fertility response curve. However, this would not adequately capture the known interactions between nitrogen and soil moisture status and the strength of CO_2 response at a seasonal time scale (see Lee et al. 2013). For this reason the choice was made to not apply a fertility adjustment. This issue is considered carefully when discussing results from models in individual chapters, along with the broader limitations of models in representing all known biophysical and management processes that farmers are exposed to.

5.2.2 Setting up the case study farms

Case study farms were selected from six major dairying regions in New Zealand: Northland, Waikato, Bay of Plenty (BOP) and Taranaki in the North Island, and Canterbury and Otago in the South Island, covering different climatic zones with differing ranges of anticipated responses to climate change. All of the case study farms were commercial farms, and the farmers were identified as respected operators by regional consultants and/or researchers. The farmers provided detailed information on their farming system and current management practices, which are summarised in Table 5.

System intensity has been categorised by the New Zealand dairy industry organisation DairyNZ into five 'production systems[5]' based on the level of imported feed, where one on the scale is fully grassfed and self-contained, and five refers to a farm that imports around 25-40% (but can be up to 55%) of total feed in order to provide cows with supplementary feed all year round. The case study farms were approximately average in size for their regions, with average or

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[5] http://www.dairynz.co.nz/farm/farm-systems/the-5-production-systems/

slightly above-average stocking rates. The farms in the more challenging and drought-prone climates of Northland and BOP were less intensive and described themselves as system 2 farms. The Waikato, Taranaki and Canterbury farms were system 4, and the Otago farm was a system 3.

For each of the case study farms, a model farm was created using the WFM to mimic the setup, management practices and outputs of the real farm as closely as possible. The strength of the WFM for analysis of climate change adaptation options lies in the dynamic representation of management in the model, based on a mix of internal decision rules and inputs. However, accurately mimicking real, complex farming systems in a model brings with it a number of challenges and the modelled farms were necessarily a highly simplified representation of the real farms. For example, only the dominant soil type was chosen, whereas in reality the farms often covered a number of different soils. Slope was not modelled, and apart from tall fescue, it was not possible to model a wide variety pasture species or pasture mixes.

In order to efficiently run the model with the computing power available, the case study farms were modelled at 1/10th of the scale of the real farms, since the simulation model can be linearly scaled up to a whole farm and all results presented on a per cow or per hectare basis. Management practices such as drying off, culling, mating, silage making and supplement feeding, as described by the farmers, were calibrated with outputs from the model for the year 2010-2011 (corresponding to a farm season 1 June 2010 – 31 May 2011).

Economic input (including e.g. costs and prices) for the 2010-2011 year (DairyNZ, 2012) was used repeatedly for all scenarios and climate years. To ensure the management policies were flexible within the current range of weather for each farm, the culling rules, drying off rules and supplementary feeding rules were set to be flexible enough to cope with historical drought years 1995-1996 and 2007-2008. These management rules were based on the farmers' description of their tactical management practices (e.g. using a flexible supplementary feeding policy and maintaining stocking rate according to the farmer's stated management priorities). The current management setup for each of the model farms also ensured that there were minimal carry-over effects to the next year. For example, culling rules were set to ensure the number of potential milking cows remained the same from year to year with no major changes in starting and finishing liveweight.

5.2.3 Climate scenarios

To gain an understanding of the range of potential impacts within a time frame that would still be potentially relevant to farmers, the six farms were run under a 'high and 'low' CO_2 emissions scenario at the mid-century time slice (2030–50).

The climate scenarios utilised for this study were developed specifically for the analysis of New Zealand agricultural systems by the National Institute of Water and Atmospheric Research (NIWA) using the physical Regional Climate Model (PRECIS, RCM) nested in the HadAM3P Global Circulation Model (GCM). Meteorological fields were generated at a 30 km^2 resolution across New Zealand for the IPCC A2 (high CO_2 emissions) and B1 (low CO_2 emissions) scenarios to generate the climate scenarios used in this study out to 2050. The future scenarios were selected from the Special Report Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) to represent a range of future outcomes, (IPCC, 2000; Solomon et al., 2007):

- The 'high emission' A2 scenario, also referred to as the "business as usual" scenario, describes a very heterogeneous world where human fertility patterns across regions converge very slowly, resulting in continuously increasing global population. Per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The low emission 'global sustainability' B1 scenario assumes a global population that peaks in mid-century and declines thereafter, with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

Although the RCM simulations were generated from a single GCM, they have been compared with the full range of climate change projections for New Zealand (Mullen et al., 2008). They have been shown to represent a mid to high end temperature change and to cover the broad range of seasonal and locational changes in rainfall (Clark et al., 2012). The simulations were bias corrected and

Table 5: Current farming system and management practices for the six case study farms

	Northland	**Bay of Plenty**	**Waikato**	**Taranaki**	**Canterbury**	**Otago**
General description	OAD milking with Jersey cows.	Coastal BOP farm	Modelled dairy farm is part of a diverse 300ha operation.	Coastal Taranaki farm	Milking platform of the 'No. 2' farm of a larger operation	Demonstration/ training farm
Milking platform(ha)	75	118	175	104	141	166
Support block (ha)	not modelled	14	30	53	not modelled	88
Stocking rate (cows/ha)	2.4	3.0	3.7	3.6	3.8	2.9
Milking	Once a day	Twice a day	Twice a day	Twice a day	Twice a day	Twice a day
Pasture	Ryegrass/ clover (Kikuyu ingression)	Ryegrass/ clover	Ryegrass/ clover	Ryegrass/ clover	Ryegrass/ clover	Ryegrass/ clover
Crops and silage	Turnip brassica	Maize and turnips grown; silage made	Maize for silage; chicory for grazing	Silage made on support block	Not on milking platform (modelled)	Turnips; swedes; silage made
Irrigation	None	Some effluent	Some effluent	Some effluent	Fully irrigated	Some effluent
N Fertiliser (kg N/ha/yr)	200	120	180	200	200	140
Drying off	Based on milk yield, 10th May, earlier if pasture covers low.	Based on cow condition in early May	Based on milk yield in May	Based on pasture cover towards the end of May	25 May, earlier if cow condition is low.	Based on milk yield, pugging danger during May
Planned start of calving	14 July	20 July	7 July	19 July	1 August	9 August
Supplements bought in	Palm kernel expeller (PKE); grass silage	PKE; maize silage; grass silage.	PKE; straw; maize silage.	PKE; maize/grass silage; molasses; hay	PKE; grass silage	Grass Silage; maize silage.
Primary soil type (represented in model)	Waitara brown clay. (Clay loam over clay at 40cm)	Tarawera ash over pumice. (Loamy sand)	Horotiu silt loam (Horotiu (Basic))	Egmont ash, (Egmont)	Waimakiriri stony silt loams, (Waimakakiri)	South Otago Pallic soil (Templeton)
Pasture yield 2010-11 (approx.) tons DM/ha/yr	11	15	13	15	16	16

downscaled to provide site-specific climate fields for WFM simulations (Clark et al., 2012). Daily weather inputs were then entered into the model from the downscaled climate projections for the closest NIWA Virtual Climate Station Network (VCSN) station to each farm. VCSN data are based on the spatial interpolation of actual climate observations made throughout New Zealand. The data provided included minimum and maximum temperature, solar radiation, precipitation and evapotranspiration on a daily basis.

5.2.4 Impact assessment

For the impact assessment, in order to efficiently run the model with the computing power available, each model farm was run for two 10-year periods under each climate scenario to form a baseline for the years 1980-2000. This was followed by two 10 year runs for each climate scenario for the years 2030-2050. In all cases, as noted above, standard economic inputs for the 2010-2011 year (DairyNZ, 2012) were utilised. No changes in future cost structures were included in this modelling work, and the cost structures were not tailored to each individual farm. For this reason economic outputs from this study may vary considerably from the actual farms, and should be considered a relative, rather than an absolute measure of economic effects.

In order to provide a measure of variability between years for these relative changes, the coefficient of variation was selected. This is calculated as the standard deviation divided by the mean and provides a standardised measure of variability.

Two-tailed t-tests with heterogeneity of variance were performed for this impact analysis, comparing the future impact with the baseline for each climate scenario for three main indicators: pasture yield, milk production and operating profit.

5.2.5 Adaptations

A set of potential adaptations were explored at two levels for each farm for the years 2030-2050. Smit and Skinner (2002) differentiated between ‘tactical’ adaptations, which can address within-season climatic variability, and more strategic adaptations that involve structural changes in farm management or land use (Stokes and Howden, 2010).

The tactical adaptation tested involved making grass silage on the main milking platform and feeding grass silage to all cows all year round, in order to effectively smooth any variability in pasture growth. The only farm already making silage on the milking platform was the BOP farm, and management policies for silage cutting were set up for the other farms in the same way: the silage cutting policy was set up to allow paddocks to be set aside for silage cutting during the period October-April if and when there was a pasture surplus. When a silage paddock reached a herbage mass of over 4500 kgDM/ha, all silage paddocks over 4000 kgDM/ha were cut to a residual herbage mass of 1500 kgDM/ha.

The next three adaptations were strategic, involving changes to the farming system. The three strategic adaptations selected reflect different approaches to increasing the capacity of the farming systems to cope with climatic change: 1) increasing the resources (in this case water) available to the farm system through irrigation; 2) more efficient use of soil water through a change to a deeper rooting pasture species; and 3) reducing the pressure on resources available by reducing stocking rates.

Irrigation management was based on the irrigation practices of the Canterbury farm, since this farm was currently the only fully irrigated system. In addition to limited effluent irrigation already used on some farms, an irrigation rule was added to irrigate 6 mm clean water when soil moisture fell below 75% field capacity, between October and April. This followed the irrigation decision rules for the Lincoln University Dairy Farm as described in Beukes et al. (2005). Irrigation was removed for this treatment for the Canterbury farm, since it was usually fully irrigated. No changes were made to fertiliser use for this treatment. Operational costs are included in the WFM in the form of a per hectare cost per megalitre of irrigation water. However, none of the capital costs of setting up an irrigation system were included in the analysis.

The second strategic adaptation was a change in pasture species from ryegrass-clover to tall fescue. Tall fescue has a deeper root system compared to ryegrass (Minnee, 2011) and may therefore cope better with increasing drought (Cullen et al., 2008). It has been parameterised for the McCall pasture model in the WFM by altering radiation use efficiency, the temperature growth factor, soil water factor, and leaf lifespan based on the available literature[6]. However, differences in pasture quality and establishment were not included in the parameterisation, reducing the robustness of the tall fescue data for the analysis of flow-on effects such as milk production and operating profit.

The pasture species was changed to tall fescue for all farms except the Otago farm, since the climate was considered unsuitable for tall fescue in the lower South Island. For the Canterbury farm, irrigation was also removed for this treatment to test whether it would contribute to reducing the farm's dependence on irrigation. Grazing rules were not altered in the model when the pasture species was changed.

The third strategic adaptation was an approximate 15% blanket reduction in stocking rate by randomly culling from the herd. The environmental consequences of intensive dairy farming have been identified as a key issue for future dairy farming in New Zealand (Basset-Mens et al., 2009; Clark et al., 2007; Knapp et al., 2014) and stocking rates have been the subject of research in the context of mitigation strategies (Beukes et al., 2011; Doole 2014). Adjusting stocking rate to changes in feed supply is considered good agricultural practice (Zhang et al., 2007), and although milk production per hectare decreases with decreasing stocking rates, per cow production increases linearly to a certain point (MacDonald et al., 2008). This suggests that efficiency gains and a reduction in variability may potentially offset production losses under a less favourable climate.

5.2.6 Farmer response

The methodology used for obtaining farmer response to these researcher-defined options is described in Chapter 4. The modelled impacts and adaptations for each particular farm were presented to the farmers in the second interview, and their response was recorded *ad verbatim*.

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[6] Romera, A. 2012. DairyNZ internal report. available on request.

5.3 Results and discussion

5.3.1 Climate scenarios

The ‘high’ (A2) and ‘low’(B1) CO_2 emissions scenarios utilised for this study represent a mid- to high-end temperature change for the mid-century (Clark et al., 2012) and cover a broad range of seasonal and locational changes in rainfall. For the B1 scenario, the average temperature rises by approximately 0.89°C from the 1980-99 baseline to the period under analysis (2030-2049), and average annual rainfall increases nationally by approximately 2.8%. The regional pattern shows drier eastern and northern summers, which is consistent with the more likely outcome in the nationally consistent projections for New Zealand (Clark et al., 2012).

The A2 scenario shows an average national temperature increase of 1.2°C and average national rainfall decrease of 1.8%. However, the spatial pattern is a plausible but less likely outcome for New Zealand, delivering what is best described as a ‘climate surprise’, in the form of a wetter summer to the North Island (Clark et al., 2012). For the farms in the middle of the North Island (Waikato and Taranaki), this has meant that, counterintuitively, the impacts of climate change under the high scenario were less severe than under the B1 scenario. While they are both plausible climate scenarios, these two scenarios may not have captured the full range of potential impacts of climate change on these dairy farms. Future work needs to further investigate these effects under a broader range of climate scenarios, in order to ensure that the analysis fully captures the potentially more severe impacts of climate change that might be expected under a more typical high CO_2 emissions scenario.

Figures 6 and 7 present changes in temperature and precipitation, respectively. These are shown at a monthly time interval to avoid artificial smoothing of seasonal averages, as this is more relevant to farm scale analysis and can be more directly compared to changes in pasture growth.

5.3.1.1 Changes in temperature

For all of the farms in this study, the downscaled climate for the A2 and B1 scenarios shows an increase in both minimum and maximum temperatures of

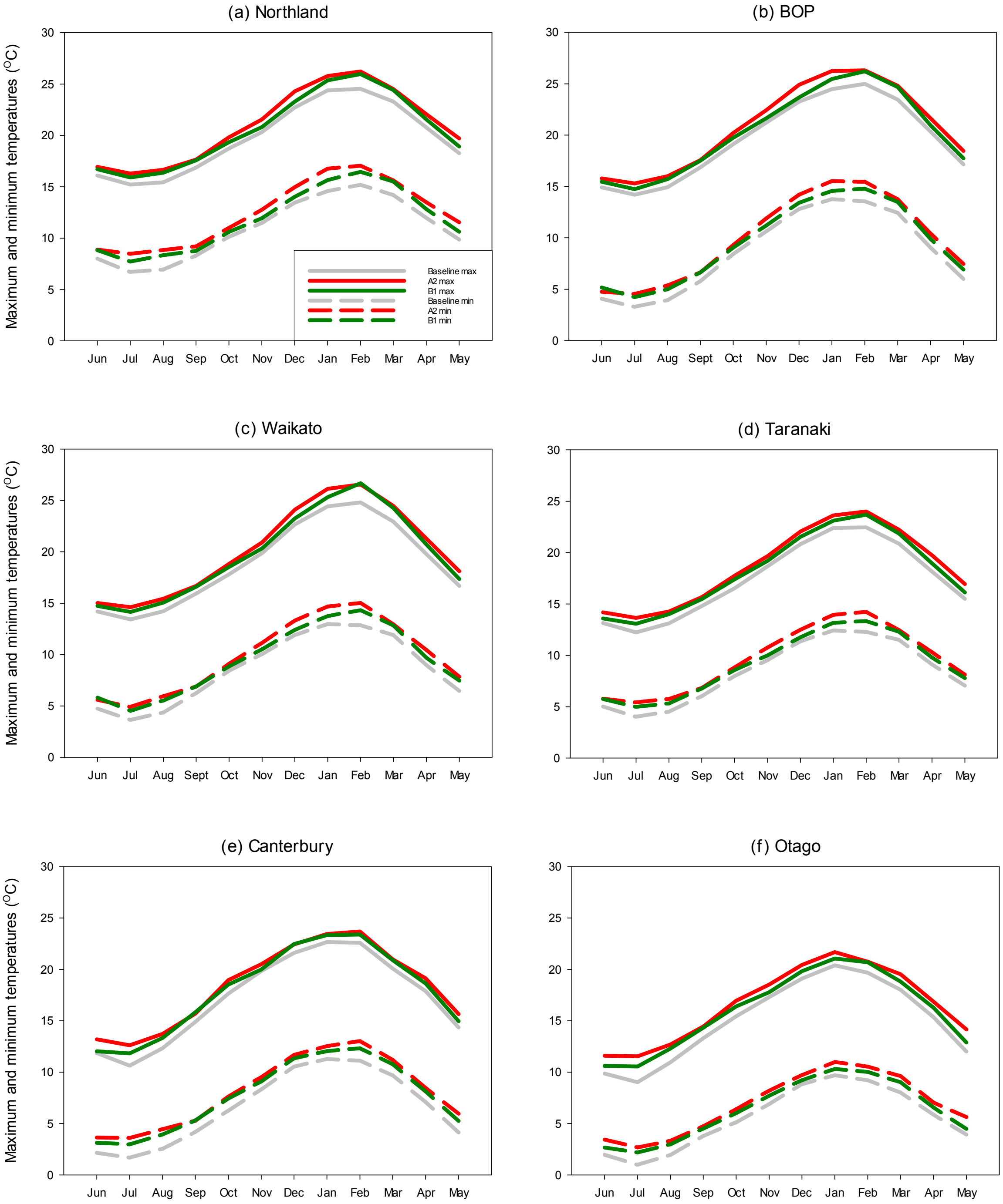


Figure 6: Projected changes in maximum and minimum temperatures for the baseline (1980-2000) and future (2030-2050) A2 and B1 climate scenarios, at the six farm sites.

approximately 1-2 °C (Fig. 6). Figure 6 shows that particularly in the A2 scenario for the farms in the warmer parts of the North Island: Northland, BOP and Waikato, temperature increases were greater in the summer months of December, January and February. In the B1 scenario the most pronounced temperature increases were slightly lower and around one month later. While heat stress in dairy cows is a complex topic (Mader et al., 2010) and was not included in the modelling carried out for this study, it is worth noting that both maximum and minimum temperatures increased at these sites during the hottest part of the year. This may be important in future consideration of heat stress, particularly as minimum (night time) temperatures have been identified as important for reducing heat stress (Clark et al., 2012; Igono, 1992; West, 2003). The Taranaki farm showed a similar pattern, except that the largest maximum temperature increase under the A2 scenario occurred in April-May. For the Canterbury and Otago farms, there was a greater average increase in winter temperatures.

5.3.1.2 Changes in precipitation

Projected changes in precipitation between the baseline and the future climate were highly variable depending on the location of the farms. In all cases, change in average annual precipitation was small. The greatest change in average annual rainfall, for the A2 scenario on the Northland farm, was less than 8mm. However, the changes in average monthly precipitation were often substantial, as shown in Fig. 7. For example, the 61mm increase in average Northland rainfall for May under the B1 scenario is equivalent to a 38% increase in rainfall for that month.

Monthly analysis also showed considerable variation between the two climate scenarios (Fig. 7). While some general trends can be identified, such as a general decrease in autumn rainfall under the A2 scenario for all the North island sites, this pattern was reversed for April and May under the B1 scenario. Presenting these data at a monthly time scale particularly highlights the challenges inherent in predicting precipitation changes and the difficulty in providing clear guidance to farmers on such projected changes at farm level.

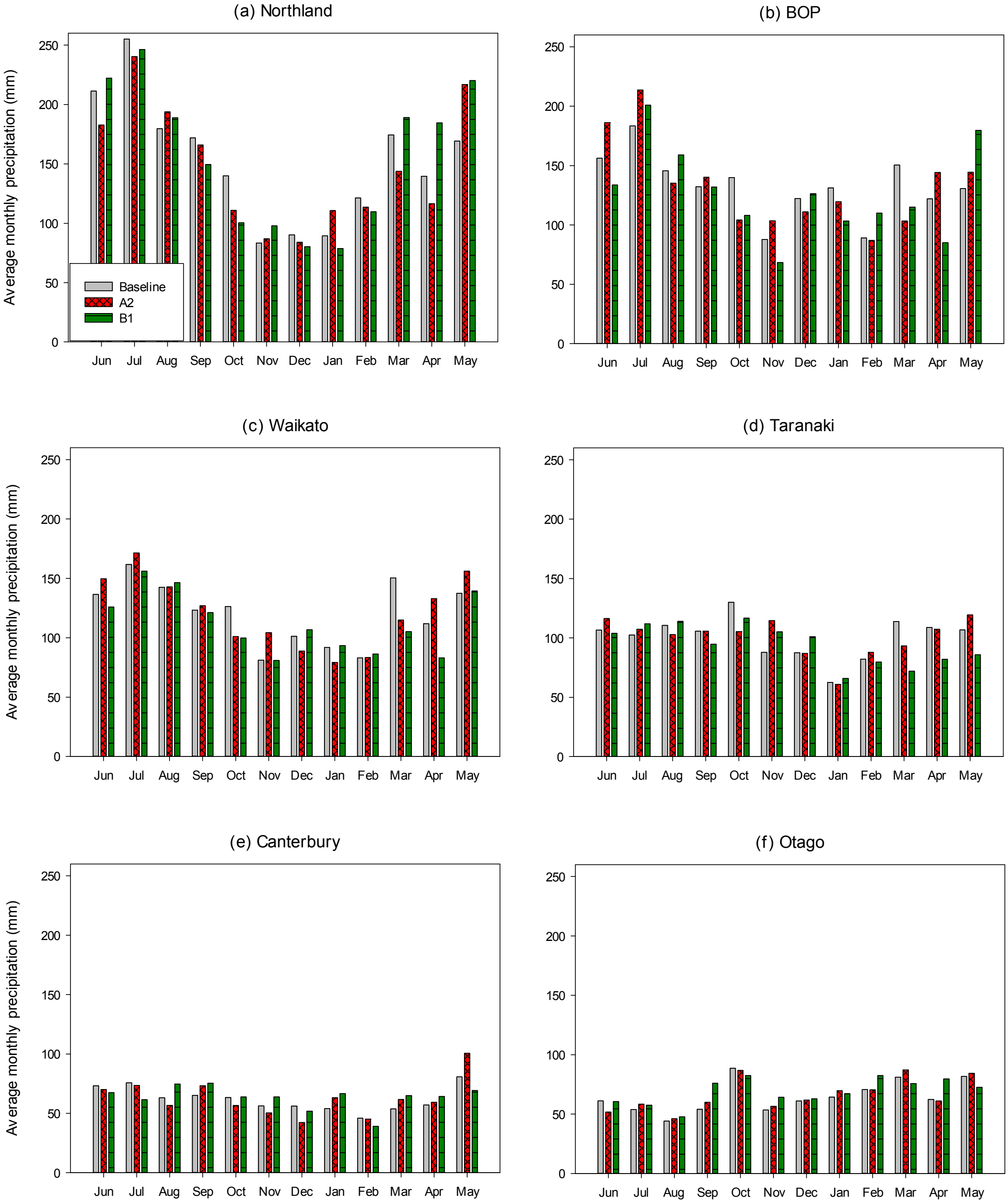


Figure 7: Average monthly precipitation for the baseline (1980-2000) and future (2030-2050) A2 and B1 climate scenarios, for the six farm sites.

5.3.2 Impact analysis

Projected pasture growth under the baseline and the two climate scenarios for each of the farms are presented in Fig. 8. The simulated pasture growth for the baseline scenario is within expected ranges for the species for this site, reflecting previous validation work carried out for the WFM as described in section 5.2.1.

While the impact of climate change was negative for most farms and regions under the scenarios tested, particularly in the North Island, there were clear differences both between farms and between the two climate scenarios. Under the B1 scenario, there was a more negative impact for the North Island farms than under the A2 scenario.

The strong regional variation in the severity of the impacts, influenced by local geography and weather patterns, is supported by previous New Zealand research on potential changes in pasture growth (e.g. Clark et al., 2001; Wratt et al., 2008; Zhang et al., 2007). It is also consistent with the variability observed in comparable work on the impacts of climate change in temperate areas of Australia which suggests that pasture-based production systems can likely continue as the basis of the dairy industry in some areas of Australia, but may require changes in some regions (Cullen and Eckard, 2011; Phelan et al., 2014).

For both the Northland and BOP farms, there was a projected decrease in pasture growth rate during the middle of the milking season (Nov-Jan). For the Northland farm, pasture growth is negative during the month of January due to senescence which is built into the WFM (Romera et al., 2009). Lower rainfall is a clear driver. However, higher temperatures in the summer months may also be impacting pasture growth in the upper North Island farms (Northland, BOP and Waikato), as cool-temperate C3 pasture species such as ryegrass generally have an optimum temperature range between 20 and 25°C (Lee et al, 2013).

For both the Northland and BOP farms, the drop in pasture growth occurred earlier in the A2 scenario and slightly later in the season for the B1 scenario. For the Northland farm, this was followed by an increase in autumn growth (March-April). The pattern was mirrored less dramatically for the Taranaki and Waikato farms, with an increase in March growth for the A2 scenario. Pasture growth rates

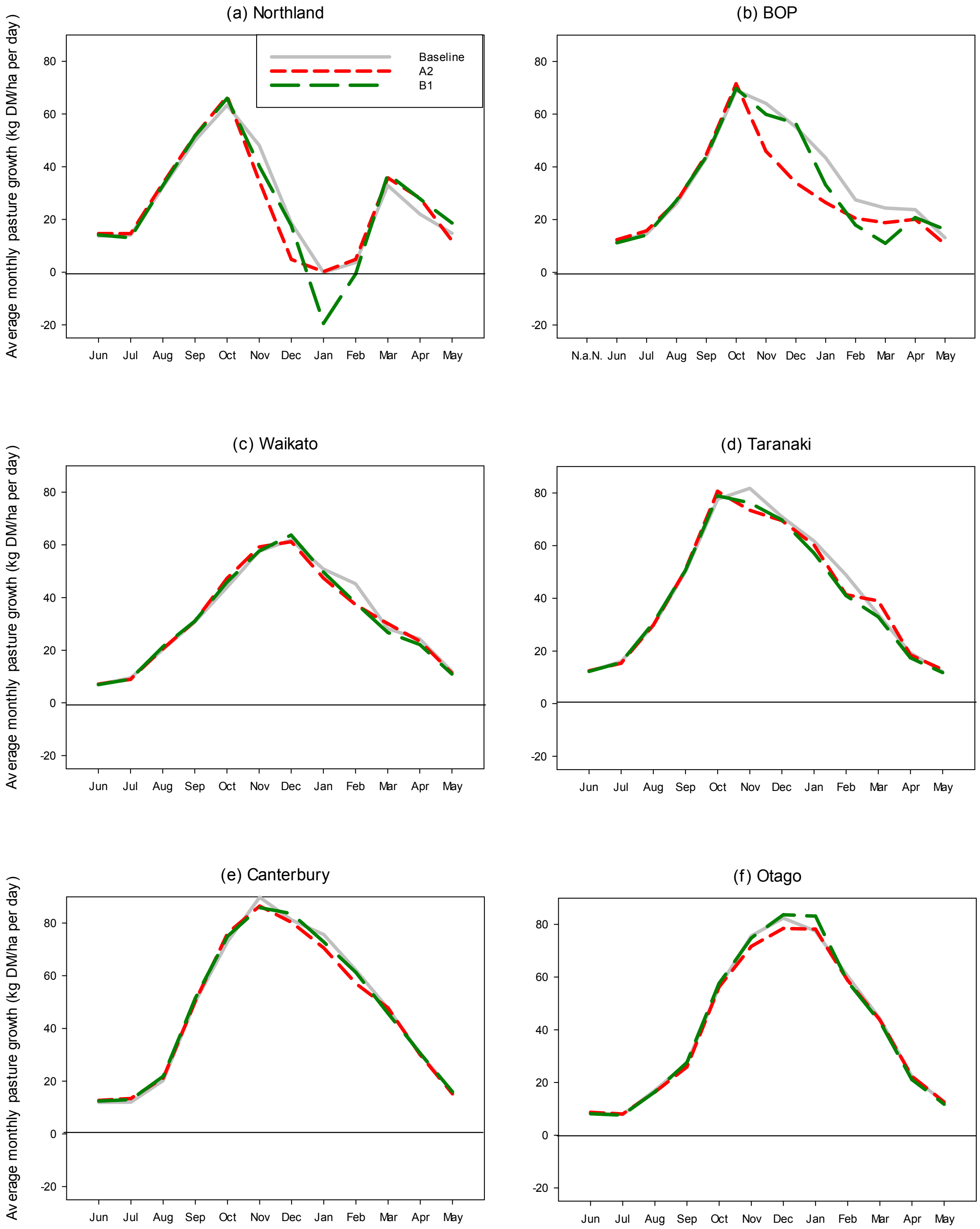
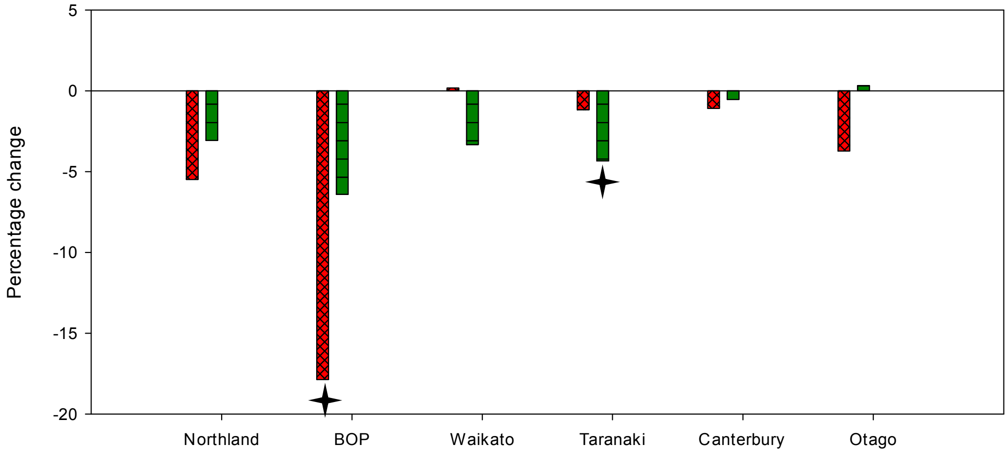
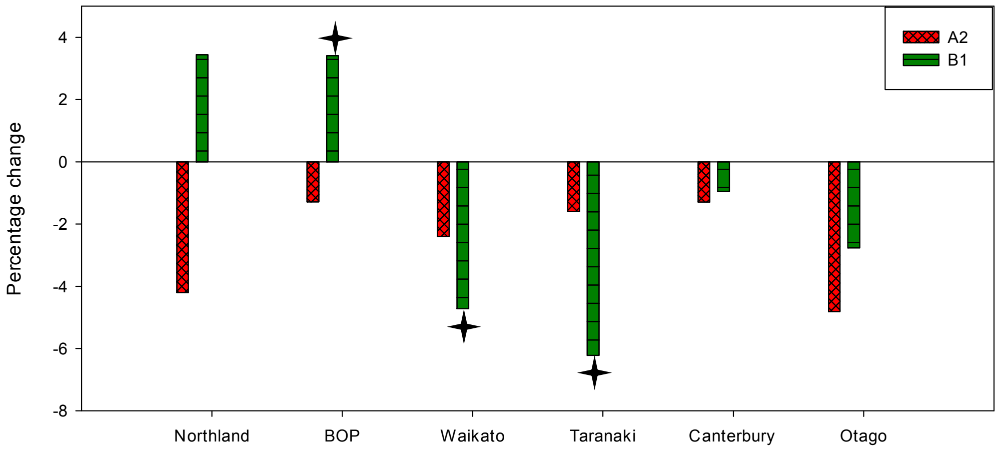


Figure 8: Average monthly pasture growth for the baseline (1980-2000) and future (2030-2050) A2 and B1 climate scenarios, for the six farm sites.

(a) Pasture



(b) Milksolids



(c) Operating profit

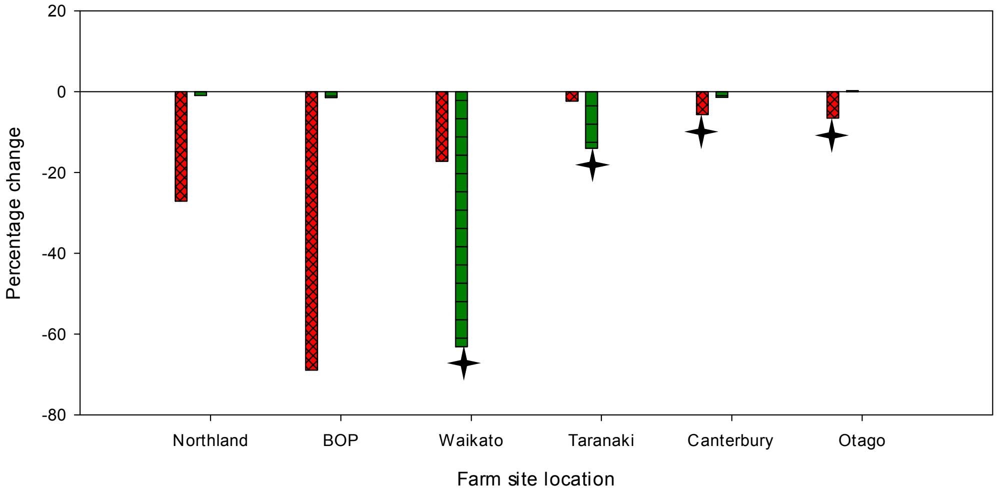


Figure 9: Projected percentage change for (a) average annual pasture yield; (b) total annual milksolids production; and (c) operating profit between the baseline (1980-2000) and future (2030-2050) for the A2and B1 climate scenarios for the six farm sites. Significant differences from the baseline (p=0.05) are shown with stars.

appear to be less affected in both South Island farms, but there were differences between the two scenarios.

These monthly changes in pasture growth, presented as kgDM/ha per day, can be contrasted with the average change in annual pasture yield as a percentage change, presented in Fig. 9 (a). Figure 9 shows the impact of the two climate scenarios as percentage change from the baseline (1980-2000) for three key indicators for each farm: pasture yield, milksolids production and operating profit.

Statistical comparisons between past and future pasture yield, milk production and operating profit produced different and often counterintuitive results depending on the region and also on the relative variability of the three indicators from year to year. For example, in the BOP, pasture growth was significantly reduced under the A2 scenario. However, the large observed decrease in average operating profit is not statistically significant according to the test applied (two-tailed t-test with heterogeneity of variance). This is a result of the large increase in the underlying variance in the future scenario and highlights the need to interpret statistical tests with caution, particularly in the context climate impact assessment. It is important to note that the statistical test used here is for diagnosing significant changes to the mean, rather than the underlying variance structure of the data. In this case, where there was a large increase in variance, this statistical test may not be an appropriate diagnostic tool.

Likewise, while the decrease in annual pasture growth for the Waikato farm under the B1 scenario was not significant, the decrease in operating profit for the whole farm was significant. For the two South Island farms, the reduction in operating profit was significant despite the fact that the reduction in annual pasture growth was minimal compared to some of the North Island farms.

In terms of operating profit, the A2 scenario had a particularly strong impact on the Northland, BOP and Waikato farms, while the B1 scenario had a large impact on the Waikato farm and to a lesser extent, the Taranaki farm. The negative impact on the South Island farms was much less marked.

Impacts on the different indicators (pasture yield, milk production and operating profit) of the system performance were often complex and in many instances depended on timing. In addition, although the six case study farms were selected on the basis of being of average size and intensity for their regions, they exhibited a diverse range of approaches and management practices, reflecting the local climate and resources available, as well as the personal management choices of the farmers. For example, the fact that pasture growth rates were less affected in both South Island farms reflects both the smaller change in rainfall patterns and the fact that the Canterbury farm is irrigated, smoothing any climate-related changes.

Predicted changes in annual pasture yield (Fig. 9) and particularly seasonal pasture growth rates (Fig. 8) were more evident for Northland and the Bay of Plenty, especially under the A2 scenario (Fig. 8), and these changes were important contributors to changes in milk production and operating profit. For the Northland farm, under current management in the B1 climate scenario, the feed gap resulting from reduced pasture growth rates in the middle of the season was compensated for by supplement feeding. The need for additional bought-in supplementary feed was balanced by the increase in autumn pasture growth, which effectively extended the milking season and resulted in no overall change in operating profit. In the A2 scenario, pasture growth rates decreased towards the end of the season; cows were dried off earlier, less milk was produced and operating profit decreased (Fig. 9).

For the BOP farm, the overall decrease in pasture growth under the B1 scenario was compensated for, to some degree, by an increase in early summer growth, and the feed gap in late summer was filled with surplus pasture from the early summer months, made into silage. Combined with a slightly longer milking season due to the slight autumn increase, overall higher milk production meant that there was only a small decrease in average operating profit.

Responses to potential changes in growing conditions under climate change scenarios varied for different pasture and crop species. This was highlighted in the case of the Waikato farm, where maize is an important component of the existing farming system. Under the B1 climate scenario, less maize was grown (approximately 1400 kg DM/ha less on average) due to seasonal effects. This was strongly reflected in the lower operating profit. In the A2 scenario, maize yield increased under the A2 scenario by approximately 1300 kg DM/ha, largely because of its high water use efficiency (Neal et al., 2006), providing more feed even though pasture yield did not increase overall.

Maize production can play an important role in improving stability of a farming system under more variable rainfall (Fariña et al., 2013), and this is also consistent with a Tasmanian study that showed different reactions to climatic changes in rainfed pastoral and wheat crop systems. These results further highlight the need to ensure the availability of appropriate crop varieties for different sets of conditions, a "basket of options" with e.g., crops suited to different harvesting and sowing dates (Phelan et al., 2014).

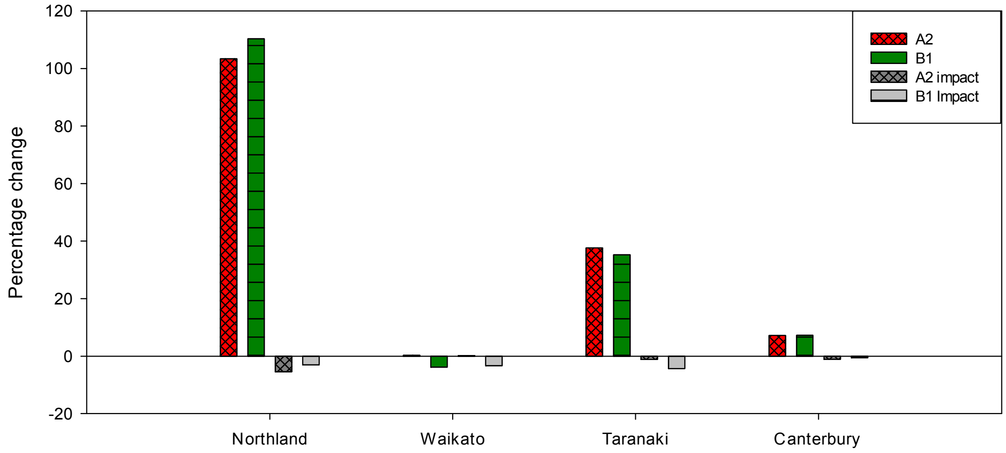
5.3.3 Tactical adaptation

The simple tactical adaptation tested, of making and feeding out more grass silage, was shown to mitigate effectively the impacts of climate variability in most cases (Fig. 10). This supports the conclusion of Dynes et al. (2010) that positive outcomes may be achieved under climate change scenarios using management strategies that are already well known and readily available to farmers.

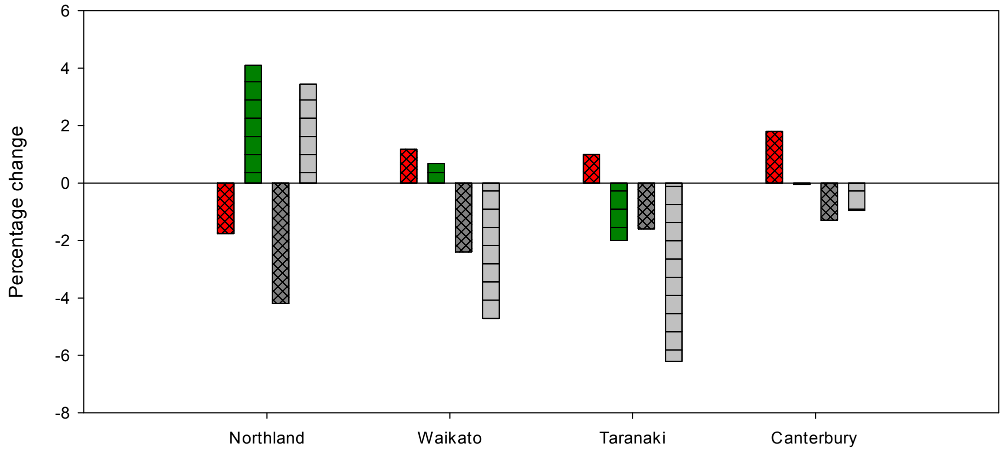
This adaptation consisted of increasing grass silage making on the main milking platform and feeding grass silage to all cows as required all year. Only four of the six farms were tested for this adaptation, since the BOP and Otago farms already made silage on the milking platform. This strategy had a positive impact on all four farms tested when compared with the impact of climate change under current management (Fig. 9). The strategy also nearly compensated for changes in the seasonal variation and variability in pasture growth for all scenarios. In most cases, operating profit was equal to or higher than the baseline scenarios.

For the Northland farm the effects were particularly pronounced, with a 150% increase in average operating profit for the A2 scenario and over 200% increase under the B1 scenario, mainly because silage making in the model reduces average farm covers and this promotes pasture growth and annual yield.

(a) Pasture growth



(b) Milksolids



(c) Operating profit

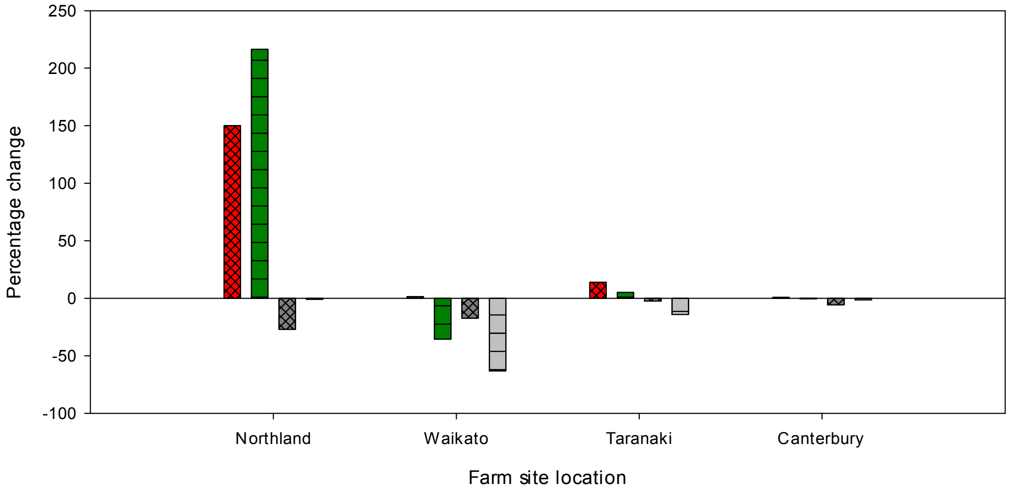


Figure 10: Projected percentage change in (a) average annual pasture yield; (b) total annual milksolids production and (c) operating profit between the baseline (1980-2000) under current management and future (2030-2050) *with the tactical adaptation (increased silage making)* for the A2 and B1 scenarios for the four farm sites tested. Impact under current management (see Fig. 9) is presented in grey for comparison.

However, a number of management issues should also be considered in the context of silage making as a tactical adaptation. While the cost of silage making was included in the model, considerable labour and energy inputs are required and considerations such as the availability of staff and machinery, as well as slope may also play a role in determining whether such options are practical for a particular farm. In considering the practical application of this tactical adaptation, different silage making technologies and their relative benefits (including how long it can be kept in storage without losing quality), costs (including energy) and workload need to be considered.

5.3.4 Strategic adaptations

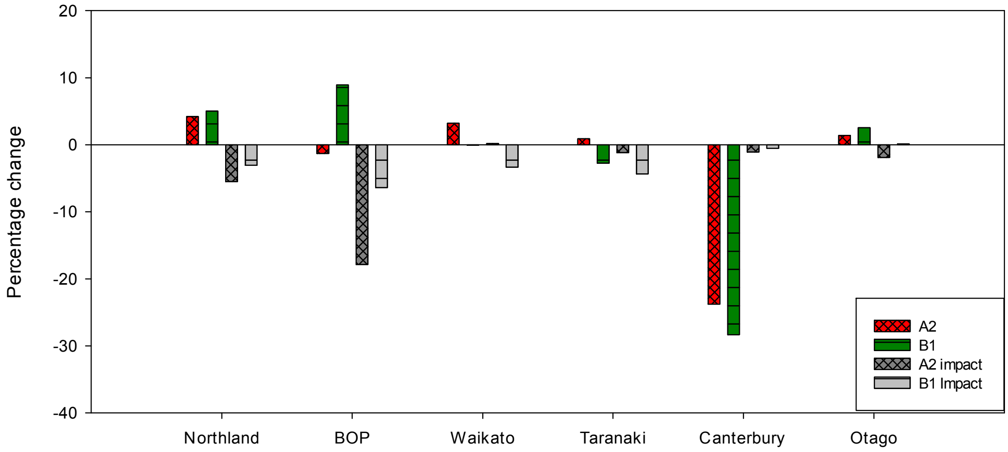
5.3.4.1 Irrigation

Irrigation as an adaptation option had an overall positive effect, particularly for the Northland, BOP and Waikato farms, which otherwise showed the greatest increases in year-to-year variability in operating profit under the climate change scenarios. For the Northland, BOP and Otago farms it more than compensated for the negative impact of climate change under both scenarios (Fig. 11).

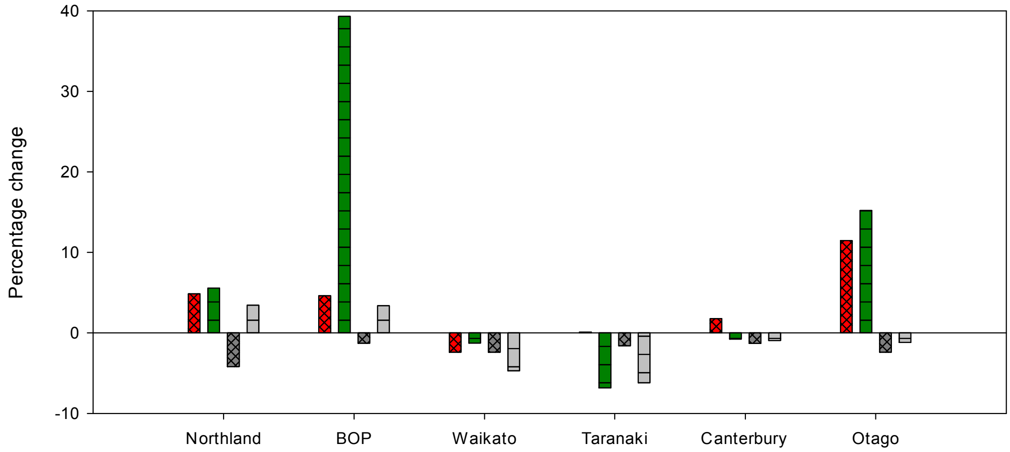
Removal of irrigation for the Canterbury farm had a strongly negative effect, although production of milksolids was maintained at a high level as the system is set up to buy in supplementary feed. This effect may also have been underestimated due to the setup of the model, as it was only possible to make the model irrigate around half of the amount of water indicated by the farmer for the 2010-11 calibration year, before the modelled soil became pugged and started producing less pasture. While the model setup reflected the correct soil type, in reality, soils of the same name can vary considerably. Further communication with the farmer indicated that the soil on the Canterbury farm was more free-draining than that represented in the model, implying the irrigation effects would be even more pronounced on the real farm.

While operational costs for irrigation are accounted for in the WFM model, capital (setup) costs for irrigation were not included. Consideration of irrigation as an adaptation option clearly also needs to include water availability and this may

(a) Pasture



(b) Milksolids



(c) Operating profit

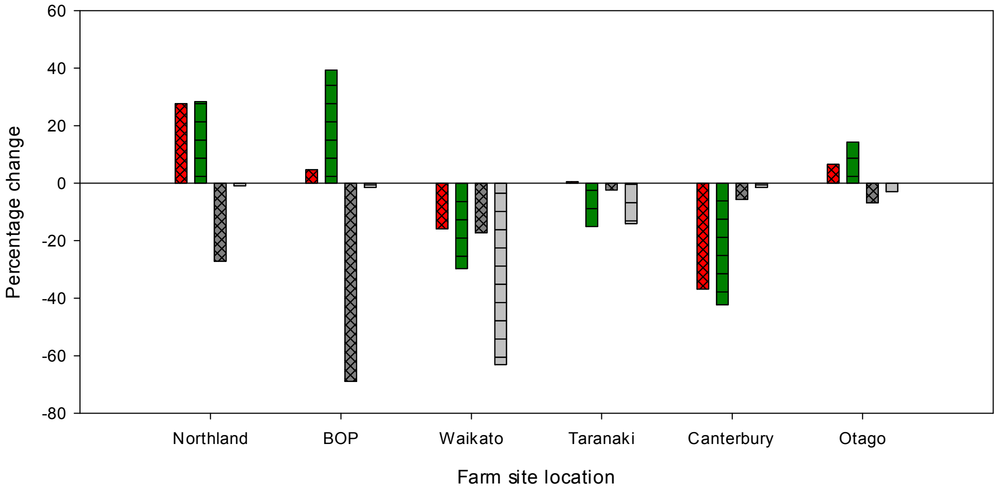


Figure 11: Projected percentage change in the three key indicators between the baseline (1980-2000) under current management and future (2030-2050) *with irrigation* for the A2 and B1 climate scenarios for the six farm sites. Impact under current management (see Fig. 9) is presented in grey for comparison.

decrease under climate change scenarios (Clark and Tait, 2008). In New Zealand, increasing regulation of water resources is also a potential limitation to the expansion of irrigation (Memon and Skelton, 2007).

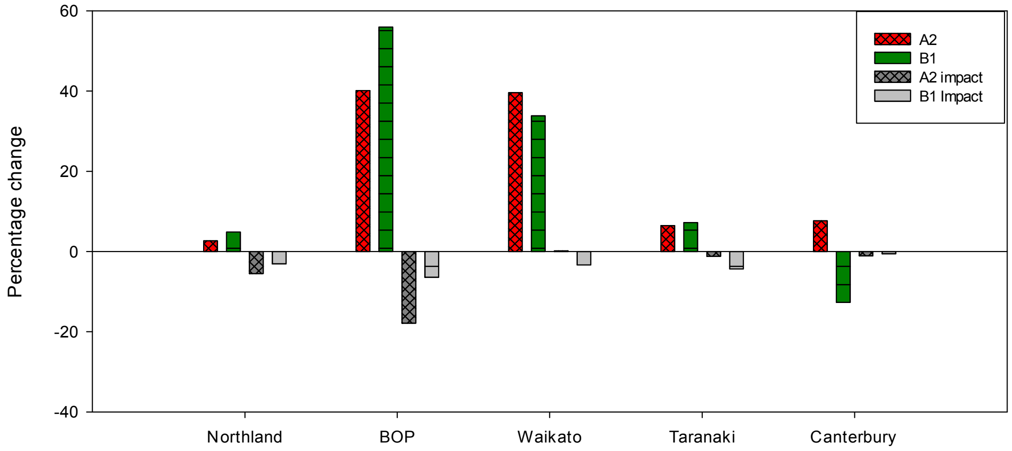
Full irrigation is a major investment, and topography can be a limiting factor to large scale irrigation systems. Most of the farms already irrigate some effluent, and extension of small mobile irrigation options may be a more flexible and viable option for many farmers. Such decisions will be individual and need to be balanced with consideration of labour and water use efficiency.

Irrigation is a potential adaptation to climate change, but can also be a source of vulnerability. In Australia, Cullen et al. (2008) found that irrigation requirement increased under climate change scenarios in areas where the water resource was already limiting, such as the northern Victorian dairying region. Higher water requirements, and reduced water availability in dry seasons, are placing pressure on dairy systems to improve water use efficiency (Lawson et al., 2009).

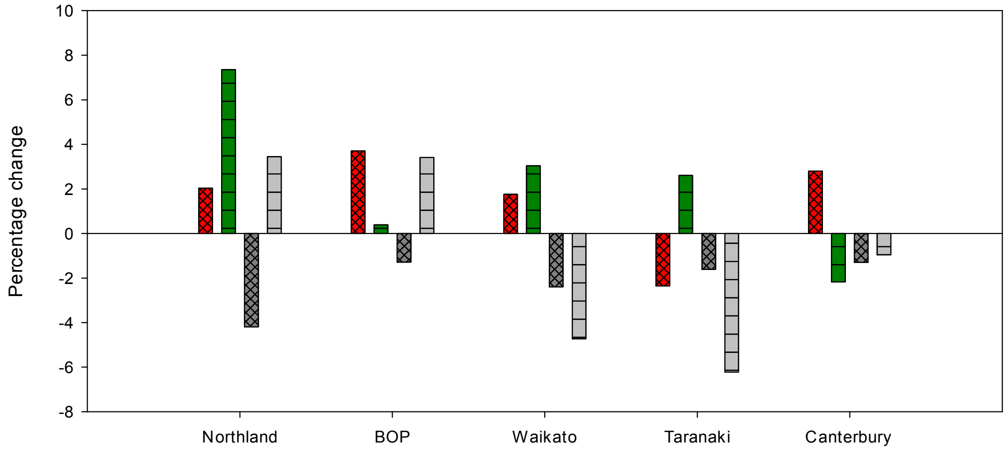
5.3.4.2 Pasture species

The change of pasture species to the deeper rooting tall fescue had a positive impact on pasture production and operating profit for all the farms modelled, compared to ryegrass. It changed the picture under climate change to a strongly positive one for the North Island farms (Fig. 12). Figure 13 shows monthly growth rates for tall fescue for the five farms tested, compared with the baseline under ryegrass. The increased pasture growth is clearly evident in summer for the BOP and Waikato farms, whereas it is more apparent in spring for the Northland and Taranaki farms (Fig. 13). In Canterbury, the comparison is for ryegrass with irrigation, compared with unirrigated tall fescue under the climate change scenarios. Increased spring growth is apparent for both scenarios even without irrigation. However, the B1 scenario still shows a large decrease in the summer months. For the A2 scenario, pasture growth appears competitive with the irrigated ryegrass in the summer, with a slight increase in autumn (Fig. 13). In Canterbury, under unirrigated tall fescue, pasture production still increased under the A2 scenario, suggesting that alternative pasture species may offer potential to reduce dependence on irrigation.

(a) Pasture



(b) Milksolids



(c) Operating profit

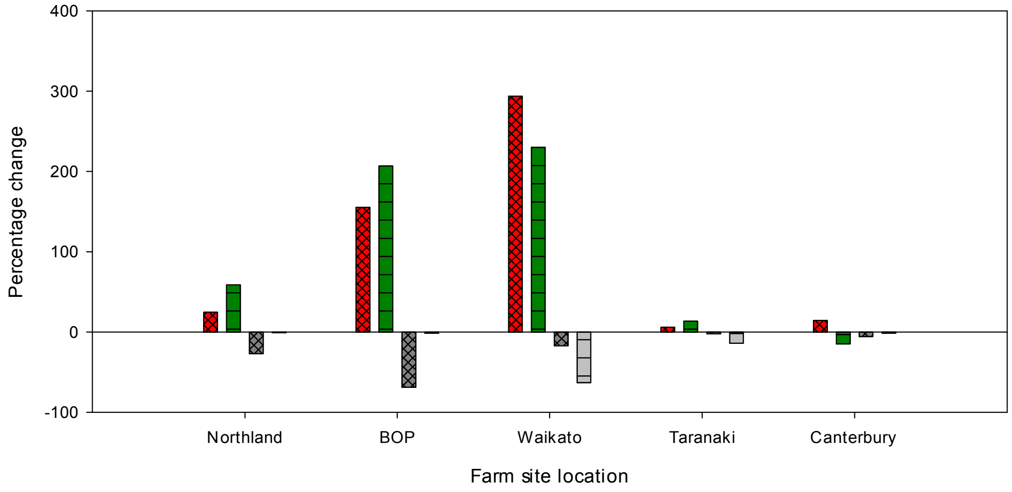


Figure 12: Projected percentage change in the three key indicators between the baseline (1980-2000) under current management and future (2030-2050) *with a different pasture species (tall fescue)* for the A2 and B1 climate scenarios for the six farm sites. Irrigation was removed for the Canterbury farm. Impact under current management with ryegrass (see Fig. 9) is presented in grey for comparison.

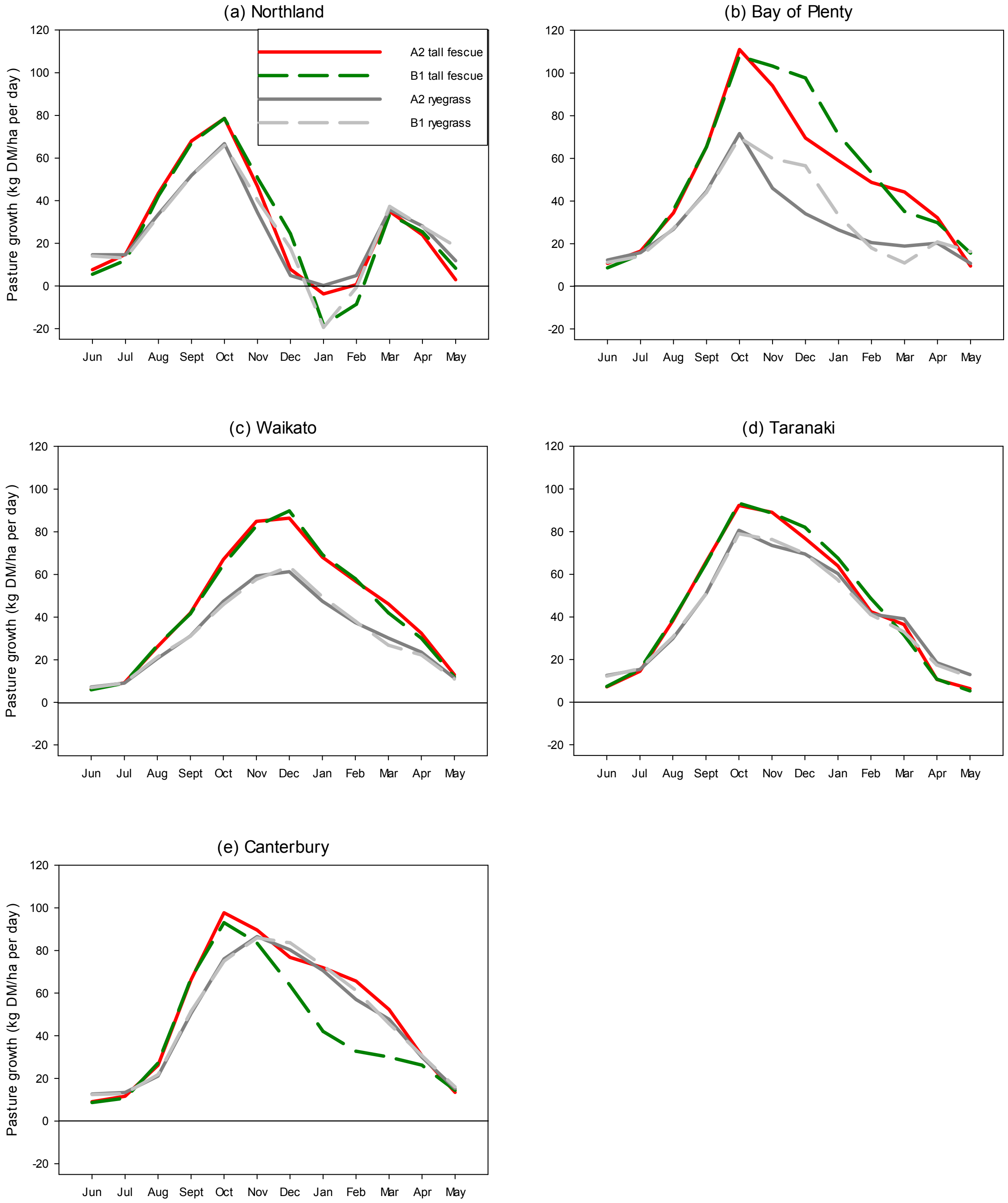


Figure 13: Pasture growth for the future (2030-2050) A2 and B1 climate scenarios on the six farm sites *with a different pasture species (tall fescue)*. Irrigation was removed on the Canterbury farm. Impact under current management with ryegrass (see Fig. 8) is presented in grey for comparison.

New Zealand's pasture breeding programmes have traditionally focussed heavily on ryegrass but the use of tall fescue has been increasing (Easton et al., 1994; Williams et al., 2007) and it is being grown successfully in many parts of New Zealand. Its more efficient use of water and tolerance to both drought and waterlogging (Reed, 1996; Turner et al., 2012) may prove to be assets in the climate change context in a range of environments. In addition, tall fescue grows better in warmer climates than ryegrass, with an optimum temperature of around 25°C (Robson, 1972). This may have been a factor in the upper North Island farms (Northland, BOP and Waikato) where average maximum summer temperatures are close to or above the optimal temperature range for ryegrass growth.

However, there are management challenges associated with this pasture species that reduce its popularity with farmers (Easton et al., 1994). In particular, while the digestibility of tall fescue compares well with other pasture species, if left unchecked it can lose quality much more quickly than ryegrass (Easton et al., 1994) and differences in pasture yield are not always reflected in milk yield if feed is of lower quality (Easton et al., 1994). The modelled tall fescue did not account for differences in quality compared to ryegrass. Tall fescue also requires careful management during establishment and can be much slower to establish than ryegrass, as well as being less competitive in a mixed sward (Easton et al., 1994). Further research is warranted on ways to reduce management challenges, either through further development of the species or by building the knowledge and capacity available to manage it effectively.

There is a growing interest in the use of pasture species other than perennial ryegrass (Turner et al., 2012) from both researchers and farmers. The relative value of alternative pasture species and/or mixes (e.g. cocksfoot, phalaris, annual ryegrass, kikuyu, prairie grass, lucerne, chicory and plantain) may increase under climate change, as factors such as water use efficiency, drought and heat tolerance and response to elevated atmospheric CO_2 are likely to become more important (Lee at al., 2013).

5.3.4.3 Reduced stocking rate

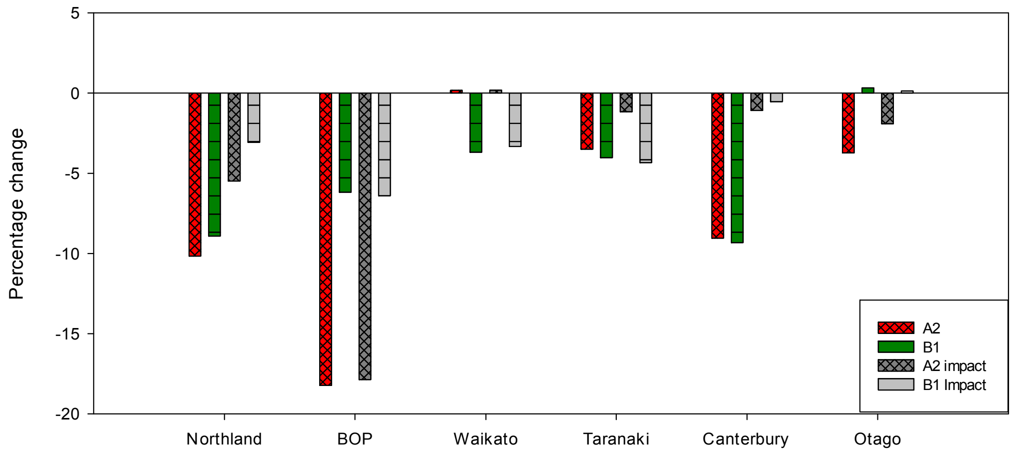
Modelled stocking rates were reduced by approximately 15% for each farm. This had a negative effect on all three indicators for the North Island farms and Canterbury. In Otago, although milk production decreased, there was little effect on operating profit (Fig. 14). Compared with the no-adaptation future scenario, profit reductions were small for the B1 scenario on the Taranaki farm, and for both scenarios in the Waikato and Otago.

The relative profitability and environmental impacts of dairying under different system intensities are heavily debated issues, both of which are highly relevant in the climate change context. While Dynes et al. (2010) included increased stocking rates as part of their adaptation package to mitigate the economic effects of climate change; Zhang et al. (2007) suggested adjusting stocking rate to match changes in annual feed supply as a good management practice.

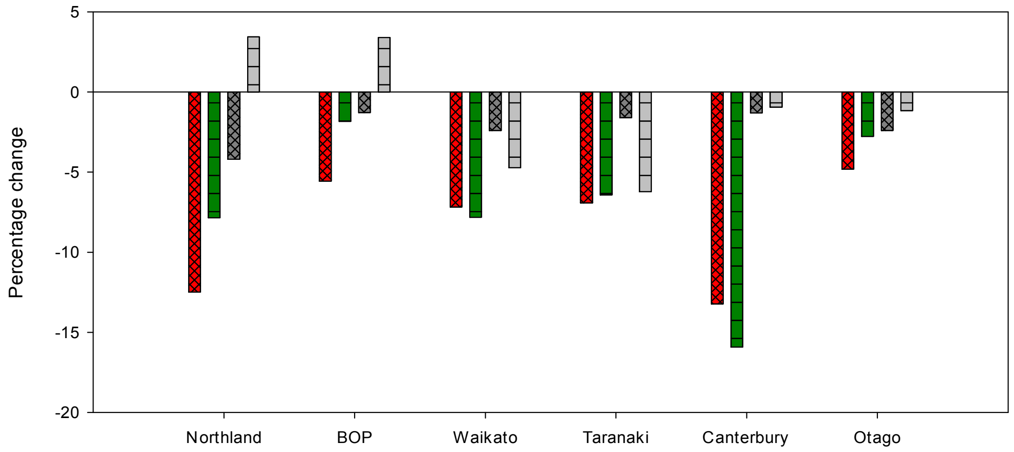
This modelling exercise suggests that a blanket recommendation to reduce stocking rates under climate change scenarios is not economically feasible. This corresponds well with a recent modelling study (Romera and Doole, 2014) showing that decreasing stocking rates will in most cases come at the cost of both production and profit.

For the purpose of a more controlled comparison, cows were “culled” randomly in this study. However, when farmers reduce their herd size in practice, they would not cull cows randomly but rather cull the lowest producing cows, and are likely to do so in small increments until the most profitable stocking rate is achieved. Ideal stocking rates depend on a range of factors such as the body weight of the cows, the potential of the land to produce pasture, and the amount of supplement purchased (MacDonald et al., 2008). For some farms and scenarios, a reduction in stocking rate did not significantly affect profitability. The question of stocking rates therefore needs to be approached on a farm-by-farm basis. In addition, environmental concerns and climate change are only one of a number of increasing pressures on dairying systems in New Zealand (Clark et al., 2007).

(a) Pasture



(b) Milksolids



(c) Operating profit

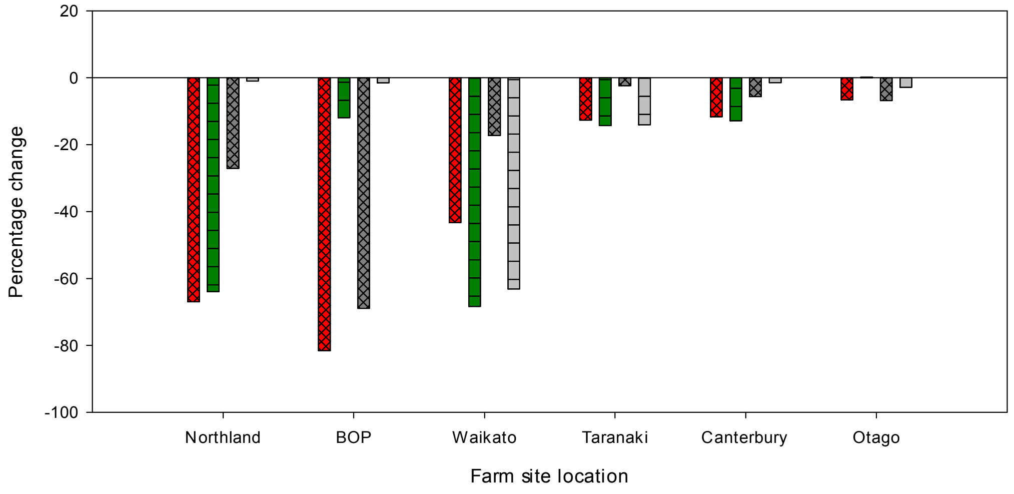


Figure 14: Projected percentage change in the three key indicators between the baseline (1980-2000) under current management and future (2030-2050) with a reduced stocking rate (by 15%) for the A2 and B1 climate scenarios for the six farm sites. Impact under current management (see Fig. 9) is presented in grey for comparison.

5.3.5 Variability in operating profit

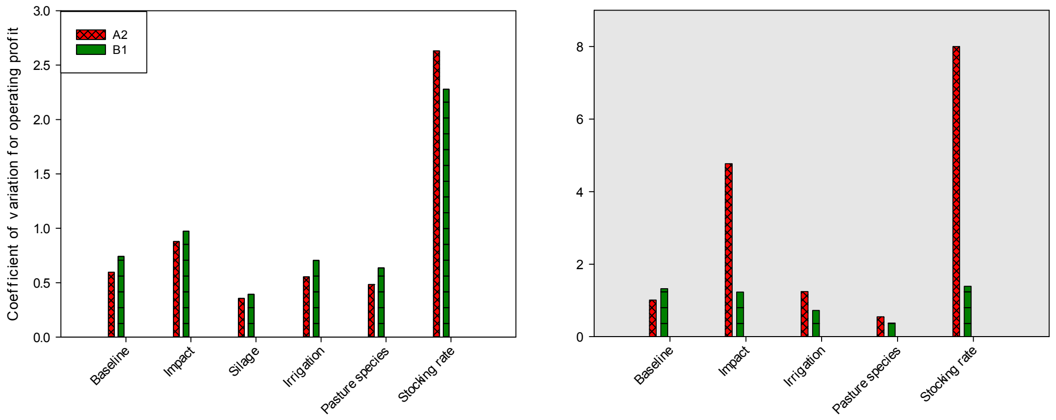
Figure 15 shows the coefficient of variation for operating profit for the baseline, impact and the four adaptation options. The Northland, BOP and Waikato farms have a much higher degree of variability in operating profit than the other farms. For these three North Island farms, variability increased under both climate change scenarios. A reduction in stocking rate also resulted in a large increase in the variability in operating profit. However, the change in pasture species and addition of irrigation reduced the variability generated by the impact of climate change. There was much less variability in operating profit for the Taranaki and South Island farms, although variability increased on the Canterbury farm when irrigation was removed for both the "no irrigation" and the changed pasture species adaptations.

Variability in profit can have a major impact on whether a farm is likely to be viable under future climate change scenarios. Irrigation effectively removes some of the variability in pasture growth, and the change in pasture species had a similar effect because of the improved capacity of tall fescue to cope with moisture stress. The increased variability in operating profit under a lower stocking rate for the Northland and BOP farms was an unexpected result. However, the stocking rate for these two farms was low to start with. Randomly decreasing the stocking rate further, effectively removes some of the economic buffering effect provided by greater cow numbers.

5.3.6 Farmer response to modelled climate projections and adaptations

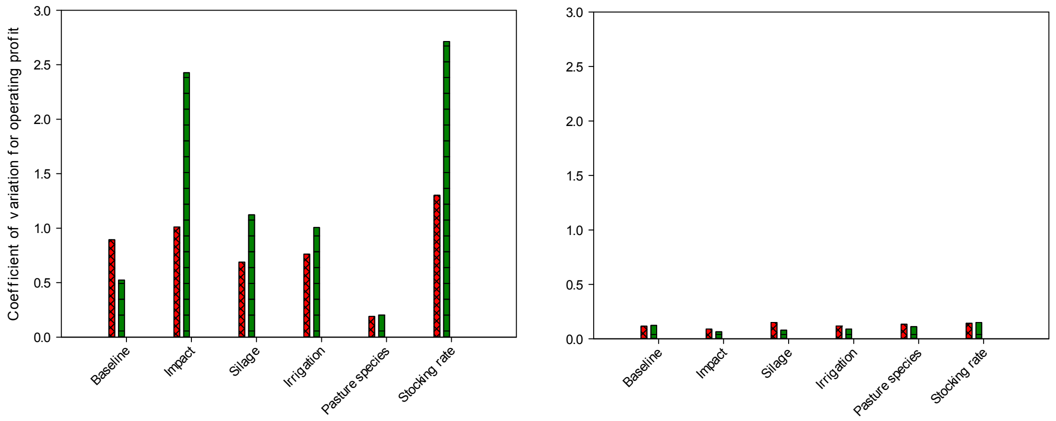
When presented with the specific climate projections for their farms, the reaction of all the farmers was first to ask a series of questions, and as soon as they fully understood the projections, to start discussing the particular challenges and what changes they would make to their systems, mostly in terms of the feed available. The projected impacts varied by region, with the North Island farms the most negatively impacted.

The farmers paid particular attention to the seasonal impacts on pasture production, identifying potential feed gaps and considering different ways to fill



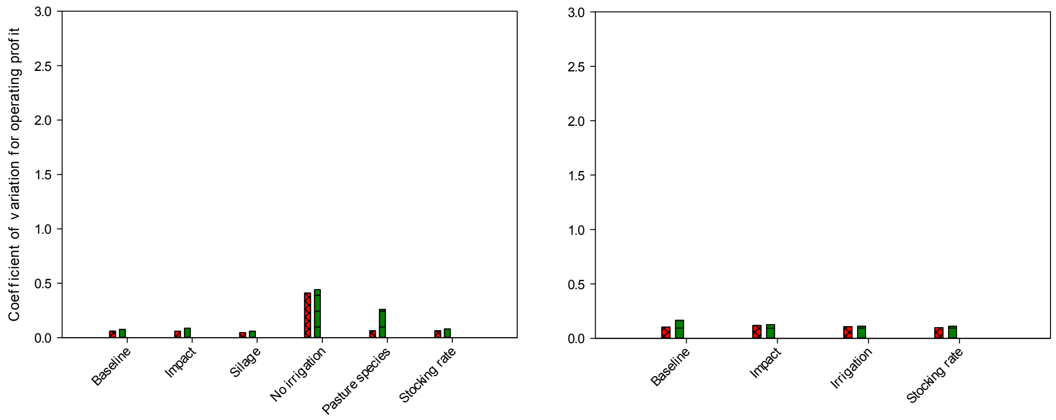
(a) Northland

(b) BOP



(c) Waikato

(d) Taranaki



(e) Canterbury

(f) Otago

Figure 15: Coefficient of variation for the baseline (1980-2000) and future impact under current management (2030-2050) and the four adaptation options for the six farm sites. The BOP site is presented on a different scale to the other five farm sites.

them. Generally, they indicated that the projections based on average changes were of less value than indications of likely variability, and that they would like more information about potential changes in extremes, which were not analysed in this study. All were generally confident in their capacity to cope with the changes as presented, which were shown as average percentage change in pasture yield, milk production, and profit, from the baseline:

> We have so much variability that we wouldn't notice those differences… Well it won't change my behaviours. It might change some – people who run on the knife-edge all the time…will probably have more problems.

However, there was considerable concern and some discussion around potential impacts from climate change that were not able to be represented in the model. In this context, pests, weeds and diseases were discussed with increased concern. The farmers particularly mentioned a potential increase in facial eczema, the potential for new pests, and ingression from more weedy grass species as issues of concern. Other pasture management issues were also raised – for example, whether the balance of other pasture species would be altered by CO_2 fertilisation effects, especially clover- and the potentially increasing importance of kikuyu grass in the Northland system, as it grows well after drought.

A summary of farmer responses to the adaptation options tested is presented in Table 6. The first adaptation was a tactical adaptation of making surplus grass into silage more often, and feeding grass silage to demand all year. This had a strongly positive effect on both pasture growth and operating profit for most of the farms modelled as it effectively provided more control over feed supply. The farmers were interested, but questioned the model's results for the silage making.

There was a clear discrepancy for this adaptation between the results produced by the model, and what the farmers thought was possible. They were open minded about the idea, but wanted to know how the practice would result in more grass overall, as the model suggested, and in most cases assumed that this would require the addition of more nitrogen fertiliser.

The WFM carries out silage-making in a highly optimised way. In the modelled scenarios, some paddocks were put aside as "conservation paddocks" and grass was always cut when it reached a certain level, keeping the pasture in an earlier and more productive growth phase. This may be unrealistic in the context of managing a complex farming system. In addition, although a calculation is included for the cost of the silage making, the model is unable to account for issues like whether contractors are available.

Table 6: Farmer's assessment of modelled adaptation options.

Adaptation option	Recognised limitations	Farmer perspective
Silage making	- Only four farms tested, since BOP and Otago were already making silage on the milking platform - 'Ideal' modelled setup, grass is cut whenever it reaches a particular biomass - Kikuyu could not be modelled on Northland farm (unavailable in model)	- Validity of modelled results questioned - Pasture would require more N fertiliser to grow as shown in the model - Interest in knowing more.
Stocking rate reduction	- Blanket reduction of 15%	- Would cull poor performing cows, not carry out a blanket reduction - Despite negative economic results, continuing interest in finding ideal stocking rate - Active resistance by some farmers to pressure of intensifying; others were already planning to invest in more infrastructure and more stock.
Irrigation	- Setup/capital costs not included in the model	- Many already irrigating effluent - Northland, Waikato and BOP farmers had considered the option and decided benefits were marginal. Setup costs were a significant barrier - Otago farmer still weighing up the option, but drainage considered more important than irrigation - Impact of large irrigation: removal of trees for large pivots reduces available shelter - Terrain a limiting factor in Northland - Large difference between scenarios adds to uncertainty - Energy consumption a consideration
Change pasture species to tall fescue	- Feed quality difference not accounted for - Not run for Otago farm	- Positive but cautious about establishment, quality and palatability issues - Management a challenge – need to top (cut) pasture to maintain quality - Not sure staff would have right skills to manage it - Positive: clover friendly - Risk of loss of quality, less palatable for stock - Otago farmer suggested the change to tall fescue was worth considering in the region; it grows well in wet conditions and had been taken up by a neighbouring farm.

The exercise has highlighted a discrepancy in the understanding of these farmers and the researchers involved. For researchers, consideration needs to be given to the capacity of the WFM to simulate silage making in a more realistic fashion. For farmers, it implies that there may be scope for further extension on the potential benefits of increasing silage making, in particular relating to a more in-depth understanding of pasture growth phases.

Regarding the irrigation adaptation, the results were quite well in line with farmer's observations that while it may provide some benefits, it was likely not worth the capital investment for most of the farms at present. A further trade-off was highlighted in the fact that in order to install large centre pivot irrigation systems, trees would need to be removed. For the Northland farm, the hills and the fact that most of the steeper slopes were planted in trees would make such an irrigation system highly impractical.

As with the silage-making adaptation, the farmers were reserved about the highly positive results shown in the modelling exercise for tall fescue. However, they were clear in recognising that dependence on only ryegrass represented a source of vulnerability in their farming systems:

> You need an alternative to ryegrass I believe – because if ryegrass gets wiped out with a new mealy bug or a fungus or something because of the change of climate… plant breeding is so slow that by the time that we found a cultivar that was resistant or more tolerant, you would have lost a heap of potential production. With another species like fescue…if you've got the right cultivar, you could leap-frog that… you actually bypass the pest with a species that can already handle it rather than trying to breed up a ryegrass that would perform under that challenge.

The modelled adaptation of a switch to tall fescue sparked further discussion on pasture quality and persistence. In some cases, farmers expressed frustration and a sense of powerlessness about the cultivars they were delivered by seed companies, suggesting that it was hard to choose the right grass for their specific climate and environment:

> (They) try to sell us stuff that was not for our climate …they just say… you've got to experiment… we say we don't want to experiment that's what we pay research for! …an example: [name of cultivar] …very good under irrigation, it's very good up under the mountain but anywhere else it's no good and over the first two years a lot was planted…from the coast right through … it's taken three, sometimes three regressing exercises to fix one mistake…

The challenge of appropriate cultivar selection for a particular environment is recognised in the NZ dairy industry (Clark, 2011) and recently, DairyNZ has developed a new Forage Value Index (FVI)[7] to assist farmers in choosing appropriate cultivars for their area. However, it is unlikely that the current range of the FVI (ryegrass-only cultivars and four regions) will be specific enough to address the problems identified above. The FVI has been developed along the lines of the Cow Indices for animal genetics[8]. However, the highly soil- and climate specific nature of pasture growth implies that new approaches may need to be considered for pasture evaluation, which incorporate a higher level of local (farmer) knowledge.

5.3.7 Limitations of the study

As with all modelling studies, this research was limited by the capacity of the model. The ability of the model to accurately represent a particular farming system will vary depending on the particular challenges of the farm in question. The effects of the four adaptation options tested also depended on the scenario, the localised climate effects and current management practices. The Northland farm, for example, faces an ongoing struggle with the incursion of kikuyu, a C4 African grass species that is utilised as pasture in Australia, but considered undesirable in the New Zealand context as it is less productive than ryegrass. The Northland farmers therefore renovate their pastures regularly, which may limit the accuracy of modelling based on ryegrass only. For the Northland farm in particular, the tactical adaptation of making more grass silage and feeding this out to demand showed strongly positive results. However, the accuracy of these results may be limited by the fact that kikuyu could not currently be modelled in the WFM although it has a strong presence in the system. C4 species are likely to increase production (but reduce quality) with higher temperatures (Cullen et al., 2009; Dynes et al., 2010). Under climate change conditions kikuyu, as well as other C4 species that form a component of NZ pastures in drier areas, such as paspalum, may become even more competitive.

As described in the methods section, the effects of CO_2 fertilisation on pasture growth were not included in this study, mainly because the study was focused primarily on management adaptations. In addition, the challenge of accurately modelling these effects at the daily and monthly scale, for different climate

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[7] http://www.dairynz.co.nz/feed/cultivar-selection

[8] http://www.dairynz.co.nz/animal/animal-evaluation/interpreting-the-info/cow-indices/

scenarios, was beyond the scope of this study. However, these effects may be highly important in the climate change context and further research is required in order to accurately assess its implications at the daily and monthly scale relevant to farmers.

Many elements of the farm system may be beyond the scope of the model and yet contribute significantly to improving or reducing the system's resilience to climate change. For example, changes in soil quality or vegetation on the farm such as shelter belts. Biophysical models are generally limited in their ability to model inherent complexities of farming systems such as extreme events like frequencies of very high temperatures, systematic animal-mediated nutrient transfers, pests, weeds and gene-environment interactions (Newton et al., 2008; Snow et al., 2014) and do not address the capacity of the farmer to cope with adversity (Newton et al., 2008).

A more general conceptual challenge is the fact that farmers are constantly adapting their management practices. Setting up the model based on the current thinking and management practices of the farmer is a logical choice for this kind of study, but it does not represent the 'autonomous adjustment' that will take place in the farming system under future conditions. For example, under the current management practices of the Waikato farmer, total supplement feeding was limited so that increases or reductions in pasture production may have a greater impact on operating profit than on farms where the cows were fed to demand. In practice, however, it is highly likely that the farmer would further adapt his supplementary feeding policy to a greater degree under these climate scenarios.

5.4 Conclusions

The results of this study indicate that the impact of climate change on New Zealand dairy farms is likely to be highly location-specific, with the Northland and BOP regions most negatively affected. The adaptation options tested here showed that a great deal of potential exists in current technologies to compensate for the projected impacts of climate change in most New Zealand dairy systems, while still improving production and profitability.

This work particularly supports the call for further research on the potential advantages of tall fescue and other deep-rooting and drought-resistant pasture species, including improved parameterisation of the WFM for such species. Alternative pasture species may potentially provide an economic and practical alternative to the installation of large irrigation schemes, particularly in areas where the economic benefits of irrigation are marginal, or water resources are increasingly regulated.

This study has sought to mimic as closely as possible the specific challenges and management practices of actual working farms in an integrated farm systems model. This has enabled a closer examination of the relationship between location-specific impacts of climate change and context-specific management practices of the farm in question. It is concluded from this analysis that climate change impacts on New Zealand dairy farming systems are complex and will depend strongly on the setup and management practices of each farm, as different aspects of the farming system may be affected differently by climate changes. This is a positive finding, as it implies significant scope for adaptation to changes in climate. However, such adaptation will depend on the skills, experience, knowledge and financial capability of each farmer.

Currently, the management options available to test in the WFM are based on farming practices that are well known and currently practiced in New Zealand. In order to support farmers in areas that may be more severely affected by climate change, it may be necessary to broaden the scope of options available to them, for example by looking to climate analogues, e.g. in Australian dairy systems.

Any analysis of potential climate change adaptation also needs to be placed in the context of a broader perspective, which can include, for example, increasing energy and fertilizer costs, market and financial constraints, as well as environmental considerations. Failure to consider these broader issues may result in maladaptation - a positively motivated adaptation for one type of threat that may turn out to have negative consequences for another.

Modelling studies are a useful way to ‘pre-test’ adaptation strategies and form the basis for further analysis. Hypotheses generated by modelling studies can also contribute to raising awareness, as well as highlighting the potential efficacy of implementing adaptation options. However, it is important to consider these studies as one of several possible tools for the analysis of adaptation strategies together with farmers, taking into consideration the many practical elements of the farming system that are beyond the scope of the model.

This study has particularly highlighted the need to contextualise agricultural systems modelling under climate change scenarios. The modelled adaptations presented to the farmers provided a good basis for a highly context-specific discussion on the viability of different adaptations. However, they also highlighted some disconnects between the ways that researchers and farmers perceive risks and how to address them.

Most of the farmers expressed a sense of being ‘ahead of the game’ (Chapter 4) and there is some evidence to support this. In some cases, the adaptations suggested by these farmers were difficult to model, particularly suggestions for crops that were not parameterized for the WFM. The WFM’s capacity is based on tried and tested research. The development of each new component of the model requires a significant investment of time and capital, and less common strategies or crops are not easy to simulate. For a management technique or strategy to be recommended in the research/industry support context, it must have been thoroughly researched and this can take several years.

Farmers, conversely, have the freedom to experiment with whichever strategies they think may work. Where they have the resources, the information and the confidence to try new or different strategies, this represents a key contribution to innovation in the dairy industry that should not be overlooked. In such cases, these farms can be valuable partners and in some cases leaders of innovative research.

In order to support adaptation to climate change, there is a need to more formally recognize and promote the role of on-farm innovation, exchanges with farmers in other countries, and create an effective and dynamic feedback mechanism with the research sector. Forward thinking farmers with the capacity and confidence to experiment are an invaluable resource in driving the innovation that will be required to successfully and continuously adapt to climate change.

6 Scenarios of adaptation 2: Will incremental adjustments made by farmers be enough?

Abstract

Farming systems are by nature complex and highly diverse, and appropriate adaptation options under climate change will also be context specific. This study builds on the analysis in the previous chapter (Chapter 5) to explore the factors that will be important to the six case study farms as they adapt to a changing climate. Based on interviews with the farmers (see Chapter 4), as well as their response to the previous modelling analysis for their farms, context-specific adaptation options are modelled under selected downscaled climate change projections for three different climate scenarios. The suggestions made by farmers were predominantly incremental adaptations, which may reflect the farmer's positive assessment of the current level of resilience in their farming systems.

For the climate scenarios utilised in this chapter, although the impacts of climate change under current management were mostly negative, for some farms under some scenarios there was a positive impact. Modelling of these adaptations under present conditions and future climate projections showed that many of the adaptations did mitigate the negative impacts of climate change. However, when compared to the same adaptations carried out under the baseline climate, there was still a generally negative impact. This implies that while improving management practices according to farmers' current knowledge may mean that these farmers can stay in business, ongoing work and innovation will be required to optimise farming systems under future climate.

6.1 Introduction

While there is consensus among scientists that climate change is occurring and likely to affect agriculture, the effects at farm level are still highly uncertain. This is particularly the case in temperate regions such as New Zealand, where conditions for rainfed, pasture-based agriculture are currently still profitable in most areas.

Adaptation is a process of ongoing, continuous interaction between human and natural systems (Nelson, 2014). Climate change is only one of many factors affecting a particular system, and it is important to understand the interactions between climate and other influences. Even in farming systems that are often viewed as relatively homogeneous, such as New Zealand dairy farms, a wide range of farming practices are utilised depending on the physical, social, economic and regulatory environment, the worldview of the farmer, their personal capacity and the resources available to them (Chapter 4).

Early impact assessments that did not take into account any adaptation response from farmers were referred to as having a ‘dumb farmer’ approach (Füssel, 2007; Schneider et al., 2000), and those that considered adaptive responses were referred to as having a ‘smart farmer’ approach (Füssel, 2007; Kenny, 2011). While the early idealised modelled concept of a ‘smart farmer’ was a farmer who responded perfectly within the parameters of the modelled scenario, the concept is now used more broadly as a ‘practical smart farmer’ approach to apply to farmers who display a strong adaptive capacity (Kenny, 2011).

New Zealand dairy farmers have adapted to increasing market volatility by developing new skills and management practices to mitigate risks and capture opportunities (DairyNZ, 2014). This adaptive capacity may mean they are also well equipped to cope with increasing climatic volatility.

However, incremental adaptation has limits (Park et al., 2012) and there are concerns that it may reduce the incentive to carry out more costly, but more beneficial transformational changes to the system (Reisinger et al., 2014). Increasing variability under climate change has been identified as a potential obstacle to overcoming path dependency that is already locked in, because it tends to muddy the change signal (Chhetri et al., 2010).

This chapter represents a further step in an ongoing analysis of six dairy farms located in different regions of New Zealand, following the mixed methods framework outlined in Chapter 3 (Kalaugher et al., 2013). The results from Chapter 5 suggested that in many cases, tactical adjustments such as making and feeding out more pasture silage may be enough to minimise the impact of climate change for most of the scenarios analysed. However, discussions with farmers (Chapter 4; Chapter 5) highlighted the limitations of a 'one size fits all' approach, and the range of practical factors on which appropriate adaptation strategies will depend. Adaptation is ultimately constrained by local, even household level parameters and phenomena (Nelson et al., 2014) and appropriate adaptation options under climate change scenarios will therefore also be highly context specific and require an in-depth knowledge of the particular environment in which the farm operates (Nelson et al., 2014).

By modelling adaptation options suggested by farmers, this study seeks to analyse whether tactical adaptations suggested by these experienced farmers will be adequate to cope with a wider range of the downscaled projections most recently available from the National Institute of Water and Atmospheric Research, New Zealand. The adaptations tested in this study have been based on interviews carried out with the farmers (Chapter 4), taking into account the particular challenges of the region and specific farming system, the farmer's own goals, and specific suggestions made by the farmers themselves about ways in which they would potentially alter their systems to adapt to climate change.

6.2 Methods

As outlined in previous chapters, the six case study farms were selected from major dairying regions in New Zealand: Northland, Waikato, Bay of Plenty (BOP) and Taranaki in the North Island, and Canterbury and Otago in the South Island, covering a range of climatic zones with different anticipated responses to climate change. All of the case study farms were commercial farms, and the farmers were identified as experienced and successful by regional consultants and/or researchers.

While each of the farms was selected on the basis of being approximately average in farm size and cow numbers for their respective regions, they represented a diverse range of management approaches. For example, the Northland farm milks jersey cows once a day, and is run almost entirely by a husband and wife team; the Waikato farm grows a large amount of maize silage; and the Canterbury farm is fully irrigated. The farm set-up for each operation, and the goals and perspectives of the farmers, are described in greater detail in previous chapters (4 and 5).

For each of the case study farms, a model farm was created using the DairyNZ Whole Farm Model (WFM) (Beukes et al., 2011) to mimic as closely as possible the management practices and outputs of the farm being studied at 1/10th of the scale of their actual farms. Management policies were set up in the model to be flexible enough to cope with the baseline weather scenario by maintaining the farmers' usual tactical management practices (see Chapter 5).

Each farm was run for three 10 year periods for three climate scenarios (A2, A1B and B1) to form a baseline for the years 1971-2001. This was followed by three 10 year runs for the three climate scenarios (2030-2060) to provide an impact assessment with no adaptation.

The six farms were then run for the period 2030-2060 (three 10 year runs) for each adaptation (described in section 6.2.2) for the baseline and each of the three climate scenarios, using economic inputs from the 2010-11 year.

Finally, the impact assessment and the farm-specific tactical adaptations were re-run under the economic data from the year 2007-08, to provide an analysis of sensitivity to economic inputs.

6.2.1 Climate Projections

For the purpose of the present analysis, an updated set of climate projections was provided by the National Institute of Water and Atmospheric Research (NIWA). As with those used in the previous analysis (Chapter 5) these projections were based on the physical Regional Climate Model (PRECIS, RCM) nested in the HadAM3P Global Circulation Model (GCM), and meteorological fields were generated at an approximately 27km^2 resolution across New Zealand for the future climate scenarios.

In addition to the 'high' (A2) and 'low' (B1) CO_2 emissions scenarios utilized in the previous analysis (see Chapter 5), a 'middle of the road' (A1B) scenario was added for this study. The A1B scenario assumes very rapid economic growth with more balanced and diverse energy sources, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies.

Climate impact models place stringent demands on the resolution and accuracy of driving fields for realistic output (e.g. pasture growth, river runoff), which is unlikely to be satisfied by the RCM model results alone. Biases in modelled variables, in particular in temperature and precipitation RCM hindcasts, remain on regional to local scale due to the spatial resolution of the simulation and model errors (Ackerley et al., 2012; Sood, 2015). RCM hindcast data are therefore corrected by comparing them with observed data. In this case gridded data developed from the station observation network were used. This is known as the "Virtual Station Network" developed at NIWA (Tait, 2008) for New Zealand. Error correction statistics derived for the past climate are applied to correct past and future RCM climate data in a consistent manner. The bias corrected RCM climate data are then further downscaled using local parameters and physical relationships to the required resolution (Sood, 2015).

6.2.1.1 Comparison with the previous set of climate projections

As described in Chapter 5, the Primary Sector Adaptation Scenarios utilised for the previous analysis (Clark et al., 2012), suggested a wetter summer to the North Island with the A2 scenario. This is a physically plausible climate future, but on the outer range of the spread of scenarios for this part of New Zealand when considering a broader range of GCMs as carried out by Mullen et al. (2008) and Clark et al. (2011), although these studies used empirical downscaling techniques at coarser monthly timescales. The new set of climate projections utilised in the present analysis is the result of ongoing work in NIWA to refine the physically based RCM simulations, producing a larger number of runs than previously available to provide an estimate of the most likely scenario. The bias correction scheme for the new RCM scenarios has also been refined (Sood, 2015).

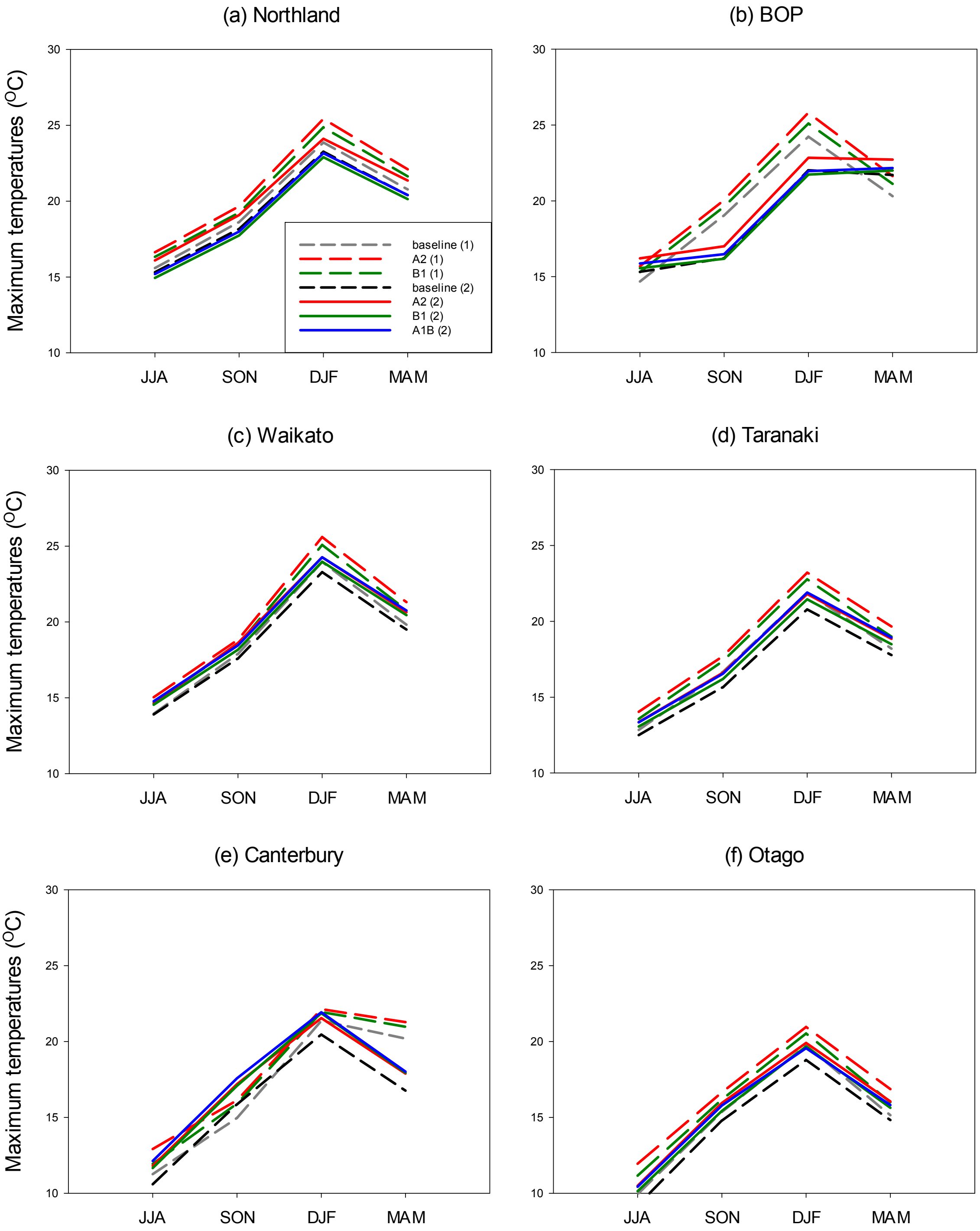

Figure 16: Comparison of projected seasonal maximum temperatures for the two sets of climate scenarios; the baseline (1980-2000) A2 and B1 scenarios (2030-2050) for the first set of projections; and the baseline (1971-2001) A2, B1 and A1B (2030-2060) scenarios for the second set of projections.

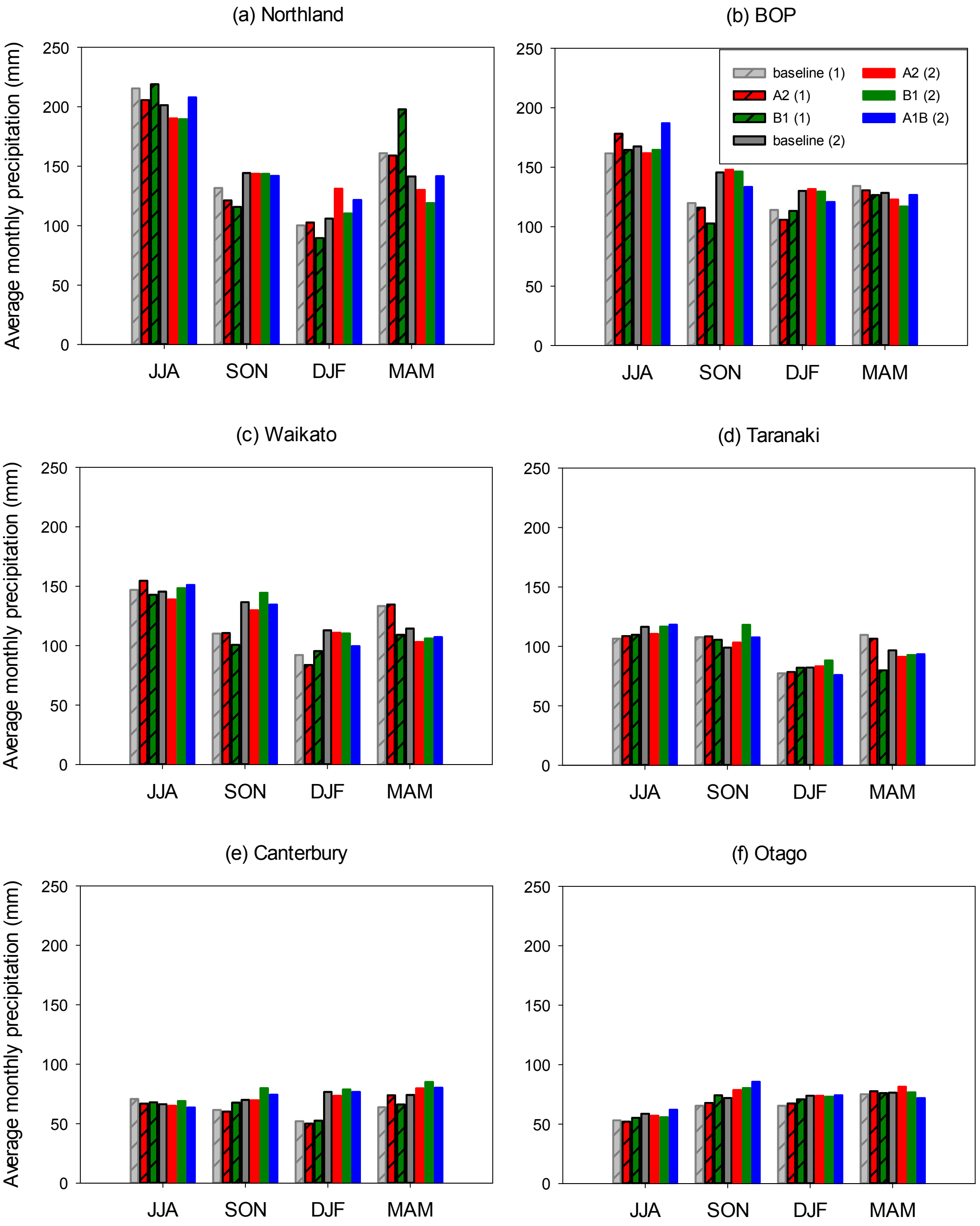

Figure 17: Comparison of projected seasonal average monthly precipitation for the two sets of climate scenarios; the baseline (1980-2000) A2 and B1 scenarios (2030-2050) for the first set of projections; and the baseline (1971-2001) A2, B1 and A1B (2030-2060) scenarios for the second set of projections.

In order to provide an overview of the similarities and differences, Fig. 16 and Fig. 17 show a comparison of seasonal temperatures and precipitation for the two sets of climate scenarios, respectively. The comparison highlights a number of key differences. Maximum temperatures are higher for the first set of projections (A1 (1) and B1 (1) in Fig. 16). This is particularly pronounced on the Bay of Plenty farm. There is also a marked divergence for the Canterbury farm in the autumn (March, April, May (MAM)) season. Rainfall projections (Fig. 17) also show some key differences, with less rainfall projected for the first set of climate scenarios in the spring and summer months.

While these two sets of projections are based on the same GCM and the same RCM, these differences highlight the sensitivity of local-scale projections to differences in bias corrections techniques.

6.2.1.2 Variability and extremes

Climate variability and the frequency of extreme events may be at least as important as mean changes, particularly for agriculture (Thornton et al., 2014). The importance of variability and extremes was also highlighted by farmers in this study (Chapters 4 and 5). For this reason, a brief analysis was also carried out on the projected frequency of dry periods and heavy rainfall events. The parameters chosen for this analysis were:

- Dry periods: periods of over 28 consecutive days with less than 4mm rainfall/day
- Heavy precipitation events: Periods of 24h with more than 100mm rainfall.

The ‘dry days’ parameters were selected on the following criteria:

- Based on the climate data, the average summer evapotranspiration across the six sites was close to 4mm/day.
- Four weeks without rain was identified as a point at which these farmers put plans in place for dealing with a potential drought:

> …if we have a period of 4 weeks without rain, that becomes - not a crisis, a risk management area. Because if you’ve grazed a paddock and you don’t get rain on it and you want to graze it again, usually your growth rates are down.

The ‘heavy precipitation’ criteria were also based on the way farmers described extreme events, for example:

> …we had three instances of 150mm of rain over 48 hours which is a lot of rain...

After subsequent discussions with farmers on different criteria and an initial analysis of the data at three different levels (50, 100 and 150mm events in 24h) it was decided to present the data as periods of 24h with more than 100mm rainfall as a broad indication of changes to rainfall extremes.

6.2.2 Adaptations suggested by farmers

In response to questions on what they would do to adapt to climate change or further climate proof their farms, and what they would like to see modelled, farmers provided very individual responses depending on their own context. Most were incremental adaptations that the farmers had been considering for some time:

Stocking rates and Breeding Worth (BW): Despite the results of the previous modelling exercise (Chapter 5), most of the farmers were still interested in further investigating "ideal" stocking rates, in particular by culling the worst producers in the herd. Improving per head milksolids production is seen as one option to address the requirements of potential future environmental regulations, particularly with regard to nitrogen. Most of the farmers were aware of DairyNZ's work showing the potential to reduce stocking rates and increase per head production without reducing operating profit. The Taranaki farmers suggested going back to a system 2 setup, thereby improving the resilience of the system by reducing reliance on supplementary feeding.

Standoff area/feedpad: Most of the farmers suggested either building or making greater use of a standoff area/feedpad as a climate change adaptation. This was seen as a way to make more efficient use of supplementary feed and to reduce pugging in the winter. Pugging refers to the breaking down of soil structure due to stock trampling of wet soils, and can lead to a significant reduction in pasture growth (Drewry and Paton, 2000).

Supplement strategies. Different supplement feeding strategies were of interest to all the farmers. Currently, all of the farms except the Otago farm used Palm Kernel Extract (PKE), and maize and/or grass silage. They were interested in experimenting with different qualities and types of feed, both silage and concentrates, in different ratios, and experimenting more with diet balance.

Cropping strategies: There was interest in increasing the cropping area on farm. Specific suggestions included growing chicory, Sudax (a hybrid of sorghum x sudangrass (*Sorghum* sp.) and increasing the maize growing area.

Nitrogen use: Fertiliser application strategies were of particular interest. There was interest in increasing nitrogen applications, influenced by the "silage making" adaptation above, and also in increasing nitrogen use efficiency, for example by using the nitrification inhibitor, dicyandiamide (DCD, see Di and Cameron, 2005), or liquid N rather than granular.

Timing adjustments to calving and/or milking: A number of strategies related to timing were suggested, including a later calving date, changing to autumn calving, and changing to once-a-day milking with jersey cows. Timing adjustments considered were all directly related to pasture growth times and aiming to make more efficient use of the feed available.

Some of the adaptations suggested were directly climate related, such as consideration of winter milking. Others were more like 'tweaks' to the system that farmers had been considering for some time, and there was no obvious link to climate change. For example, reducing the number of reared heifers and replacing them with carryover cows. Whether these changes can be considered adaptations to climate change or not is less relevant to the farmers than to the researcher, as the farmers are looking for solutions that will address a range of risks and challenges.

Considering the Canterbury farmer's extremely high rating of risk from environmental regulation, his interest in increased nitrogen use efficiency is likely to be driven more by concern over potential changes in the regulatory environment than by concern about climate change. For this irrigated farm, too, water availability is likely to be limited by environmental regulation before it is directly limited by climate.

Economic considerations clearly also play a large role in adaptation choices. For example, the Northland farmers initially considered and discussed the potential for a change to winter milking. However, in the end decided it was not a viable option due to the fact that winter milk does not receive a premium in Northland as it does further south.

In some cases, despite the question being framed in a modelling context, some of the adaptations suggested by these farmers would be difficult to model, particularly suggestions for crops that were not currently parameterized for the WFM. Likewise, some of their suggestions for adaptations were outside the usual mainstream recommendations: For example, experimenting with carryover cows, or alternative forages such as Sudax. In some cases, these ideas relate directly to quite recent research, or practices by farmers in other countries. For example, Sudax is used as a summer forage crop in Australia, and it has been suggested in the context of New Zealand trials (Silungwe, 2011) that in drier areas, sorghum species may be higher yielding than maize.

6.2.3 Options modelled

The selection of adaptation options took into account the results of the previous analysis (Chapter 5), as well as the interviews carried out with farmers about their farming systems, their impressions of the previous analysis, and their suggestions about what they would like to see modelled for their farms. The ideas farmers had for their systems were in many cases difficult to model, or beyond the scope of the model.

6.2.3.1 Stocking rate

In Chapter 5 the WFM was run under climate change scenarios with a stocking rate reduction of 15%. This reduced stocking rate, implemented in the WFM by randomly culling cows from the herd, was found to reduce operating profit compared to the impact scenario for all the farms, although for some farms and under some scenarios the reduction was minimal.

Despite these previous projections, farmers indicated an ongoing interest in the subject of stocking rates (Chapter 5), highlighting the fact that 15% is a large reduction for some farms; and that in practice if a farmer were to reduce their stocking rate they would not carry out a blanket reduction, but rather cull the worst performing cows. The stocking rate question was therefore revisited in this analysis, considering the high level of interest and its key relevance to questions of environmental regulation and climate change mitigation.

Each farm was run under the climate change scenarios with a reduced stocking rate that was based on the original stocking rate of the farm, by culling the lowest producing cows across each age group based on 'daily peak milk' as defined in the WFM. For the Waikato, Canterbury and Taranaki farms, which had the highest original stocking rates (3.6-3.8 cows/ha), stocking rate was still reduced by approximately 15%. For the other three farms, which had lower stocking rates, the total reduction was just over 10% of the original herd[9].

6.2.3.2 Farm-specific tactical adaptations

The next set of adaptations for each farm consisted of tactical adaptations that were based on the discussions with farmers, including suggestions put forward by the farmers after receiving the original set of climate projections for their farms.

The adaptations selected for each farm reflected both the farmers' suggestions and in some cases, a more general background understanding of the challenges of the farm gained through in depth interviews (Chapter 4). The adaptations were as follows:

Northland farm: A summer crop was selected as an adaptation for the Northland farm. As Sudax was not available in the model, it was decided to include a summer chicory crop, and feed this out. Chicory has been identified as a potentially valuable summer crop for New Zealand dairy farms (Romera et al., 2014; Tozer et al., 2011) with yields between 9-14t DM/ha/yr (Waugh et al., 1998), but more commonly between 9-11 t DM/ ha/yr (Lee and Minnee, 2012). As the modelled chicory was not weather driven, the chicory crop was set at 10,500 kg DM/ha, grown between 1 October and 15th April. Chicory can be

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[9] Northland 2.40 to 2.13, Waikato 3.77 to 3.20, BOP 2.96 to 2.61, Taranaki 3.56 to 3.08, Canterbury 3.76 to 3.26, Otago 2.88 to 2.59

grazed *in situ*, however this option was not available in the WFM so the yield was instead made available for feeding out.

Bay of Plenty (BOP) farm: A doubling of the area planted in maize was used together with feeding out more maize. Because of the combined challenges identified on the farm of less predictable summer pasture growth, and staffing issues (Chapter 4), it was decided to also try milking only once a day for the second part of the summer.

Waikato farm: The results of the modelled farm in Chapter 5 indicated that the cows may be underfed. It was therefore decided to aim for improving per-cow production by maintaining the reduced stocking levels and setting up a management rule to ensure cows were fully fed, by making maize silage available "to demand" all year round.

Taranaki farm: In the previous analysis (Chapter 5) these climate runs showed a positive outcome under most of the climate scenarios. Based on the farmers' expressed wish to maintain a low intensity system, the potential economic viability was evaluated of reducing intensity under the climate change scenario with a more "self-sufficient" farm by maintaining the lower stocking rate, removing Palm Kernel Expeller (PKE) from the system, and making and feeding out more grass silage on farm.

Canterbury farm: Due to the farmers' interest in lower stocking rates, the 15% reduction in stocking rate (compared with the current farm) was maintained for the "adaptation". In addition to the lower stocking rate, the Production Value (PV) of the herd was improved, by "culling" the 10% worst performers according to their PV, and duplicating the equivalent number of best performers in the modelled herd. In addition, up to 2kg barley was supplemented, as suggested by the farmer.

Otago farm: There was limited impact from the previous climate change scenarios (Chapter 5). However, pugging remains the most pressing challenge. For this reason the adaptation chosen was to increase the number of standoff hours. In the original farm setup, management rules specified that the cows should be stood off pasture for 8 h per day when there was a danger of pugging (soil saturation levels >90%) during the months August-September and April-May. In the adaptation, this was increased to 13 h per day.

6.2.4 Economic sensitivity

The importance of economic factors was emphasised by farmers during discussions (Chapter 4). For both this study and in the previous one (Chapter 5), economic input for the 2010-2011 year was used for all scenarios and climate years, since the 2010-11 year was considered relatively 'normal' because it was not a drought year.

In order to gain a measure of the sensitivity of the analysis to economic inputs, the second set of adaptations was re-run for a recent year in which extreme weather played a significant role: 2007-08, which was a drought year. Selected key economic inputs for the years 2010-11 and 2007-08 are provided in Table 7. A significant difference in this year was that feed prices were exceptionally high, changing the playing field in a way that may arguably be considered analogous to some projected scenarios under climate change, if feed supply were to become more limited as predicted (Challinor et al., 2014; Lobell and Tebaldi 2014; Teixeira et al., 2013). As shown in Table 7, the two main drivers of profit - milk prices and the price of cull cows - were almost identical between the two years.

Table 7: Selected economic inputs from the WFM for modelled years 2007-08 and 2010-11.

Economic input	2010-11 ($)	2007-08 ($)
Milk payout (per kg milksolids (MS))	7.36	7.37
Cull cows (per cow)	700	700
Grass silage (per tonne dry matter (DM))	290	650
Maize silage (per tonne DM)	340	400
PKE (per tonne DM)	270	440

6.3 Results and discussion

6.3.1 Climate change signal and impact on pasture growth

6.3.1.1 Temperature change

Projected changes in average maximum and minimum temperature are shown in Fig. 18. In this set of simulations, the A2 scenario showed a relatively steady average temperature increase for all sites of about 1°C, with little change in the diurnal range (difference between daily maximum and minimum temperatures) for the North Island sites. The signal was slightly more variable for the South Island sites.

The B1 and A1B scenarios were more variable between sites than the previous set of projections (Chapter 5): For the Northland site, both maximum and minimum temperatures were slightly lower than the 1971-2001 baseline. For the BOP site, minimum temperatures showed a similar increase to the A2 scenario, however maximum temperatures increased by only around 0.5°C, and were lower for some summer months.

The Waikato and Taranaki sites also showed a fairly consistent increase of around 1°C for maximum temperature. However for the Taranaki site, minimum temperatures for the A1B and B1 scenarios increased by less than 0.5°C, increasing the diurnal range. Maximum temperature increases were higher and more variable for the Canterbury site, and around 1°C for the Otago site, however there was again a smaller increase in minimum temperatures at both sites.

As noted in Chapter 5, minimum (night time) temperatures have been identified as important for reducing heat stress (Clark et al., 2012; Igono, 1992; West, 2003) and such diurnal variation may be an important aspect to consider. Under this set of projections the Northland, BOP and Canterbury sites may be at risk of increased heat stress and further analysis considering both diurnal temperature range and the Thermal Humidity Index (THI)[10] that has been developed for New Zealand dairy cattle is recommended.

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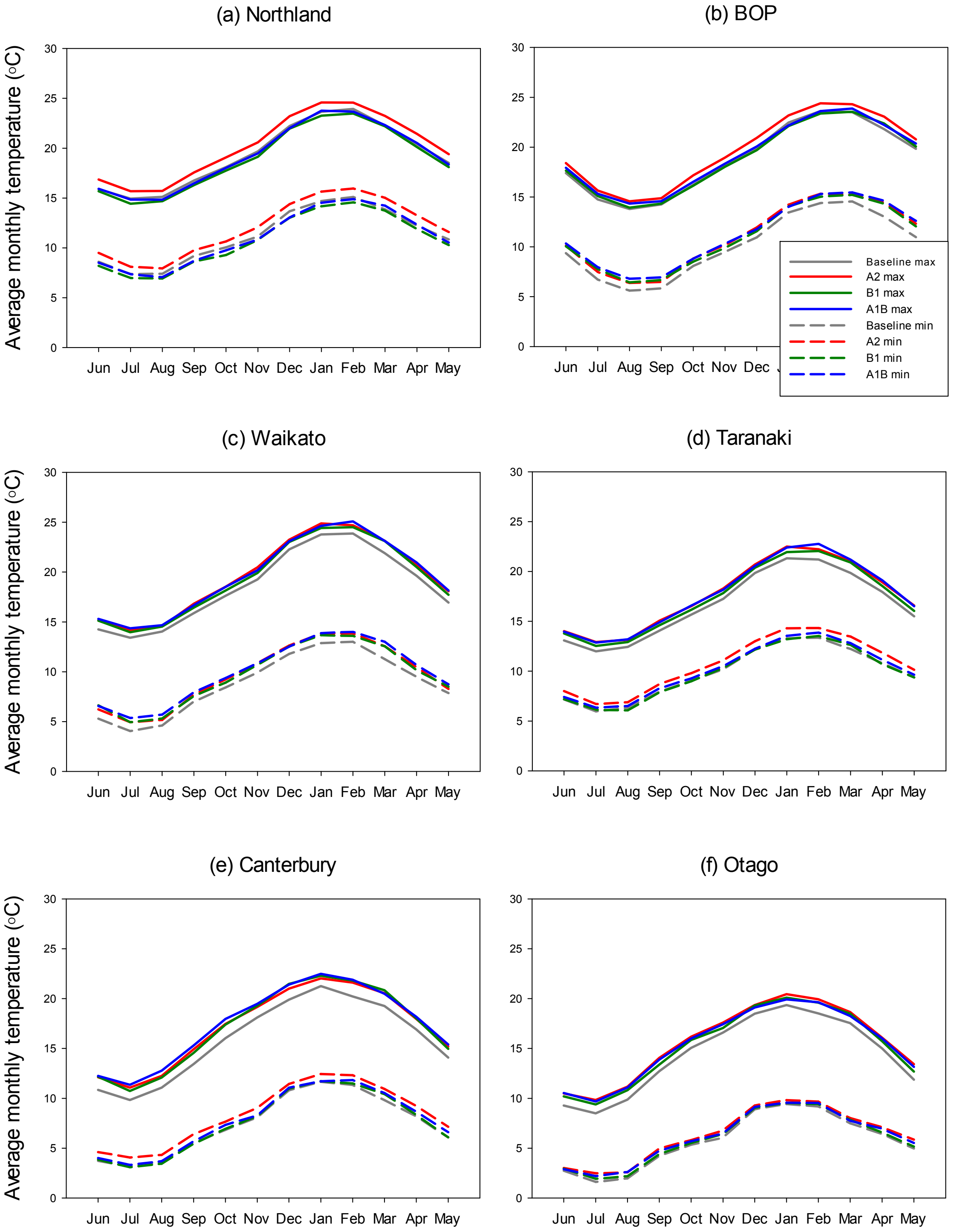
[10] http://www.dairynz.co.nz/animal/health-conditions/heat-stress/


(a) Northland

(b) BOP

(c) Waikato

(d) Taranaki

(e) Canterbury

(f) Otago

Figure 18: Projected average maximum and minimum monthly temperatures for the baseline (1971-2001) and future (2030-2060) A2, B1 and A1B climate change scenarios for the six farm sites.

The projected temperature change in the simulations presented were mostly small and even negative for a few sites, unlike other ensemble members. The temperature change results presented here should be considered in this respect outliers, resulting from specific choices of bias corrections and downscaling parameters and methods (Abha Sood, pers.comm 15 Jan 2015).

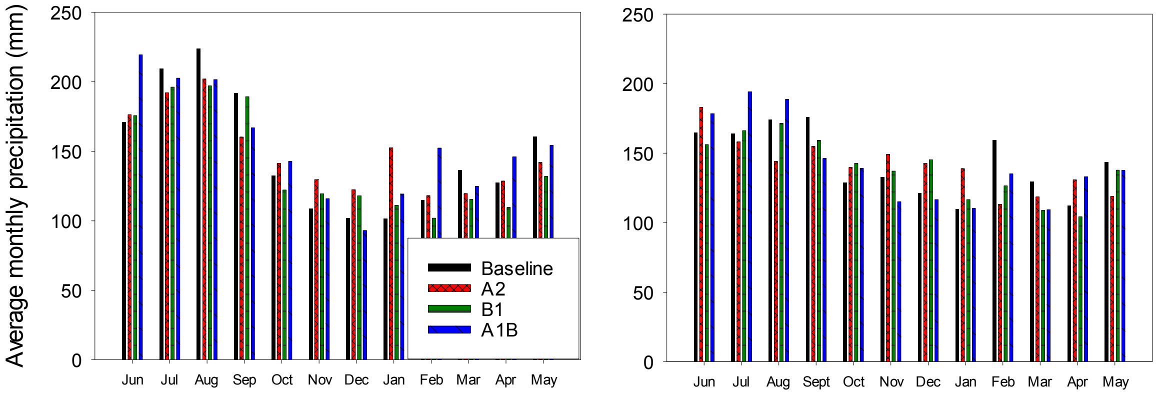
6.3.1.2 Rainfall

Across the three climate scenarios, changes in average monthly rainfall were the most marked for the north-eastern farms in Northland and the BOP (Fig.19). The changes were less pronounced for the farms in the mid North Island (Taranaki and Waikato) and less again for the South Island farms (Canterbury and Otago).

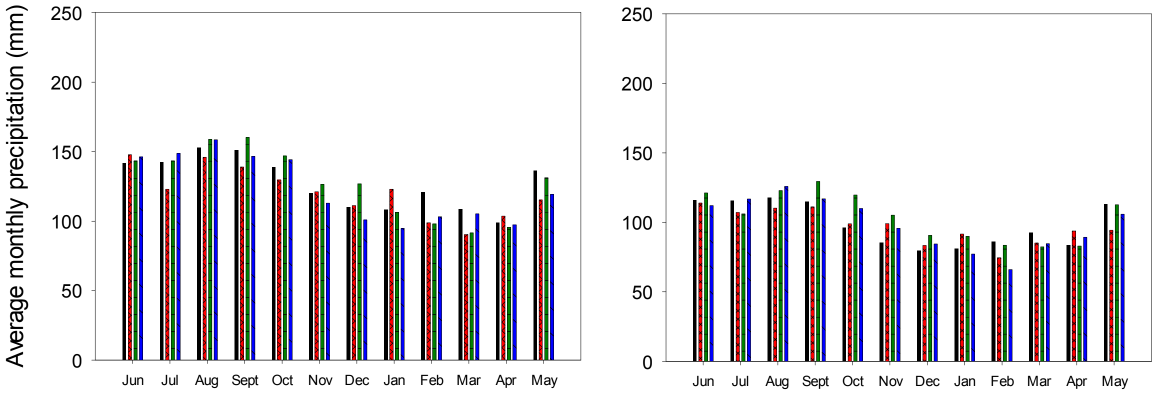
For both the Northland and the BOP farms, there was a projected increase in rainfall from October to January for the A2 and B1 scenarios, with generally reduced rainfall from February to September. The pattern was less consistent under the A1B scenario, which shows decreases consistent with the other scenarios only for July to September on the Northland farm, and in February and March for the BOP farm.

Summer rainfall was also projected to increase on the Taranaki farm, and both the Taranaki and Waikato farms showed decreased rainfall in February and March across all three scenarios. These changes in rainfall related closely to the changes in pasture growth (Fig. 18) as described in the next section.

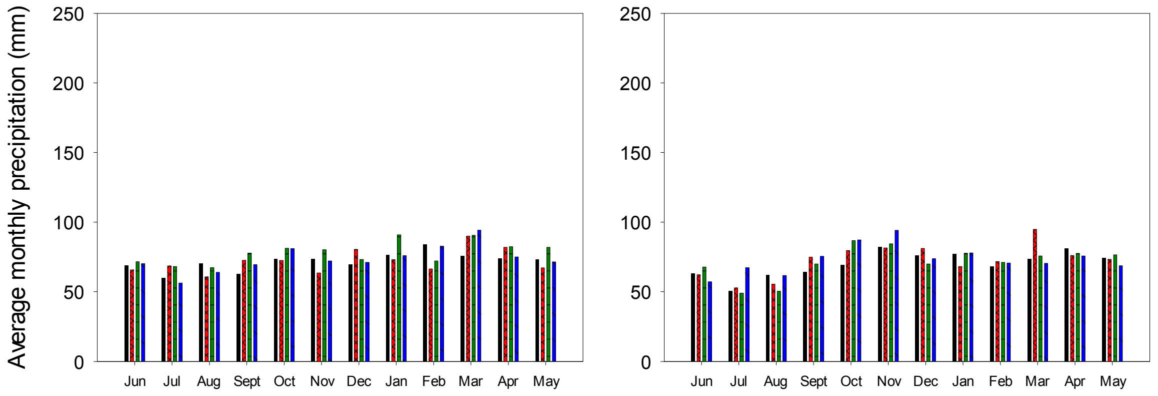
The differences between the two sets of projections (used in Chapter 5 and Chapter 6, respectively) mainly result from two independent bias correction procedures applied in the two studies. The divergence between these projections, as well as the differences between scenarios, suggests that there are large uncertainties around climate projections, in particular for the Northland farm. Without comprehensive assessment of the climate change signal derived from large climate ensembles, the climate change projections as presented here may only be used to demonstrate and develop a broad approach to adaptation. Caution should therefore be exercised when interpreting modelling results.


(a) Northland

(b) BOP


(c) Waikato

(d) Taranaki


(e) Canterbury

(f) Otago

Figure 19: Projected average monthly precipitation for baseline (1971-2001) and future (2030-2060) A2, B1 and A1B climate change scenarios on the six farm sites.

6.3.1.3 Pasture growth

Overall, pasture growth rates were lower for all scenarios except the A2 scenario in Northland, and the A2 and B1 Scenarios in Taranaki (Fig. 20). Changes in pasture growth showed consistency with changes in the rainfall patterns across scenarios (Fig. 19). For the Northland and BOP farms, this resulted in a drop in pasture growth for most scenarios towards the end of the milking season, particularly in March and April.

The Taranaki farm showed little change under the A1B scenario, but a marked improvement in summer pasture growth under the A2 and B1 scenarios. In the Waikato, mid-summer growth was reduced for all three scenarios, but with a larger increase in February under the A2 scenario, resulting in a lower impact on total pasture yield for the year (Fig. 23c). The South Island farms were less affected, although both showed a slight decrease in summer pasture growth and the Otago farm also shows a decrease in spring, corresponding with increased rainfall over this period (Fig 20). This suggests that pugging may be negatively affecting pasture growth in these wetter months (Drewry and Paton, 2000).

Rainfall was a less important driver of pasture growth for the irrigated Canterbury farm. Under irrigation, climate challenges are most likely to come not from direct weather-related impacts, but from water availability issues, including regulations around water quality.

6.3.2 Extremes and variability

Changes in precipitation extremes varied considerably across the six sites under the modelled future scenarios (Fig. 21). Increases in dry periods were most noticeable at the BOP and Waikato sites, but were restricted to particular scenarios in other areas. The A1B scenario showed increases in the number of dry periods for four of the six sites. More extreme precipitation events were also evident in the BOP and Taranaki sites, and under two scenarios for the Northland site (Fig. 21b).

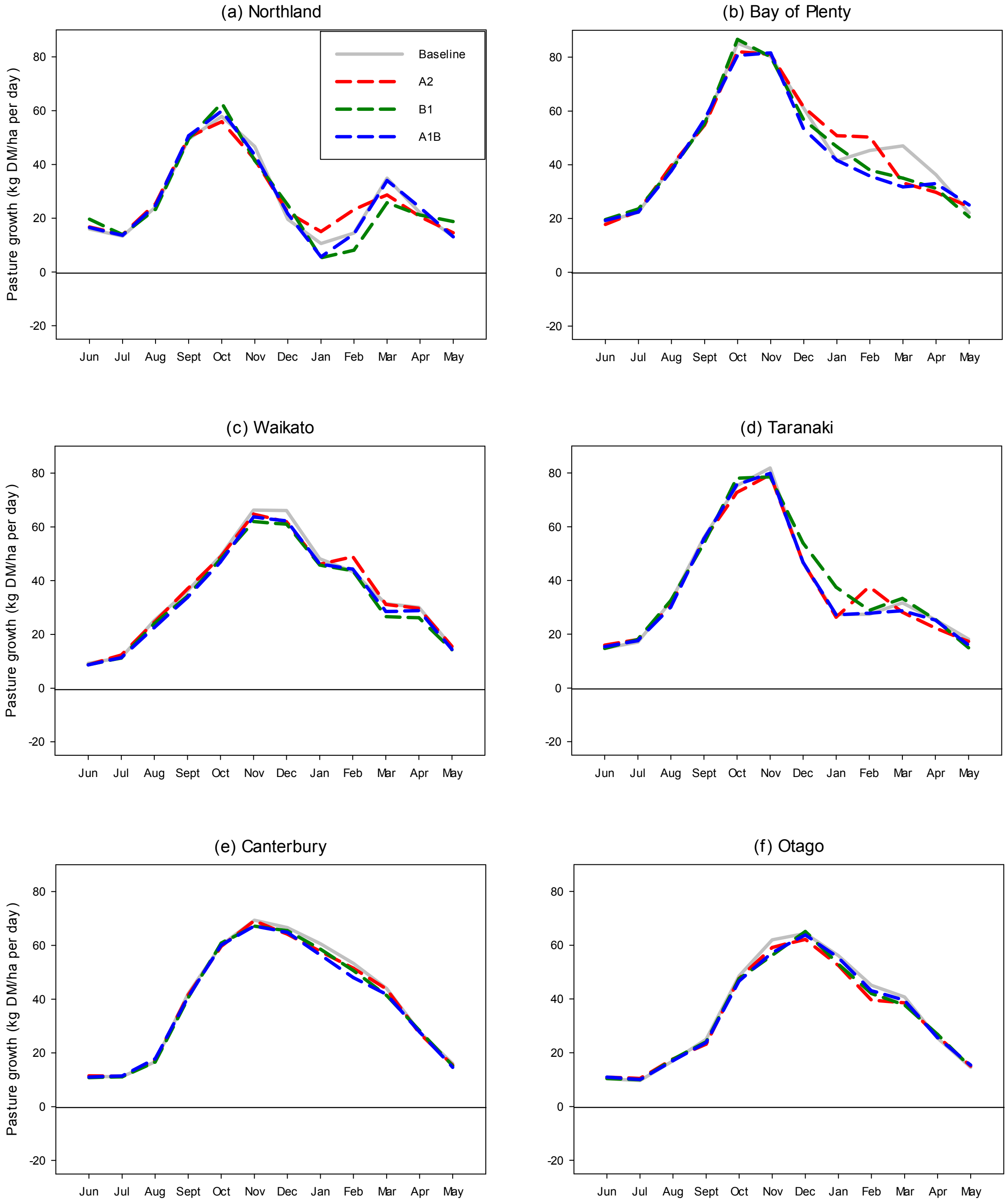
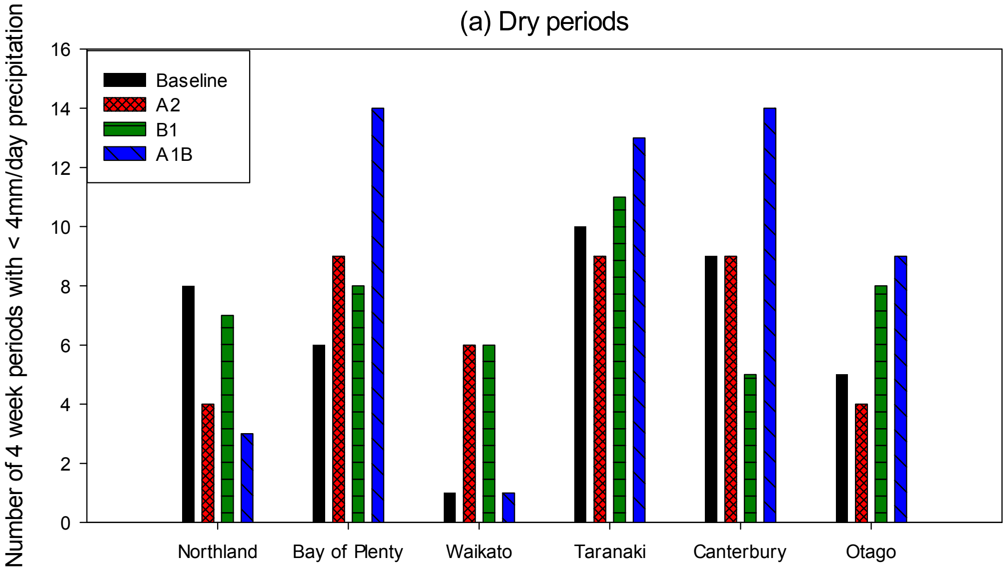
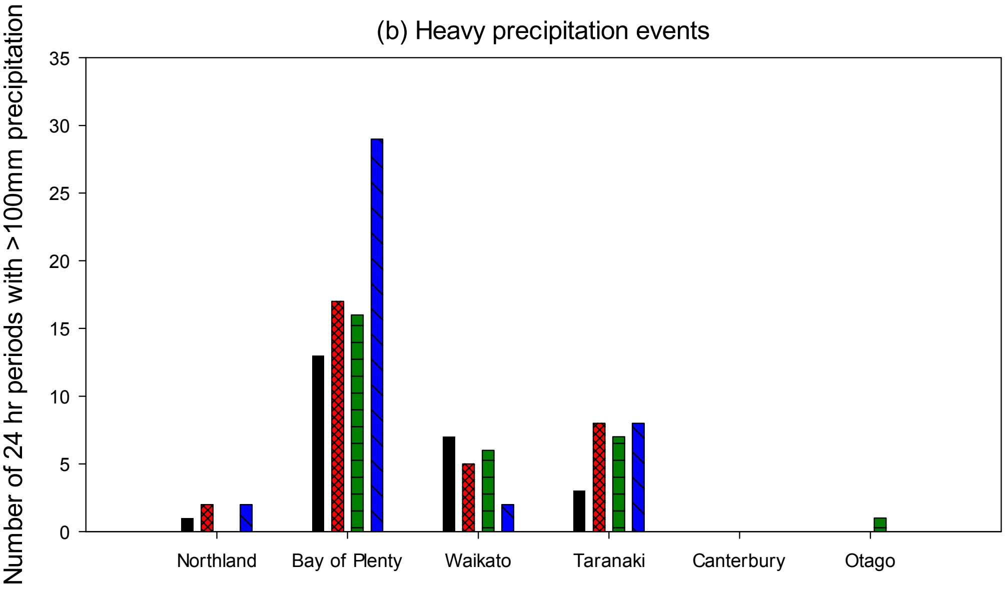


Figure 20: Average monthly pasture growth rates for baseline (1971-2001) and future (2030-2060) A2, B1, and A1B climate scenarios at the six farm sites.



(a) Dry periods



(b) Heavy precipitation events

Figure 21: Number of extreme weather events during the 30 year period for the baseline, A2, B1 and A1B climate scenarios: (a) Dry days and (b) heavy precipitation events.

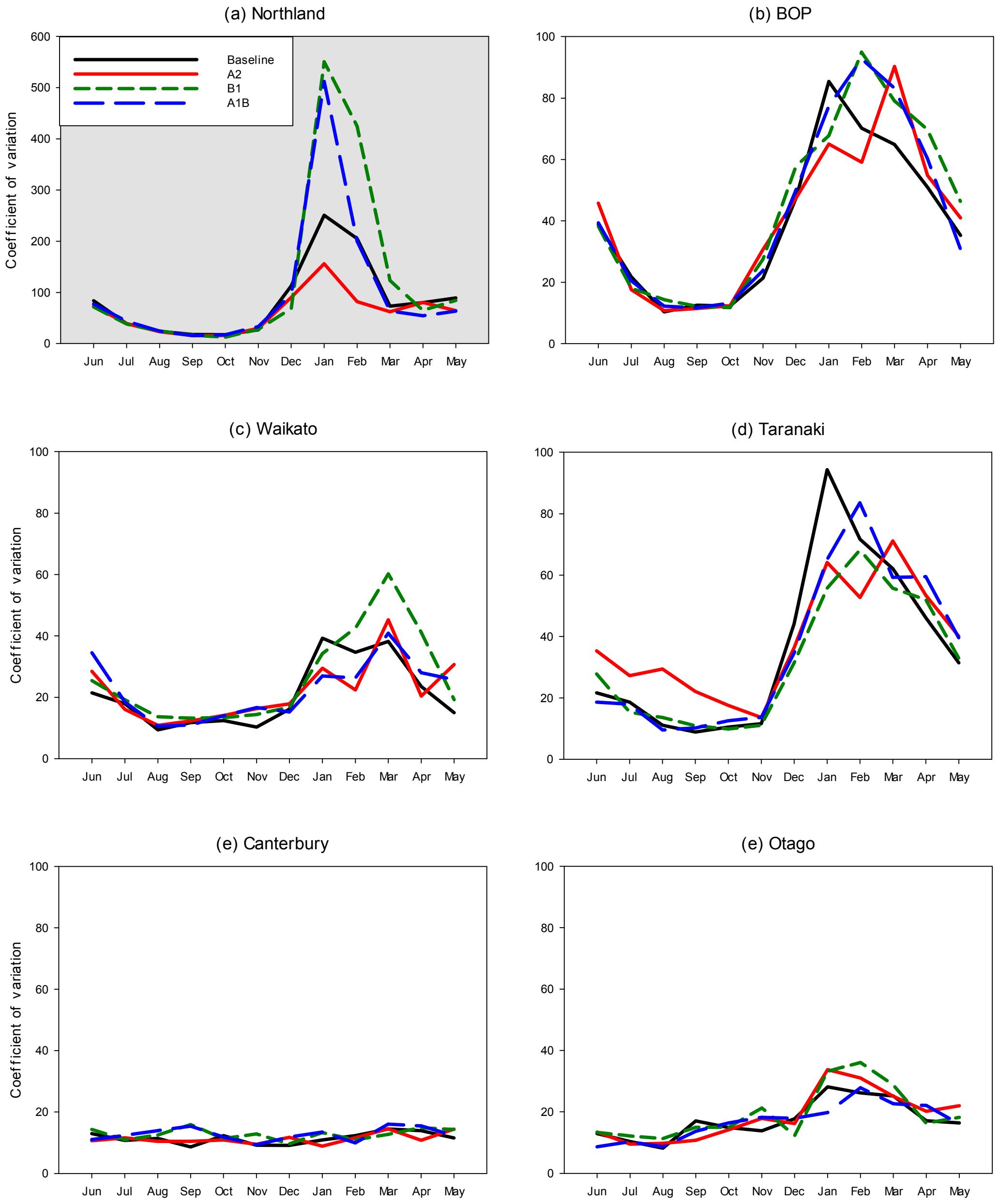


Figure 22: Coefficient of variation for pasture growth for the baseline (1971-2001) and A2, B1 and A1B climate scenarios (2030-2060) for the six farm sites.

The full effects of changes in extremes may not be reflected in this study, as the WFM does not model flooding effects. Extreme precipitation events increased for the Taranaki farm, which otherwise shows a very positive impact on pasture growth under the climate change scenarios. The combined impact of increased episodes of heavy rainfall and increasing dry periods implies that for some areas such as the Bay of Plenty, negative impacts may extend beyond what can be modelled in the WFM. In other areas (e.g. the Northland farm), even small increases in extreme precipitation under some scenarios may also exacerbate existing local challenges as identified by the farmers, such as flooding.

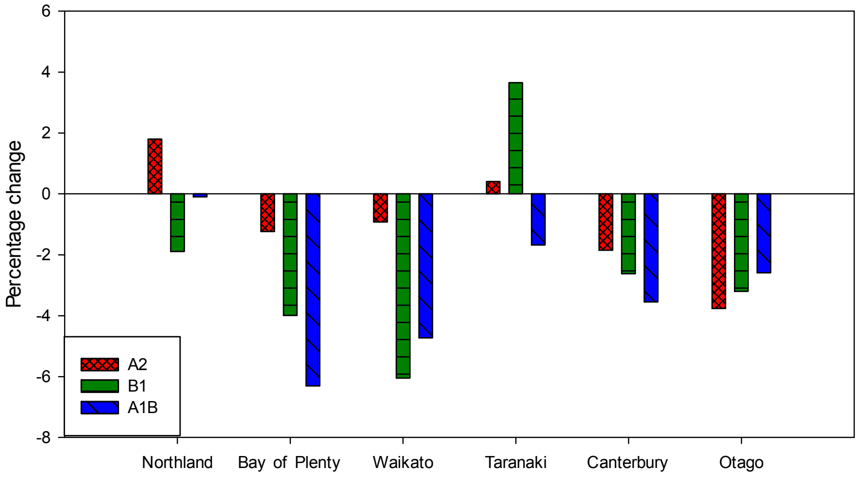
Fig. 22 shows the coefficient of variation for pasture growth (calculated as the standard deviation divided by the mean) as a standardised measure of variability. Patterns of interannual variability (Fig. 22) remained almost exactly the same for all farms between June and November, with the exception of the A2 scenario on the Taranaki farm, which showed increased variability. For the summer and autumn months, the A2 scenario was less variable for all farms, with the exception of the month of March in the Bay of Plenty. The B1 and A1B scenarios greatly increased variability in the summer months for the Northland and BOP farms, and the B1 scenario produced increased variability on the Waikato farm.

6.3.3 Impacts on key indicators

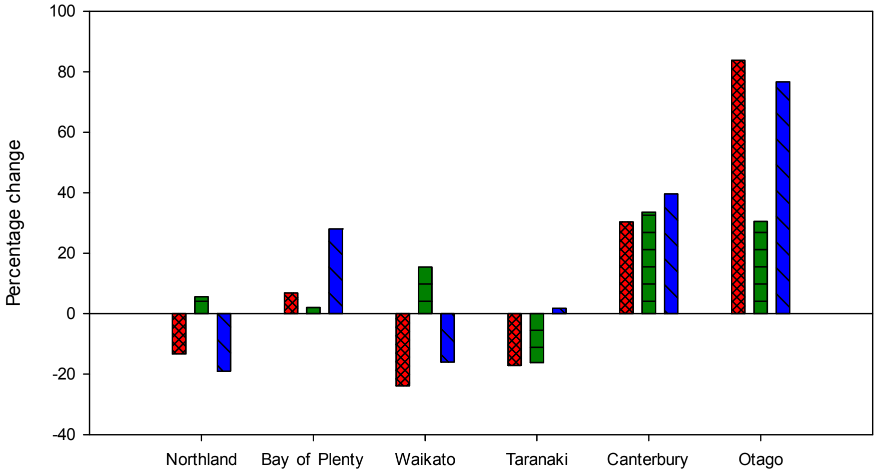
As in the previous analysis, impacts on the key factors selected as indicators of farm performance (pasture yield, milksolids production and operating profit), are presented in this study as percentage change from the baseline climate scenario, as a relative rather than an absolute measure of performance. In this way it is easier to compare relative changes in different components of the system. This relative measure was considered more appropriate for a study of future projections, particularly as cost structures were not tailored to each individual farm and may therefore vary considerably from the actual farms. However, in assessing the data it is important to remember that in each case the measure is relative to the baseline, limiting the relevance of comparisons between different farms.

While most of the farms analysed in this study showed reduced operating profit under climate change scenarios, there was a great deal of heterogeneity between

(a) Pasture



(b) Total supplements



(c) Milksolids

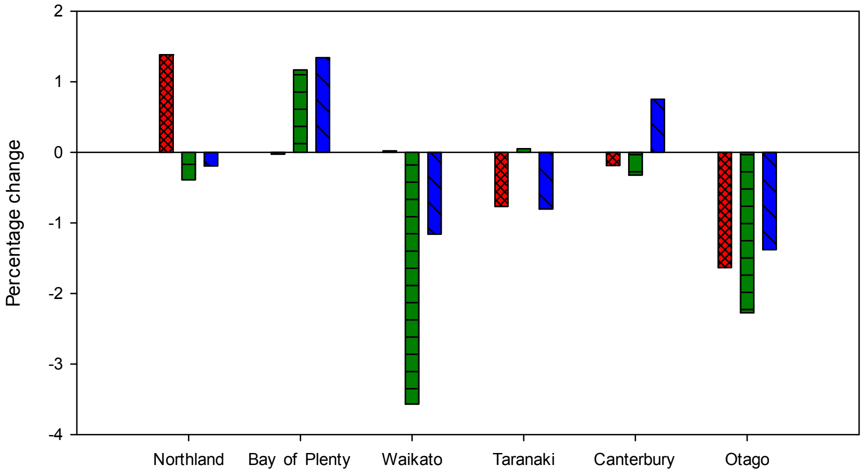


Figure 23: Projected percentage change in (a) average annual pasture yield (kg DM/ha); (b) total supplementary feed bought in (kg DM); and (c) milksolids production (kg milksolids/ha) between the baseline (1971-2001) under current management and future (2030-2060) under the A2, B1 and A1B climate scenarios for the six farm sites.

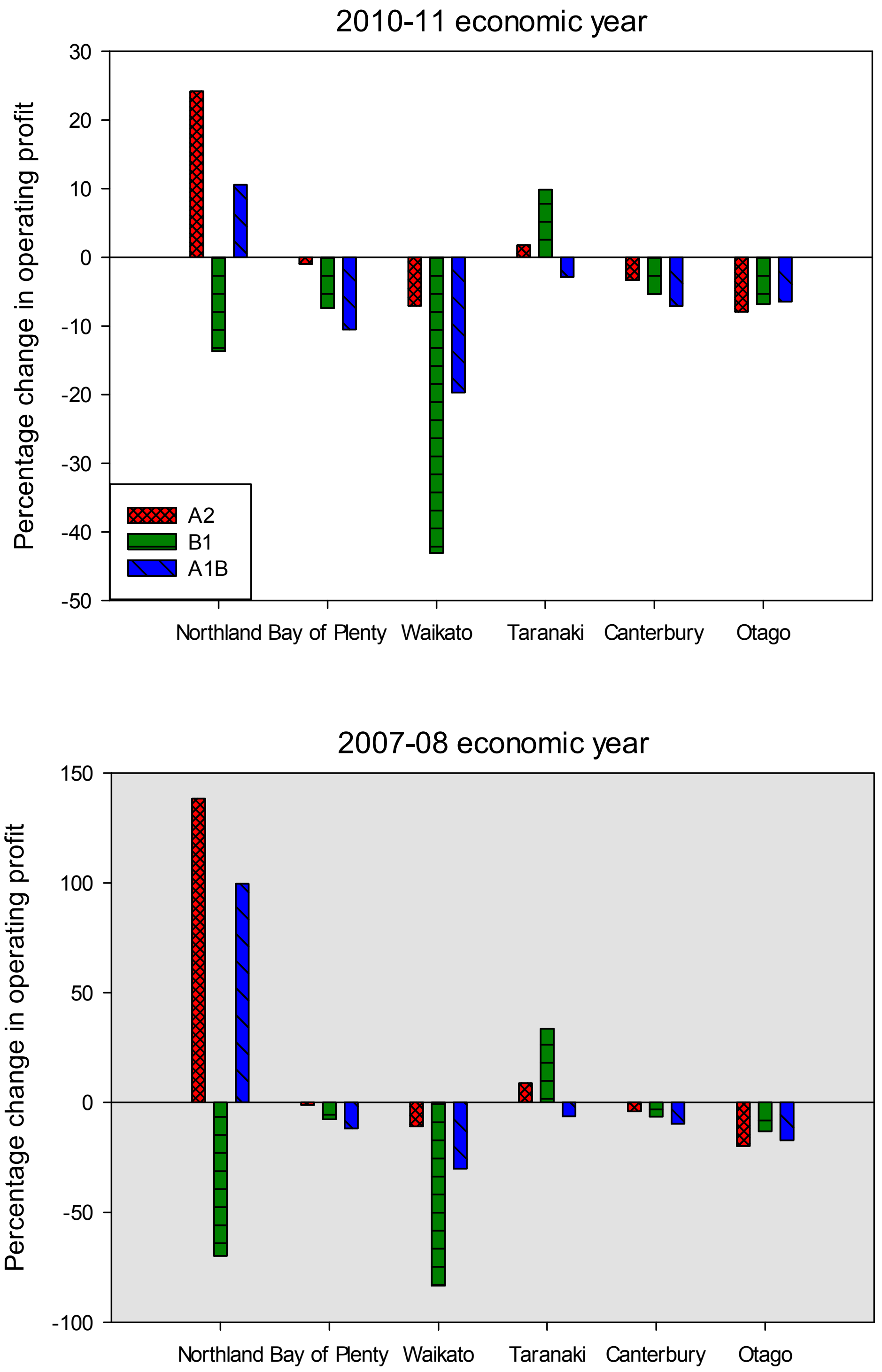


Figure 24: Projected percentage change in operating profit under (a) 2010-11 economic data and (b) 2007-08 economic data between the baseline (1971-2001) under current management and future (2030-2060) for the A2, B1 and A1B climate scenarios at the six farm sites.

the sites in different regions, both in average changes and in the degree of variability from year to year, as well as between different climate scenarios.

The impact of changes in climate on overall pasture yield, total supplements brought in and milksolids production is shown in Fig. 23. Notably, overall pasture yield decreased for all three scenarios for four of the six farms, with a corresponding reduction in operating profit. The largest decrease in operating profit was seen under the B1 scenario on the Waikato farm (Fig.24).

As shown in Fig. 23(b), more supplements were purchased on the BOP farm, for the Northland and Waikato farms under the B1 scenario, and at least 30% more bought-in supplement for all three scenarios on the two South Island farms. For Northland and Taranaki, results were mixed, with increased pasture growth and operating profit under the A2 scenario. The B1 scenario showed a reduction in pasture growth, milksolids production and operating profit (Fig. 23 and 24) for Northland, along with an increase in supplements fed; while in the Taranaki it had a strongly positive effect. The A1B scenario was the only negative scenario for Taranaki, whereas in Northland, while the overall impact of this scenario on pasture growth was negative, less supplements were purchased overall (Fig. 23) and operating profit is actually improved.

Compared with the previous analysis (Chapter 5), four of the six farm sites were fairly consistent. However, the Northland and Taranaki sites showed quite different results. For these sites, the latest set of projections indicates that conditions may improve for dairy farming under some climate change scenarios. According to most of the scenarios in this and the previous analysis, the Taranaki farm is positioned to benefit from climate change due to favourable temperature conditions in autumn, although the previous analysis (Chapter 5) showed a significant decrease in operating profit under the B1 scenario. However, without further ensemble based probabilistic assessment, the likelihood these scenarios eventuating remains unknown.

6.3.4 Adaptations for each farm

Figure 25 shows the percentage change in operating profit for the tactical adaptations that were tailored to each farm. For the six dairy farms analysed, the impacts of climate change are projected to be mostly negative, with the most pronounced changes in pasture growth (Fig. 20) being evident on the North Island farms. However, results were highly variable between sites and two of the scenarios resulted in increased operating profit for both the Northland and Taranaki farms.

For three of the North Island farms, the farm-specific, tactical adaptations suggested generally improved profitability under the baseline climate, and went some way to mitigating the negative impacts of climate change under future climate. However, in most cases they were still less economic under future climate than the same adaptation under the baseline climate. For the Northland farm, the chicory adaptation was not profitable under the 2010-11 economic inputs. According to a local Northland agronomist, chicory yields in Northland are strongly influenced by site in summer because it is sensitive to moisture. He suggested that chicory is not a reliable summer crop for the Northland region. However, he is currently carrying out research on its potential value as part of a permanent pasture (Graeme Piggot, pers.comm. 9th March 2015).

The reduced stocking rate resulted in reduced profitability for all of the farms, with one clear exception: On the Waikato farm under the B1 and A1B climate scenarios, which most negatively affected operating profit, a reduced stocking rate reduced the negative impact of climate change. Although a reduction in stocking rate was generally unprofitable even when the lowest producing cows were culled, this is likely to be a reflection of the fact that these farms were currently close to the optimum stocking rate under their present systems. Reducing stocking rate improved operating profit under climate change scenarios for one of the farms (Waikato) when combined with better feeding of the remaining stock; and for another farm, when the rest of the farm was utilised for making more grass silage (Taranaki).

Basing the adaptations in this analysis on farmers' suggestions meant that they also reflected consideration of some of the other issues facing farmers. The reduction of stocking rates under some of the proposed adaptations likely related to farmers' concerns about environmental regulation (see Chapter 4) rather than climate change itself. This emphasises the interconnectedness of the different

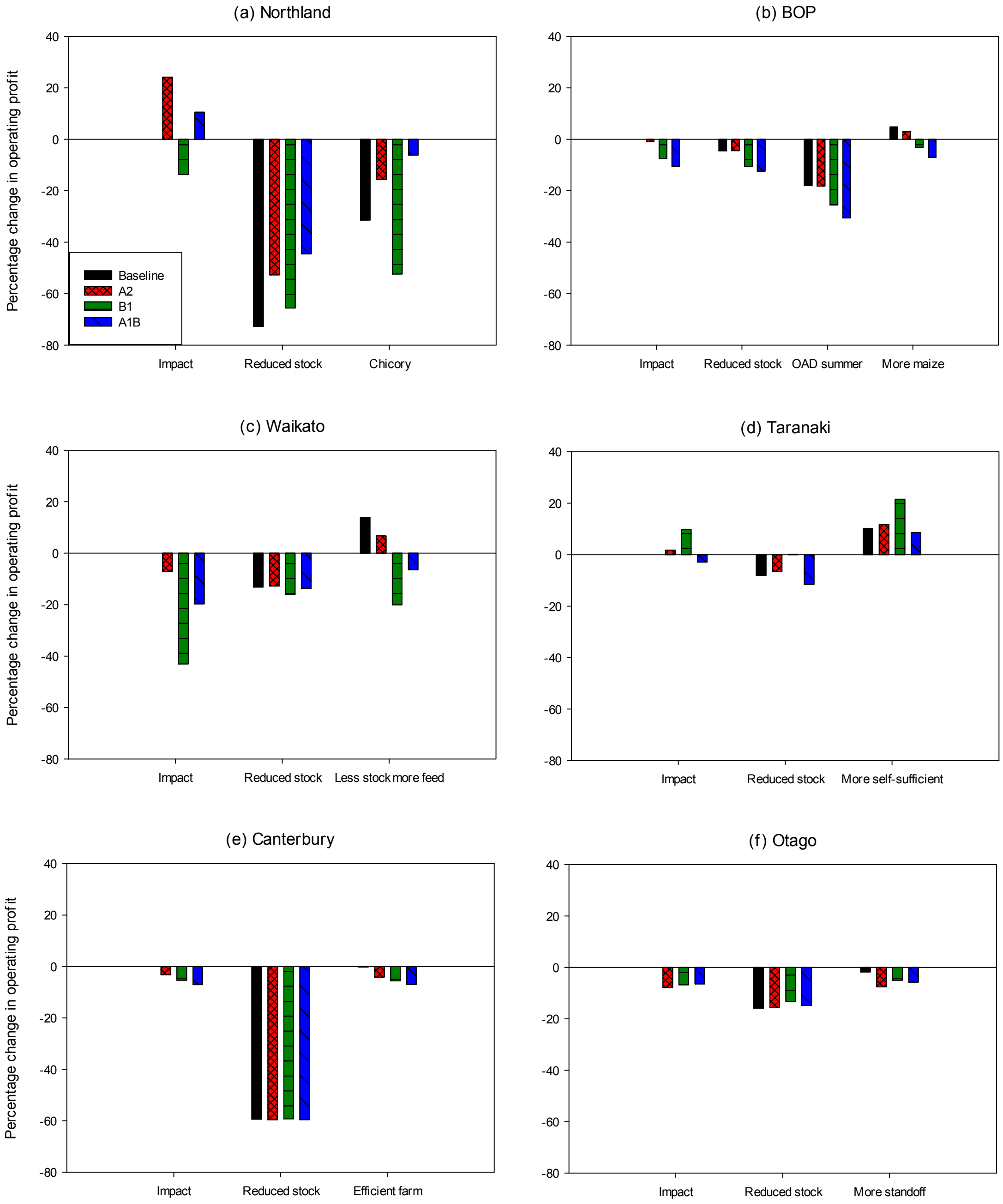


Figure 25: Percentage change in operating profit for the adaptations as carried out for the six farms under 2010-11 economic data for the baseline climate (1971-2001) and the three future climates A2, B1 and A1B (2030-2060).

pressures, and the fact that in practice, at farm level, it is not practical to address an issue such as climate change in isolation. This was particularly evident in the case of the Canterbury farm. The high level of concern about environmental regulations (Chapter 4) is likely to have been a strong influence in the farmer's choice to aim for increased per-cow production at a reduced stocking rate.

However, on the Taranaki farm, the more 'self-sufficient', lower intensity farm setup that included the removal of PKE supplementation as well as making and feeding out more grass silage on farm, was more profitable overall and particularly profitable for the two scenarios which improved pasture production under climate change.

Both from this study and the previous modelling study, a number of options were identified as viable adaptations under climate change scenarios. However, in all cases the appropriateness of a particular adaptation was specific to the particular farm context.

Increasing the area of the maize crop improved profitability both under the present climate and under climate change scenarios (BOP farm). Farmer observations (Chapter 4) suggest that interest in cropping options is likely to continue to increase, particularly if expansion is limited:

> I think some of the so-called 'leading' [farmers] are relying more on crops nowadays than they are on pasture. Like if you grow maize, you can grow 15 tonne of dry-matter to the hectare then put in oats and you'll grow…22 tonne to the hectare compared to 15 of grass. So if you put a third of your farm into maize, you're growing that much extra feed so you're running so many more extra cows. So you're doing that sort of thing rather than buying more land...

Cropping options may have considerable potential, but their profitability will likely be context-specific. In the case of the BOP farm, the increased maize adaptation was still less profitable under climate change than under the current (baseline) climate. Studies from other parts of the world have shown potential for improving crop productivity under climate change if the right cultivars and sowing dates are chosen (Teixeira et al., 2012), suggesting that further research to identify appropriate crops, cultivars and sowing dates might enable optimisation of dairy systems in areas such as the BOP, which are likely to be most negatively affected. Finding the right selection of crops for particular areas under climate change is a challenge that will require ongoing input from both farmers and researchers.

Whether a particular crop is economic or not may be very case specific. For example, the chicory adaptation did not improve the situation for the Northland farm with the exception of one scenario (A1B) under the alternative economic year (with high feed prices). As chicory in the model was not weather driven, the robustness of conclusions that can be drawn from this analysis are limited. If areas such as Northland and BOP are to maintain profitability under climate change, further thought should be given to appropriate ways to test new crops and cultivars which are not yet available in farm system models for that area.

Making and feeding out more grass silage increased profitability significantly in the previous analysis (Chapter 5). In the present study, it was used in an area projected to benefit from climate change events (Taranaki) as part of a set of adaptations aimed at reducing the intensity of the system and its reliance on imported PKE. This was highly profitable under all scenarios, particularly for the alternative economic year with higher feed prices. The very large increase in operating profit for the Taranaki farm under the “more self-sufficient” adaptation highlights an area of opportunity: If global prices for crops and hence supplementary feed increase as predicted (Teixeira et al., 2013; Lobell and Tebaldi, 2014), areas that are well situated to increase production of silage and/or crops can potentially profit (Reisinger et al., 2014).

Changes in timing were of interest to the farmers, for example the Taranaki farmer expressed interest in changing calving dates (10 days earlier) and the Waikato farmer was interested in a change to winter milking. The only option tested in this group of adaptations might be considered more of a reduction in intensity: For the BOP farm, changing to once-a-day milking for the second part of the summer negatively affected operating profit.

Changes to the timing of calving and hence the milking season represent a significant strategic change to the system. Climate change as well as a number of other related drivers, such as increasing pressure on water resources and milk companies needing to supply milk more consistently on a year round basis, may

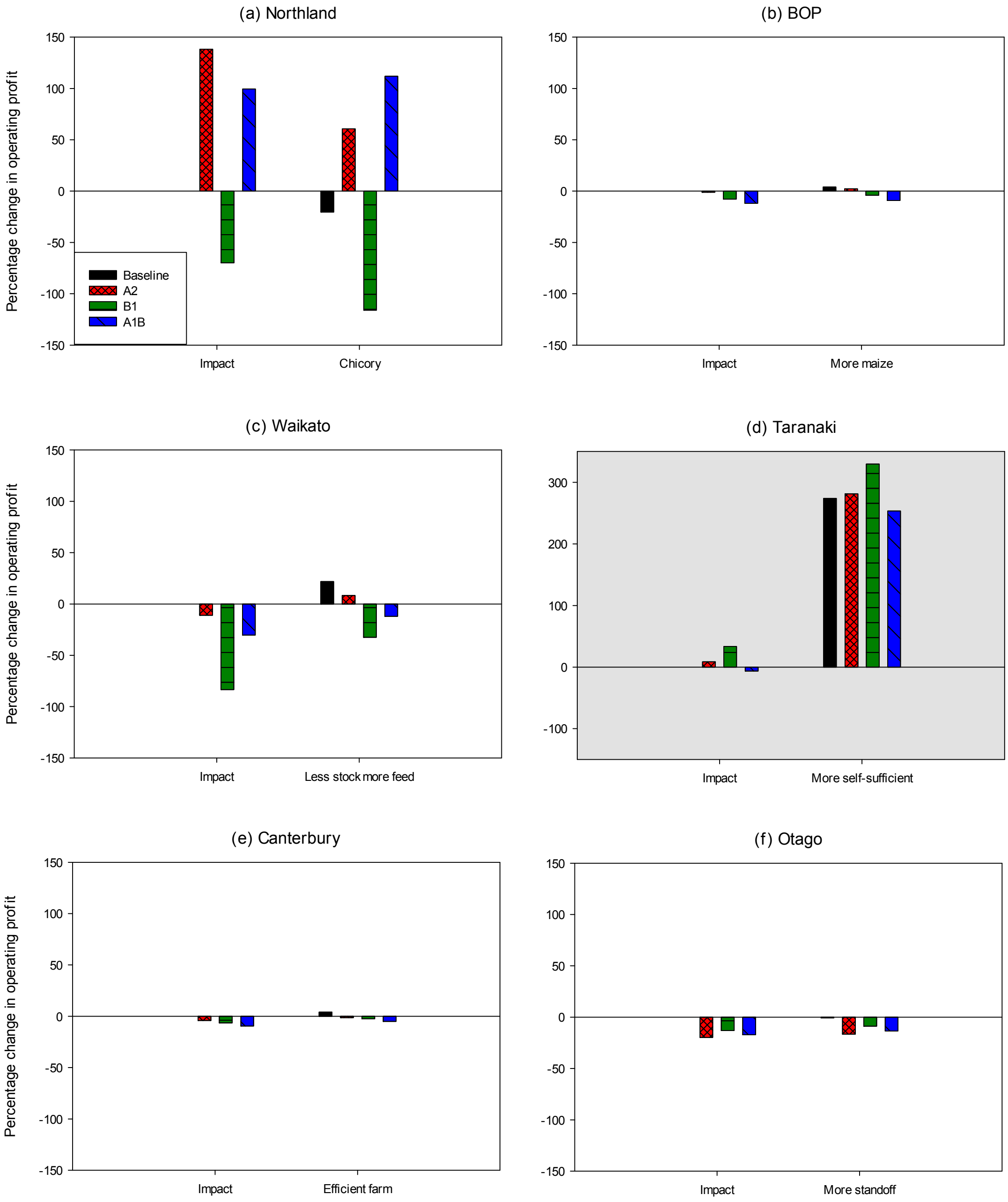


Figure 26: Adaptations under the 2007-08 economic data. Note different scale for the Taranaki farm.

make winter milking and split calving increasingly viable options. However, many other factors will affect the success of the adaptation. Animal health issues around calving, including potential changes in pest and disease prevalence under climate change, changes in feed supply as well as labour implications, need to be given full consideration in addressing such major alterations to the system. It is recommended that strategic adaptations related to the timing of the milking season be addressed separately in a future study.

The South Island farms showed little change under the tactical, farm-specific adaptations. Standoff may become an increasingly important tool in some areas under climate change scenarios, as a mitigation for increasing pugging damage (Otago farm). It may also be useful to mitigate damage to pastures during dry summer periods.

Most of the adaptation options described in this study, if taken up on a broader scale, would imply an increased need for resources and infrastructure, for example cropping and silage making contractors, as well as potential environmental impacts such as increased agrichemical usage, and more plastic silage wrap. In light of increasing environmental regulation, it will also be important to consider the potential environmental impact of an increase in the area growing different crops, at different times of the year. These potential pressures and their implications may require further analysis.

6.3.5 Sensitivity to economic inputs

Changing the economic year used in the analysis to the 2007-08 year (Fig 26, note different scale to Fig. 25) did not have a marked impact on most of the farms, with two main exceptions: For the Northland farm, it resulted in a much greater increase in profitability under the A2 and A1B scenarios, and the chicory adaptation became more profitable under the A1B scenario than under the baseline climate. For the Taranaki farm, the ‘more self-sufficient’ farm set up became highly profitable for the baseline as well as the three climate scenarios. The Taranaki farm is presented on a different scale to the other farms in Fig. 26.

For the Waikato farm, the 2007-08 economic year also further emphasised the negative impact of the B1 climate scenario. As noted in the previous analysis

(Chapter 5) maize production is a very significant component of this farm's strategy, and the drop in profit under the B1 scenario may be driven largely by a reduced maize yield under this scenario, compared with the other two climate scenarios.

The choice of economic year provides a further source of variability and adds another layer of uncertainty to the analysis. It lends support to the argument that indirect climate change effects may have a greater impact overall than direct weather related impacts (Reisinger et al., 2014; Tait et al., 2008).

6.3.6 Limitations and future research

A major limitation in the context of studies such as this one, where climate projections are analysed at farm level, is the uncertainty surrounding climate projections. With the set of projections utilised in this study, the climate response to any external forcings exhibited strong variability on all spatial and time scales, suggesting that a large number of simulations or ensembles would be required in order to adequately capture uncertainty in mean and extremes of the climate change signal. However, in this limited study, results based on only one ensemble member (HadCM3-run1) from the CMIP3 dataset for each scenario were used to demonstrate response to selected adaptation measures. Additional uncertainty in the climate change signal was due to the choice of bias correction and downscaling methods and the adjusted parameters (Sood, 2015). The difference between the two sets of climate projections emphasises further the need to take an adaptation-focussed approach to such analyses rather than focussing heavily on the projections themselves (Dessai 2005; Wilby and Dessai, 2010).

The WFM is a robust system model, capable of representing farming systems in most of the country. However, this study has again highlighted the limitations of the WFM's capacity to accurately represent less typical systems such as the Northland and BOP farms, where climate change is likely to have the greatest impact. Many of the challenges and opportunities confronting these farms are simply outside the range of science that has so far been applied to the WFM. For example, kikuyu cannot be modelled on the Northland farm, whereas it forms an integral part of the actual farming system and much of the farm is regularly regrassed in order to combat its incursion.

Socio-ecological systems are complex and at best, can be only partially modelled. This can be important in the climate change context. Many impacts from climate change, particularly those related to extreme weather events, are difficult to model.

Models are excellent tools for quantifying and recombining potential impacts and adaptations that are already well understood. However, for the purposes of innovation, which by definition requires thinking outside our present mental models and bringing in new elements, their capacity is limited.

It is impossible to identify and trial every possible scenario and combination of adaptation options. More complex sets of adaptations further increase the uncertainty and complexity and need to be approached in a comprehensive and interdisciplinary way. For example, soil hydrophobicity and increased runoff resulting from consecutive dry days followed by a heavy rainfall event, will not be represented. CO_2 fertilisation effects were also not included in this study, whereas as noted in Chapter 2 (section 2.6), and outlined in the methodology section of Chapter 5, the modelling of plant responses to elevated CO_2 under variable environmental and management conditions has been identified as a major source of uncertainty in our understanding of how global change processes will be manifested at farm level (Li et al., 2014; Rötter et al., 2011; Soussana et al., 2010).

In addition, many strategies employed by the farmers to manage microclimate and water flow through the system are currently beyond the scope of the model. This study has not considered biosecurity risks and this represents a significant gap in this research to date. Small changes in climate can alter the distribution and abundance of potential pests and diseases significantly (Reisinger et al., 2014).

Theoretically, with research investment, many of the factors identified as gaps could be modelled. For example, pests and diseases are not included in the WFM, although other modelling studies have analysed potential changes in distribution of pest species under climate change (e.g. Diffenbaugh et al., 2008; Garrett et al., 2013).

Each set of adaptations will be specific to the context of the farm in question. The goal of such research, therefore, is to identify likely cascades of impacts, and principles that will support adaptive future farming systems.

In many cases, it needs to be recognised that research may lag behind farmer experimentation. Incremental adaptation on farm is ongoing and continuous, and can happen much faster than research. Before this study was completed, for example, the maize area on the BOP farm had already been increased. It is important, therefore, to recognise on-farm experimentation as a source of both innovation and context-specific research questions, and look for ways to further stimulate this, as well as improving farmer-researcher communication.

In order to promote local experimentation, farmers need as much local level information as possible. Support for experimentation on, and sharing information from, focus farms becomes extremely important in this context.

There is also a need to expand the options available, for example by looking for climate analogues. Cropping may increase under climate change but it will be important to support this with a broader range of cropping options and information. For example, fodder sorghums are used for autumn grazing by cattle in Australia; and it has been suggested that they might have potential in the New Zealand environment (Silungwe, 2011). The Northland farmer was interested in the potential of sudax, a sorghum hybrid. However, this crop was not available in the WFM and no information is yet available on the DairyNZ website. Analogue studies, and interactions with farmers from different countries may become increasingly important under climate change.

6.4 Conclusions

This study has particularly emphasized the uncertainty that farmers have to deal with in making choices about adaptation. Firstly, the difference between the two sets of climate projections used in this chapter and Chapter 5, highlights the heavy influence of bias correction techniques when it comes to downscaling climate projections to farm level. While the general trends shown by both datasets follow the broad projections for New Zealand climate, localised effects are very difficult to predict in a country with such a diverse topography. This is especially the case for the northland farm site in this study. However, some insights can be drawn from the modelled results of the adaptation options. For example, that the Bay of Plenty farm is likely to experience increasingly challenging weather extremes; and that the Taranaki farm may be able to capitalise on improved growing conditions, unless limited by flooding events.

The adaptation options suggested by farmers in this study mainly took the form of tactical or incremental adjustments that can be carried out without significant changes to the farming system. Although farmers were asked to suggest climate change adaptations, in practice the suggestions reflected a range of concerns, including whether options for less intensive farming systems might be profitable in the case of increasing environmental regulation (Chapter 4). This further highlights the interconnectedness of challenges facing farmers.

In general, farmers indicated a high level of confidence in the resilience of their systems (Chapter 4). However, when the suggested changes were modelled under climate change scenarios, they did not fully compensate for the negative impacts in many areas. In addition, the adaptations tested performed consistently better under the baseline climate than under the future scenarios. This implies that while improving management practices according to our current understanding may mean these high-end farmers can stay in business under climate change scenarios, ongoing work and innovation will be required to optimise the farming systems under future climate. However, a number of adaptation options have shown promising results. In particular, making and feeding out more silage showed real benefits for the farm tested. Cropping options may also hold significant promise, but this will depend on highly context-specific factors.

It should be recognised that for the purpose of assessing new innovations, modelling has significant limitations as a tool to assess future farming systems. While integrated models such as the WFM can provide a picture of recombinations of management practices we already know well, new crops and pasture species, and innovative adaptation options and strategies, will by definition, be beyond the scope of the current model.

Both farmers and researchers, in different ways, can be limited in their thinking which can create blockages for innovation. In order to overcome these limitations, an increased number of options need to be researched and made available to farmers, for example, through active searches for climate analogues and mutual sharing of information.

Finally, careful thought needs to be given to ensuring that both research and regulatory drivers promote flexible, adaptive farming systems; and that they support the maintenance of diversity across the different types of farming systems that will be appropriate in different regions.

7 General discussion and conclusions

7.1 Introduction

The overall goal of this research was to identify and analyse potential strategies for New Zealand dairy farms to adapt to projected climate change within a complex framework of interlinking socio-economic and biophysical variables. To structure the research, three research questions were formulated (Chapter 1). They were:

1. How can climate change impacts and potential adaptation options be assessed in a way that will adequately reflect their implications for the whole farming system?
2. Will New Zealand dairy systems need to adapt to a changing climate?
3. Which adaptation strategies have the potential to enhance both the productivity and resilience of dairy farming systems under future climate change scenarios?

In order to address these questions in a way that would adequately capture some of the challenges and complexities of adaptation at farm level, a mixed methods framework was developed (Kalaugher et al. 2013, Chapter 3). Section 7.2 reviews the strengths, weaknesses and broader applicability of this research method.

Section 7.3 then addresses the second research question, drawing conclusions from the modelled impact analysis and the social research undertaken to gain a more in-depth understanding of both likely impacts and the farmers' capacity for autonomous adaptation. In section 7.4, addressing the third research question, adaptation options are reviewed and conclusions drawn, highlighting the trade-offs inherent in the choices available. The wider implications of such choices are then considered from the perspective of future pathways for the New Zealand dairy sector.

7.2 How can potential adaptation options be evaluated in a way that will adequately reflect their potential impact on whole farm systems?

Evaluation of climate change adaptation strategies for adaptive socio-ecological systems such as dairy farms is complex, heavily influenced by uncertainty, and occurs at multiple levels (Chapters 2 and 3). It requires an in-depth understanding of both the dynamic nature of the farming systems themselves and the changing environment in which they operate. As highlighted in Chapter 3, much of the ongoing adaptation research at both the theoretical and practical level has a strong disciplinary focus, either on the use of quantitative models or on framing adaptation in the social and management research sphere. The poor integration of socioeconomic and biophysical studies was further emphasised in the most recent IPCC assessment, where it was noted as a factor limiting our capacity to effectively assess both future vulnerabilities and the potential effectiveness of adaptation strategies (Reisinger et al., 2014).

The Mixed Methods framework (Kalaugher et al. 2013, Chapter 3) was developed to provide a practical way to integrate quantitative and qualitative research and support the potential for different disciplines to complement each other. It sought to move beyond the ongoing debate about whether adaptation research is best approached from a qualitative or a quantitative worldview, in order to profit from the interplay and feedback between the different approaches.

Applying the Mixed Methods Framework in this research has provided a structured approach to the integration of different methods. This combined methodology meant that it was possible to reach beyond the limitations of each discipline and form a more holistic picture of potential adaptation strategies. Some strategies lent themselves easily to testing in a model, while others were beyond its scope. Conversely, the modelling work enabled a more objective and quantified assessment of farmer perceptions about the resilience of their systems.

Approaching the assessment from different perspectives enabled cross-referencing of ideas generated and provided clear insights about the limitations of each approach, adding significantly to the robustness of the analysis. The approach was effective in adding depth to the analysis which would not have been possible using these methods in isolation. For example, this provided a better understanding of the practicalities of some of the adaptation options modelled (Chapter 5), as well as a broader perspective on how other changes such as staffing issues may impact on adaptive capacity (Chapter 4).

7.2.1 Challenges and limitations

A key limitation of the approach taken in this study was that such a case-based methodology remains exploratory in nature and the conclusions drawn cannot be confidently extrapolated as a general assessment of the adaptive capacity across New Zealand's dairy farmers. In order to build a more comprehensive understanding, a broader scale approach would be necessary across a larger number of farms with an expanded set of methodologies.

Models are one of the best ways to track the complex movement of resources in a farming system. They are valuable tools for quantifying and recombining potential impacts and adaptations that are already well understood. However, for the purposes of innovation, which by definition requires thinking outside our present mental models, their capacity is limited. In most applications, practices and processes that can be represented by the current suite of models will limit the evaluation to tactical responses only.

Many impacts from climate change, particularly those related to extreme weather events, are difficult to model. In addition, many strategies employed by the farmers, for example, to manage microclimate and water flow through the farming system, are currently not part of the Whole Farm Model (WFM). Theoretically, with research investment, many of the factors identified as gaps could be modelled. CO_2 fertilisation effects have been included in other modelling work (Cullen et al., 2009; Stokes et al., 2012) although these effects are not yet included in the WFM and further work may be required to improve the accuracy of such estimations (Li et al., 2014). Likewise, other modelling studies have analysed potential changes in distribution of pest species under climate change (e.g. Diffenbaugh et al., 2008; Garrett et al., 2013). The need to improve process-based modelling of grazed farming systems has been identified (Snow et al., 2014).

However, to more fully reflect farm system changes in the climate change context, models may also need to evolve to incorporate more landscape-scale processes.

There are certain choices relating to the research techniques that could make application of the Mixed Methods Framework more effective in the future. For example, for the purpose of supporting farmers to find new options, it may be more useful to incorporate a broader set of climate analogues and projections in the initial stage of brainstorming potential options. In addition, alterative social research instruments such as group workshops (e.g. Sautier et al., 2014) where a set of defined criteria are explored utilising tools like multi-criteria mapping might be more effective in the early stages. A broader suite of options could be identified before the more intensive modelling process is carried out, and other methods of analysis sought for the options that cannot be easily modelled.

It is important to recognise on-farm experimentation as a source of both innovation and context-specific research questions. In order to promote local experimentation, farmers need as much local level information as possible, aided by information sharing from peers and researchers. Evaluating management strategies from other countries such as Australia and South Africa and potentially modifying these for the New Zealand environment may also be a useful way to expand the suite of adaptations.

There are good reasons why integrated, transdisciplinary research is often called for but rarely implemented. While it is generally recognised as desirable to carry out integrated research, there are few models to follow, and little practical advice on how to integrate knowledge from different disciplines.

Different scientific disciplines have different cultures, different languages and different definitions of what is considered quality science. On the one hand, social science methodologies aim to encompass ‘on the ground’ real world complexity. They rely on interpretation and judgement and as such, are heavily dependent on the skill of the researcher. The admission of subjectivity and level of interpretation required in analysing qualitative data reduces the robustness of the results, an important criterion for many biophysical scientists. Biophysical scientists aim to uncover facts or laws relating to the function of systems that are robust with replicable results. On the other hand, biophysical science, in aiming for complete objectivity, is constrained in what can be measured or observed directly, and this limitation is considered unacceptable to many social scientists.

Integrating knowledge from different disciplines significantly increases the complexity of the analysis as it is more difficult to trace the origin of a particular idea or conclusion when information has come from a range of different sources. Where the research method is both integrated and iterative, this can pose a challenge to showing the path that lead to a particular conclusion in a manner that it considered robust in the context of a specific discipline.

7.2.2 General applicability

The framework utilised for this study is specific to the analysis of climate change adaptations for farming systems (Chapter 3). However, the framework could readily be adapted to suit the analysis of other kinds of 'messy' problems.

Initially, the methodology was conceptualised as moving between quantitative and qualitative sciences in clear steps. In practice, the real value of the methodology lies in the interaction between the different disciplines, and the approaches used became less clear-cut as the study developed.

The challenges to interdisciplinary research as described here highlight potential areas for further work that could support wider use of approaches like the Mixed Method Framework. One of the important contributions of interdisciplinary research is that it presents a challenge to the epistemologies of each scientific discipline. It would be useful to carry out further research to consciously challenge and make explicit both the underlying assumptions and the value of the different kinds of knowledge generation, and address the challenges in combining them in a more structured way. Particularly where interdisciplinary research is carried out by teams rather than individuals, investment may be required for team members to learn the basic culture of each discipline so that research can be interactive and iterative, rather than simply parallel investigations into the same research questions.

This study has intentionally moved between different worldviews, finding points of convergence and divergence. This approach highlighted some of the tensions present in striving for a dynamic and innovative approach to knowledge generation that is also scientifically rigorous. For example, for the farmers interviewed, who possessed the personal skills and experience to innovate, research was seen as a much slower, heavier process than what could be achieved directly on-farm.

To meet the requirements of future farmers, research and on-farm innovation will need to complement each other and catalyse new forms of knowledge. The need for agricultural extension to develop more in the direction of 'knowledge brokering' between different stakeholders and different forms of knowledge is increasingly recognised (Klerkx et al., 2012). Such knowledge brokering to facilitate innovation will be a key component of successful adaptation to climate change.

7.3 Will New Zealand dairy systems need to adapt to a changing climate?

Based on this study and also on previous research (e.g. Baisden et al., 2010; Clark et al., 2012; Wratt et al., 2008; Zhang et al., 2007), there is a strong case for dairy farms in New Zealand to engage in the process of strategic adaptation to climate change.

This study has highlighted the localised nature of climate change impacts. Climatic changes will be highly uncertain and vary considerably between individual farms. The individual farms have an almost unique profile of vulnerability given their biophysical setting, but also because of different farm structures, approaches to management and capability. It is therefore difficult to draw generalisations across the sector about detailed adaptive capacity, which is also compounded by changes such as in environmental regulations, changes in the structure of farms and expectations and skills of staff, and economic changes.

However, the six case study farms in this study were identified as high performing farms by researchers and consultants, and taken to represent current good management practice for their given region. While it is not possible to extrapolate conclusions about the adaptive capacity of New Zealand dairy farmers from these six case studies, it is suggested that if these experienced farmers will need to adapt, there is a strong likelihood that less experienced farmers with higher debt levels will be more heavily impacted.

7.3.1 Evidence of impacts

For the six case study farms, the impacts of climate change under current practice were mostly negative in terms of economic performance. In general, the farmers indicated a high level of confidence in the resilience of their systems (Chapter 4). However, when the suggested changes were modelled under climate change scenarios (Chapter 6), they did not fully compensate for the negative impacts in many areas. In addition, the adaptations tested performed consistently better under the baseline climate than under the future scenarios. This implies that while improving management practices according to our current understanding may improve current farm performance and may mean farmers can still stay in business under future climate, ongoing work and innovation will be required to optimise farming systems under future climate to meet the full range of pressures.

The in-depth consultation with farmers established that the baseline management benchmark used in this study is not a static or set factor. It moves within the bounds of a range of well-proven management tactics and practices given the skills and resources of individual farmers. Farming systems are constantly adapting to variability in the environment around them, including a range of shifting pressures and influences. As highlighted in Chapter 4, principal among these risks from the farmer perspective is potential change to environmental regulations, and also management/labour issues, both of which may be impacted indirectly by climate change and will in turn affect farmers' capacity to adapt.

There is still significant uncertainty present in the projected impacts of climate change. In previous broad-scale studies, the results of the different analyses varied depending on uncertainties present in factors such as the role of the CO_2 fertilisation effect. In some cases this made the difference between a positive and a negative impact of climate change. This study has shown the importance of seasonal effects at farm level. In practice, CO_2 fertilisation effects will be limited by nutrient and water availability and also exhibit seasonal patterns. They are therefore likely to strengthen patterns of seasonality shown in this study, as well as interannual variability that has yet to be accurately modelled (Li et al., 2014). Further work is required to adequately capture these interannual and seasonal effects in integrated farm scale models such as the Whole Farm Model.

Another major source of uncertainty in this analysis lies in the climate projections themselves, particularly for rainfall. The climate projections used in this work are storylines from the broader set of scenarios that are available in New Zealand (Mullan et al., 2008). These highlight large differences in projections of precipitation in some parts of the country, with consistencies in others. The range of outcomes is wide across GCMs, but becomes even wider when considering global emissions scenarios into the future. To some extent these are compounded by errors in the downscaling methodologies used.

7.3.2 Capacity and incentive to adapt

There is an ongoing debate about whether the incremental adjustments farmers make continuously on-farm will be enough under climate change scenarios. Concerns have been expressed that ongoing and increasing variability under climate change can mask changes in the climate signal, and that incremental adjustments made by farmers will postpone such system breaks and reduce the incentive for potentially more beneficial, but more costly transformational changes (Chhetri et al., 2010).

When the farmers engaged in this research were asked to suggest adaptations that could be evaluated, their suggestions almost exclusively took the form of tactical or incremental adjustments to their farming systems that could be carried out without significant investment, low costs and minimal changes to the system itself. It is possible that they may underestimate the risks posed by climate change, in so far as it can be established by climate projections. The data presented to the farmers in Chapter 5 reflected only average percentage changes in the indicators selected, and further consideration is required on the best way to present climate change projections to farmers in a way that will more accurately reflect the range of potential impacts. However, the fact that incremental adaptations were preferred by these farmers is most likely because the farms were performing well under current climate conditions and it is difficult to establish a clear return on investment in the next 5-10 years for transformational change. The complexity and uncertainty associated with potential future stresses and shocks suggest that while the system is currently performing well, there is little incentive to plan for more extensive system changes. Instead, priority is given to risks that may limit future adaptive capacity, such as regulatory risks and those associated with management and staff capability.

The continued interest in reducing stocking rates on some farms may also be an indication of concern about environmental regulation, rather than climate change (Chapter 4). This further reflects the interconnectedness of challenges for farmers, and the influence that uncertainty around potential environmental regulations may have.

Novelty and innovation are essential to the ongoing viability of any system. In the case of agricultural systems, breaks occur with the onset of extreme weather events, or when they are compounded, and/or are combined with other pressures. If pressures increase concurrently with future climate change, and extreme weather events become more frequent, the incentive to carry out more strategic and if necessary, transformational adaptations is likely to increase accordingly. However, the point at which a particular farm needs to go through strategic or even transformational adaptation will vary depending on the combination of pressures, the resilience of the farm, and the capacity of the farmer(s) to adapt. Where extreme weather events are a catalyst for system breaks, it is likely that farmers in the same geographic region may go through such points at the same time. Recognising such system breaks or ‘tipping points’ as catalysts for innovation or ‘novelty pumps’ with the potential to generate the innovation required to create new structures and dynamics (Allan and Holling, 2010), may provide opportunities to proactively transform farming systems. Support for strategic or transformational change can often be provided most efficiently to farmer groups and networks when they have reached or can see an impending breaking point, for example, after a severe drought. However, there is a tension between the challenge of responding to immediate crisis and setting and implementing longer-term strategies (Nettle et al., 2012). Further research could usefully be directed at better understanding the kinds of support required by farmers for system change, and the optimal points in time for such support to be provided.

Experienced farmers can be considered successful managers of variability, and experts in adaptation by definition, having been through a range of extremes of both weather and other factors such as price fluctuations, and stayed in business. They have built up an understanding of the different mechanisms for maintaining enough flexibility and diversity in their farming systems to cope with the range of climatic and other influences they have so far experienced. As such, they represent a key resource in the development of potential future adaptation options.

7.4 Which adaptation strategies have the potential to enhance both the productivity and resilience of dairy farming systems under climate change scenarios?

7.4.1 Adaptation options

The combined methods used in this study uncovered a rich bank of practical knowledge for the dairy sector. It revealed a wide variety of current and potential future adaptations that are available to dairy farmers. It also strongly highlighted that application of this knowledge for adaptation is highly context-specific. For some areas, adapting to climate change may be about making the most of new opportunities. For others, the viability of dairy farming in the area may be challenged. Adaptation is a continuous process, and can range from small adjustments to current tactical management practices, to more substantive changes to the whole farming system, through more profound transformational changes where new systems are developed.

Several of the adaptation options modelled in this study showed considerable promise to mitigate potential negative impacts from climate change. Simply making and feeding out more silage, for example, may reduce the impact of increasing variability in the feed curve. Cropping options may also hold considerable potential. These and other adaptations such as increasing use of animal housing are already being taken up by dairy farmers, and as such are likely to have broad implications for the future trajectories of New Zealand dairy farming.

Adaptation of farming systems requires the investment of time, energy, and financial resources, and brings with it the potential for maladaptation. There are always trade-offs to be made, and evaluation of potential adaptation options needs to make these trade-offs as explicit as possible in order to understand the impact of particular choices on the farming system.

A key measure of successful adaptation is financial profit. However, this study has emphasized the importance of including also other measures in assessing whether a particular option will increase the viability and resilience of the farming system.

Based on this study (in particular, Chapter 4), some of the most important criteria underlying resilience include:

- ***Profit:*** Will the adaptation increase overall profit?
- ***Financial risk:*** Will the adaptation increase financial risk?
- ***Environmental risk:*** Will the adaptation reduce or increase risks to the environment, and compliance with environmental regulation now and in the future?
- ***Management risk:*** Do management and farm staff have the knowledge and skills required to implement the adaptation?
- ***Biological risks:*** Will the adaptation affect biological risks, such as pests and diseases?
- ***Flexibility:*** Will the adaptation increase or reduce the flexibility of the farm to change direction in future?

In Chapter 2, a number of strategies were outlined based on a literature review of adaptation strategies relevant to temperate dairy farms. While some of these strategies were able to be tested as part of this study, others were not easily modelled. However, the experienced farmers who took part in the study were able to provide insights into some of the trade-offs involved in adopting a particular strategy. Some trade-offs for the strategies identified included the following:

Adopting species better adapted to the anticipated climate has considerable potential, as shown by the modelled switch to tall fescue (Chapter 5). A potential source of vulnerability was identified in the heavy dependence on ryegrass as a pasture species. Successful use of alternative pasture species and mixes will require not only research into the pasture species themselves but improved understanding of their management, as successful management practices can vary considerably between species. Appropriate endophyte options may also be increasingly important if pest incursions increase. Improvements in cattle genetics are increasingly focussed on metabolic efficiency, both for improved feed utilisation and reduction of methane emissions; and may also be directed at alleviating heat stress in future. Genetic improvement may also improve resistance to disease.

The development of new species and cultivars also carries a high level of risk, because of the significant investment required. Early consideration of practical aspects of the integrating of new species or cultivar into current farming systems, together with farmers, can help mitigate this risk.

Reducing intensity for example, by reducing stocking rate, consistently reduces operating profit for the farms studied, with few exceptions (Chapters 5 and 6). However, the farmers continued to show interest in fine tuning their stocking rates and reducing them where possible. The farmers' continued interest stems from the fact that reducing stocking rates clearly has positive benefits in reducing risk on a number of fronts by decreasing pressure on the farm system. In particular, it reduces risk in years where less pasture is grown, and reduces environmental (and hence regulatory) risks. When combined with other management practices such as increasing per-cow production or increasing silage making, it can be positive. Once-a-day milking is another example of reducing intensity that is considered a positive choice by some famers, despite the reduction in overall profit. Reducing management pressure and thereby enabling more mental space to plan the ongoing development of the farming system, was a key recurring strategy among these experienced farmers (Chapter 4) and should be considered an important aspect of adaptive capacity.

Importing resources, particularly feed to fill feed gaps, is now commonplace in New Zealand dairy systems. This currently represents the "easy option" for filling a feed gap and as such is being increasingly utilised. However, it does not necessarily increase profit. It also represents a significant source of vulnerability, particularly if global feed stock and prices are affected by climate change and other market logistics. It may also be a source of vulnerability to biological risks such as pests and diseases.

Diversification as a strategy can be employed at different levels. Research is currently ongoing to understand the potential benefits of mixed pastures (Woodward et al., 2013, Beukes et al., 2014), with promising results for reducing risk both for productivity and environmental outcomes. At the farm/enterprise scale, cropping is an example of diversification which can also work very well to reduce risk. Growing maize for silage had a positive economic outcome when it was modelled (Chapter 6) and formed an important buffer to climate change impacts where it was already present (Waikato farm, Chapter 5). It also has a positive impact on financial risk, and depending on management practices can be positive from an environmental perspective, for example, through practices such as effluent irrigation. Cropping options will likely become more important under climate change and with potentially increasing intensification. Thus further research aimed at expanding cropping options available to dairy farmers in New Zealand would be of value. It will also be important to understand the potential environmental risks and benefits associated with different crops and different management practices, in order to avoid maladaptation.

Investment in infrastructure such as animal housing and irrigation infrastructure is a way to increase control over climate, and is therefore often considered a positive adaptation to climate change. The potential to capture more urinary nitrogen is also seen by some farmers as insurance against potential future regulations. However, the farmers in this study urged caution in taking up such options as they represent a major investment, and effectively reduce flexibility, driving future developments towards increasing intensity. Intensive, housed systems such as those utilised in other countries are not seen as profitable by many farmers. Increased stocking rates may also have a negative environmental impact even where animals are housed, as they will still require more feed and water resources. Increasing irrigation may have environmental consequences, and irrigation infrastructure may also involve other trade-offs, for example, where trees need to be removed to accommodate central pivot irrigators or when water restrictions are enforced.

Improving resource use efficiency such as water use efficiency, precision use of fertilisers, higher pasture utilisation and increasing milk production per cow are recognised as key strategies for the dairy industry to reduce risk to multiple stresses. In this study, making silage when there is surplus was shown to have a positive highly positive outcome in the modelled scenarios. The main limitation to this form of adaptation is the time, knowledge and management skill required to implement it. However, there are other considerations in relation to capacity. For example, should silage making increase significantly, other issues may require consideration such as the environmental impact of silage wrap, and the availability of contractors to carry out the silage making.

Approaches to improving resource use efficiency can be high- or low-tech, with the associated high or low investment requirements. The silage-making adaptation represented an extension of current management practices on most of the farms. In some cases, for example developments in precision farming, significant investment in technology can be required, in which case the same cautions apply as those discussed under investments in infrastructure.

Natural microclimate management, for example, planting trees and managing water flows through the farm, are likely to have potential benefits. The Northland farmers, in particular, had invested in both tree planting and improving the drainage of some paddocks. The trade-off here is in time, financial investment and sometimes in land availability. The absence of mention of this strategy during the formal interviews may indicate a need to raise awareness of the potential benefits of vegetation such as trees on farms, as they are still viewed by some farmers primarily as competition for water and nutrients, and often need to be removed for the installation of irrigation infrastructure (Chapter 4) which can have a negative effect on microclimate.

Timing adjustments such as earlier calving or a complete switch to winter milking were of considerable interest to some of the farmers. This could potentially be modelled, but a number of different system adjustments would need to be made. Winter milking, for example, would have implications not only for the timing of feed supply but would require reconsideration of cropping cycles and practices. Calving in autumn also raises potential animal welfare considerations and possibly system changes such as increased animal housing to compensate. Such strategies need to be assessed in the context of each farming system.

Planning tools and technologies such as improved weather prediction and pasture monitoring are likely to provide benefits, considering the adage cited by one farmer that “the difference between a good farmer and a bad farmer is two weeks” implying that good farmers make timely projections about the near future using the information available today. As with all new technologies, the costs and benefits of each will need to be assessed in context.

7.4.2 Wider implications

In order to sustainably adapt to changes in climate, we need to assess the vulnerability of a system beyond its current state and assess the trajectories or paths that might affect the capacity of the system to respond in the future (Nelson, 2014).

In the agricultural context it is important to consider resilience outside the traditional ‘single farm’ focus. Resilience can be built into a given set of interlinking systems or 'panarchy' in time and space. While a particular component of a system may not be very resilient, the larger system in which it is embedded may be (Allan and Holling, 2010). The converse is also true, and applies to different adaptation strategies in the dairy sector. For example, buying in feed provides a buffer to the farming system in case of drought. At a broader scale, however, if all farms employ the same strategy, this can increase vulnerability in the system at a higher level. In the same way, large scale irrigation can provide benefits at farm level, but may contribute to the depletion of water resources at a broader scale.

Global climate change is likely to have a negative impact on crop production (Teixeira et al., 2013); a slowing in global crop yield growth has also been projected (Lobell and Tebaldi 2014). This may lead to increases in crop prices around the world. The modelled scenarios in this study showed a high level of sensitivity to changes in the economics, especially feed prices.

Potential impacts from changes in feed supply imply the need to ensure a higher level of self-sufficiency in sources of feed. A reduction in the potential yield of crops in other parts of the world may be a source of vulnerability, but may also be seen as an opportunity for New Zealand. For example, the modelled scenario on the Taranaki farm provided an example of how these pressures might be capitalised on.

Many of the potential adaptations under climate change described in this study if taken up more widely, may add pressure to intensify. In particular, standoff pads and animal housing, as well as large scale irrigation, require investment in infrastructure. Farmers have voiced concerns that these investments may mean that higher stocking rates will be necessary in order to finance the required infrastructure (Chapter 4). While more intensive systems may be a profitable option for many farmers, there is a danger that investment in these systems to the exclusion of other options may reinforce the current trajectory and create path dependency. In terms of future growth, the dairy industry strategy emphasises improved technologies and an increase in per cow production (DairyNZ, 2014). However, this will still require more feed and more water, which may add to existing pressure on natural resources.

In analysing potential pathways for New Zealand dairying, climate change is only one of many challenges that will need to be taken into account in adapting to the future. Careful thought needs to be given to ensuring that both research and regulatory drivers promote flexible, adaptive farming systems; and that they support the maintenance of diversity across the different types of farming systems that will be appropriate in different regions.

Considering the high degree of uncertainty present in assessments of both climate and other pressures, the most important factor in the successful development of the New Zealand dairy industry may be the degree of flexibility that can be maintained at different levels, from farm scale management to national regulation, in order to continuously adapt.

7.4.3 A way forward

Concepts of resilience and adaptive capacity are central to the discussion around climate change adaptation, and have been defined in different ways by different authors. Resilience, for example, has traditionally been described in terms of the ability of a system to bounce back or return to its original form and function. In the most recent IPCC definition, the concept of resilience encompasses the capacity to adapt to future stresses (IPCC, 2014).

Moving from a theoretical understanding of resilience and adaptation must account for the context in which the concepts are used. In the case of dairy farming, the agricultural system is never static but in a constant state of development. Farmers' strategies focus on ensuring resilience, including the latent capacity to adapt (Chapter 4). This enables them to react appropriately to future uncertain stressors as they have an impact at farm level. Such adaptive management appears to be the best strategy available to manage a farming system within the defined boundaries over which farmers have a degree of control. From the perspective of the farmers in this study, climate change is an uncertain, potential future stressor (Chapter 4). Adaptation is already occurring, and is likely to occur in future, not based on whether farmers believe in climate change as an abstract academic concept, but rather on whether their system is working in its current form and has the potential to remain sustainable.

When more strategic or even transformational change becomes necessary, this will likely be due to compounding stresses and will be recognised by most farmers as their livelihoods will be at stake. This is the point at which an understanding of climate change becomes important: In order to define an adaptive pathway for the farm in question and avoid maladaptation (Wise et al., 2014), climate change will need to be taken into account along with other factors that will influence the viability of the future farming system. Incorporating climate change into farm planning as one of many future pressures is also a better fit with farmers' approach to managing their complex farming systems than attempting to address climate change issues in isolation.

At national level, such 'pathways thinking' (Wise et al., 2014) will be important. Currently in New Zealand, most adaptation research is undertaken in isolation from other sectoral planning initiatives. For example, while climate change research consistently indicates a likely strengthening of weather extremes, a pattern which is now also increasingly recognised by farmers (Chapter 4), sectoral planning documents regularly refer to the weather returning to 'normal' after a drought year (MAF, 2008; MPI, 2013), implying the expectation that the long term average weather conditions will be as favourable as they have been in the past. This may be due in part to the polarised and political nature of early discussions around climate change in New Zealand, which focussed primarily on mitigation. A significant danger inherent in such segregation is the underestimation of indirect impacts of climate change that may have a greater impact on the agricultural sector than direct weather effects, such as potentially increasing pest incursions.

The time has come to openly discuss climate change, not as an impending disaster for which farmers are partially responsible, but as part of an evolving picture of challenges and opportunities facing the agricultural sector. It is only by mainstreaming climate change considerations into both farm-scale and sectoral planning, together with other, interrelated issues such as environmental regulation, financial vulnerability, management and labour issues, and pest and disease threats, that we will be able to successfully adapt to the increasingly dynamic and overlapping pressures on agricultural systems.

References

Abler, D., Shortle, J., Rose, A., Oladosu, G., 2000. Characterizing regional economic impacts and responses to climate change. Glob. Planet. Chang. 25 (1,2), 67-81.

Ackerley, D., Dean, S., Sood, A., Mullan, A.B. 2012. Regional climate modelling in New Zealand: Comparison to gridded and satellite observations. Weather Clim. 32 (3) 22.

Adger,W.N. 2003. Social capital, collective action, and adaptation to climate change. Econ. Geogr.79, 387-404.

Adger, W.N, Arnell, N.W., Tompkins, E.L. 2005. Successful adaptation to climate change across scales. Glob. Environ. Chang. 15,77-86.

Adger, W.N., 2006. Vulnerability. Glob. Environ. Chang. 16 (3), 268-281.

Aldunce, P., Beilin, R., Howden, M., Handmer, J. 2015. Resilience for disaster risk management in a changing climate: Practitioners' frames and practices. Glob. Environ. Chang. 30,1-11.

Allan, C., Stankey, G.H. (Eds.), 2009. Adaptive Environmental Management: a Practitioner's Guide. Springer.

Allen, C.R., Holling, C., 2010. Novelty, adaptive capacity, and resilience. Ecol. Soc. 15 (3), 24.

Amaru, S., Chhetri, N.B. 2013. Climate adaptation: Institutional response to environmental constraints, and the need for increased flexibility, participation, and integration of approaches. Appl. Geogr.39,128-139.

Anda, J., Golub, A., Strukova, E. 2009. Economics of climate change under uncertainty: Benefits of flexibility. Energ. Policy 37,1345-1355.

Aydinalp, C., Cresser, M.S., 2008. The effects of global climate change on agriculture. American-Eurasian J. Agric. Environ. Sci. 3 (5), 672-676.

Bader, D., Covey, C., Gutowski, W., Held, I., Kunkel, K., Miller, R., Tokmakian, R., Zhang, M., 2008. Climate Models: An Assessment of Strengths and Limitations. US Department of Energy, University of Nebraska - Lincoln, 2008.

Baisden, W.T., Keller, E.D., Timar, L., Smeaton, D., Clark, A.J., Ausseil, A., Power, W., Zhang, W. 2010. New Zealand's Pasture Production in 2020 and 2050, GNS Science Consultancy Report 2010/154, 65 p.

Baldwin, R.L. 1995. Modeling Ruminant Digestion and Metabolism. Chapman and Hall, London, UK.

Barnett, J., O'Neill, S., 2010. Maladaptation. Glob. Environ. Chang. 20 (2), 211-213.

Barreteau, O., Bots, P.W.G., Daniell, K.A., 2010. A framework for clarifying "participation" in participatory research to prevent its rejection for the wrong reasons. Ecol. Soc. 15, 1 (online).

Basher, L., S. Elliot, A. Hughes, A. Tait, M. Page, B. Rosser, I. McIvor, G. Douglas, and H. Jones, 2012. Impacts of Climate Change on Erosion and Erosion Control Methods – A Critical Review. MPI Technical Paper No. 2012/45, Ministry for Primary Industries, Wellington, New Zealand, 208 pp.

Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68 (6), 1615-1625.

Beck, U. 1996. Risk society and the provident state. In: Lash, S., Szerszyenski, B and Wynne, B. (Eds.), Risk,environment and modernity: Towards a new ecology. pp. 27-43. London: Sage.

Beijeman, A., Shadbolt, N.M., Gray, D., 2009. Strategy recognition and implementation by New Zealand pastoral farming strategists. In: Peer Reviewed Paper for the 17th International Farm Management Congress, July 19th to 24th, 2009, Illinois, USA. Massey University, Palmerston North, New Zealand.

Bennett, N.D., Croke, B.F.W., Guariso, G., Guillaume, J.H.A., Hamilton, S.H., Jakeman, A.J., Marsili-Libelli, S., Newham, L.T.H., Norton, J.P., Perrin, C., Pierce, S.A., Robson, B., Seppelt, R., Voinov, A.A., Fath, B.D., Andreassian, V., 2013. Characterising performance of environmental models. Environ. Model. Softw. 40, 1-20.

Berman, A., 2005. Estimates of heat stress relief needs for Holstein dairy cows. J. Anim. Sci. 83, 1377-1384.

Berrang-Ford, L., Ford, J.D., Paterson, J., 2011. Are we adapting to climate change? Glob. Environ. Chang. 21:25-33

Berry, P.M., Rounsevell, M.D.A., Harrison, P.A., Audsley, E. 2006. Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation. Environ. Sci. Policy 9, 189-204.

Beukes, P.C., Palliser, C.C., Prewer, W., Serra,V., Lancaster, J.A.S., Levy, G., Folkers, C., Neal, M., Thorrold, B.S., Wastney, M.E. 2005. Use of a Whole Farm Model for Exploring Management Decisions in Dairying. In Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 177-183.

Beukes, P.C., Palliser, C.C., Macdonald, K.A., Lancaster, J.A., Levy, G., Thorrold, B.S., Wastney, M.E., 2008. Evaluation of a whole-farm model for pasture-based dairy systems. J Dairy Sci. 91, 2353-2360.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G.C., 2010a. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agric. Ecosyst. Environ. 136 (3,4), 358-365.

Beukes, P.C., Burke, C.R., Levy, G., Tiddy, R.M. 2010b. Using a Whole Farm Model to determine the impacts of mating management on the profitability of pasture-based dairy farms. Anim. Reprod.Sci.121, 46-54.

Beukes, P.C., Gregorini, P., Romera, A.J., Dalley, D.E., 2011. The profitability and risk of dairy cow wintering strategies in the Southland region of New Zealand. Agric. Syst. 104 (7), 541-550.

Beukes, P.C., Gregorini, P., Romera, A.J., Woodward, S.L., Khaembah, E.N., Chapman, D.F., Nobilly, F., Bryant, R.H., Edwards, G.R., Clark, D.A. 2014. The potential of diverse pastures to reduce nitrogen leaching on New Zealand dairy farms. Anim. Prod. Sci. 54,1971-1979.

Botha, N., Roth, H., and Brown, M., .2013. The Adaptation of Pastoral Farmers to Environmental Policy Changes: A New Zealand Case Study. S Afr J Agr. Extension. 41, 16-25.

Bourdôt, G.W., Lamoureaux, S.L., Watt, M.S., Manning, L.K., Kriticos, D.J., 2012. The potential global distribution of the invasive weed Nassella neesiana under current and future climates. Biol. Invasions, 14 (8), 1545-1556.

Boxelaar, L., Sharma, M., Paine, M. 2006. Sustaining Our Social and Natural Capital: Enhancing the Resilience of Dairy Farmers. Proceedings of the

12th ANZSYS conference - Sustaining our social and natural capital, Katoomba, NSW Australia, 3rd-6th December, 2006. Pp 329-338.

Briske, D.D., Washington-Allen, R.A., Johnson, C.R., Lockwood, J.A., Lockwood, D.R., Stringham, T.K., Shugart, H.H., 2010. Catastrophic thresholds: a synthesis of concepts, perspectives and applications. Ecol. Soc. 15 (3), 37.

Brunsdon, R. V., 1962. The effect of nutrition on age resistance of sheep to infestation with Nematodirus spp. . N.Z. vet. J. 10, 123-127.

Bryant, J. R., López-Villalobos, N., Pryce, J. E., Holmes, C. W., Johnson, D. L., Garrick, D. J., 2007. Environmental Sensitivity in New Zealand Dairy Cattle. J Dairy Sci. 90, 1538-1547.

Bryant, J.R., Snow, V.O., 2008. Modelling pastoral farm agro-ecosystems: a review. N.Z. J. Agric. Res. 51 (3), 349-363.

Burton, I., Huq, S., Lim, B., Pilifosova, O., Schipper, E.L., 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. Clim. Policy 2 (2,3), 145-159.

Burton, R., Peoples, S., 2008. Learning from Past Adaptations to Extreme Climatic Events: a Case Study of Drought - Part A Summary Report. Ministry of Agriculture and Forestry, New Zealand.

Cabrera, V.E., Breuer, N.E., Hildebrand, P.E., 2008. Participatory modeling in dairy farm systems: a method for building consensual environmental sustainability using seasonal climate forecasts. Clim. Chang. 89, 395-409.

Caldwell, M. M., Bornman, J. F., Ballaré, C. L., Flint, S. D., Kulandaivelue, G., 2007. Terrestrial ecosystems, increased solar ultraviolet radiation, and interactions with other climate change factors. Photochem Photobio. S. 6, 252–266.

Callaghan, T.V., Björn, L.O., Chernov, Y., Chapin, T., Christensen, T.R., Huntley, B., Ims, R.A., Johansson, M., Jolly, D., Jonasson, S., Matveyeva, N., Panikov, N., Oechel, W., Shaver, G., Elster, J., Jónsdóttir, I.S., Laine, K., Taulavuori, K., Taulavuori, E., Zöckler, C. 2004. Responses to projected changes in climate and UV-B at the species level. Ambio, 33(7) 418-435.

Casella, E., Soussana, J.F., Loiseau, P., 1996. Long term effects of CO2 enrichment and temperature increase on a temperate grass sward. Plant Soil. 182, 83–99.

Chakraborty, S., Luck, J., Hollaway, G., Fitzgerald, G., White, N. 2011. Rust-proofing wheat for a changing climate. Euphytica, 179, 19-32.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. Nature Clim. Chang. 4, 287-291.

Chapman, D., Malcolm, L., Nela, M., Cullen, B. 2007. Risk and uncertainty in dairy production systems: research concepts, tools and prospects. In Meeting the Challenges for Pasture-Based Dairying. Proceedings of the Australian Dairy Science Symposium, Victoria, Australia.

Chapman, D.F., Cullen, B.R., Johnson, I.R., Beca, D. 2009. Interannual variation in pasture growth rate in Australian and New Zealand dairy regions and its consequences for system management. Anim. Prod. Sci. 49, 1071-1079.

Checkland, P., Poulter, J., 2010. Soft systems methodology. In: Reynolds, M., Holwell, S. (Eds.), Systems Approaches to Managing Change: a Practical Guide. Springer, London, pp. 191-242.

Chhetri, N.B., Easterling, W.E., Terando, A., Mearns, L. 2010. Modeling Path Dependence in Agricultural Adaptation to Climate Variability and Change. Ann. Assoc. Am. Geogr. 100, 894-907.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann N, Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R. 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437,529-533.

Clark, A., Tait, A., 2008. Drought, Agricultural Production & Climate Change - A Way Forward to a Better Understanding. National Institute of Water and Atmospheric Research, Wellington, New Zealand.

Clark, A., Mullan, A.B., Porteous, A., 2011. Scenarios of regional drought under climate change. NIWA Client Report WLG2010-32 prepared for Ministry of Agriculture and Forestry. 135 pp.

Clark, A.J., Nottage, R.A.C., Wilcocks, L., Lee, J.M., Burke, C., Kalaugher, E., Roche, J., Beukes, P., Lieffering, M., Newton, P.C.D., Li, F.Y., Vibart, R., Teixeira, E.I., Brown, H.E., Fletcher, A.L., Hernandez-Ramirez, G., Soltani, A., Viljanen-Rollinson, S., Horrocks, A., Johnstone, P., Clothier, B., Hall, A., Green, S., Dunningham, A., Kirschbaum, M.U.F., Meason, D., Payn, T., Collins, D.B.G., Woods, R.A., Rouse, H., Duncan, M., Snelder, T., Cowie, B., 2012. Impacts of Climate Change on Land-based Sectors and Adaptation Options. Clark, A.J.; Nottage, R.A.C. (eds.). Technical Report to the Sustainable Land Management and Climate Change Adaptation Technical Working Group, Ministry for Primary Industries, New Zealand.

Clark, D. A., Caradus, J. R., Monaghan, R. M., Sharp, P., Thorrold, B.S., 2007. Issues and options for future dairy farming in New Zealand. N.Z. J. Agric. Res. 50(2), 203-221.

Clark, D.A. 2011. Changes in pastoral farming practices and pasture persistence – a review. Pasture Persistence – Grassland Research and Practice Series 15, 7-14.

Clark, H., Mitchell, N.D., Newton, P.C.D., Campbell, B.D., 2001. The Sensitivity of New Zealand's Managed Pastures to Climate Change. In: Warrick, R. A., Kenny, G. J., Harman, J. J., (eds.)., The Effects of Climate Change and Variation in New Zealand: An Assessment Using the CLIMPACTS System. International Global Change Institute (IGCI), The University of Waikato, Hamilton, New Zealand, pp. 65-76.

Cobon, D.H., Stone, G.S., Carter, J.O., Scanlan, J.C., Toombs, N.R., Zhang, X., Willcocks, J., McKeon, G.M., 2009. The climate change risk management matrix for the grazing industry of northern Australia. Rangel. J. 31 (1), 31-49.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung,

A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cornell, S., Costanza, R., Sörlin, S., van der Leeuw, S., 2010. Developing a systematic science of the past to create our future. Glob. Environ. Chang. 20 (3), 426-427.

Cowan, L., Kaine, G., Wright, V. 2013. The Role of Strategic and Tactical Flexibility in Managing Input Variability on Farms. Syst. Res. Behav. Sci. 30, 470-494.

Craddock-Henry, N. 2011. Farm-level vulnerability to climate change in the Eastern Bay of Plenty, New Zealand, in the context of multiple stressors. PhD Thesis. University of Canterbury, Christchurch.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cullen, B., Eckard, R., Johnson, I., Lodge, G., Walker, R., Rawnsley, R., Dassanayake, K., Christie, K., McCaskill, M., Clark, S., Sanford, P., Browne, N., Sinclair, K., Chapman, D., Leiffering, M., Snow, V., Hovenden, M., Perring, M., 2008. Climate change impacts on Australian grazing systems: Whole Farm Systems Analysis and Tools for the Australian and New Zealand Grazing Industries Project Report. The University of Melbourne, Parkville, Victoria, Australia.

Cullen B.R., Johnson, I.R., Eckard, R.J., Lodge, G.M., Walker, R.G., Rawnsley, R.P., McCaskill, M.R. 2009. Climate change effects on pasture systems in south-eastern Australia. Crop. Past. Sci., 60, 933-942.

Cullen, B.R., Eckard, R.J. 2011. Impacts of future climate scenarios on the balance between productivity and total greenhouse gas emissions from pasture based dairy systems in south-eastern Australia. Anim. Feed Sci. Technol. 166-167, 721-735.

DairyNZ, 2012. DairyNZ Economic Survey 2010-11. Available: http://www.dairynz.co.nz/publications/economic%20Survey/dairynz_economic_survey_2010_11/

DairyNZ, 2014. DairyNZ Economic Survey 2012-13: 50 years of economic analysis. Available: http://www.dairynz.co.nz/publications/dairy-industry/dairynz-economic-survey-2012-13/

Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2010a. Adaptiveness to enhance the sustainability of farming systems. A review. Agron. Sustain. Dev. 30 (3), 545-555.

Darnhofer, I., Fairweather, J., Moller, H., 2010b. Assessing a farm's sustainability: insights from resilience thinking. Int. J. Agric. Sustain. 8 (3), 186-198.

Dessai, S., Hulme, M., 2004. Does climate adaptation policy need probabilities? Clim. Policy 4, 107-128.

Dessai, S., Lu, X., Risbey, J.S. 2005. On the role of climate scenarios for adaptation planning. Glob. Environ. Chang. 15, 87-97.

Dessai, S., Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the east of England. Glob. Environ. Chang. 17 (1), 59-72.

Di, H. J., and Cameron, K. C. 2005. Reducing environmental impacts of agriculture by using a fine particle suspension nitrification inhibitor to decrease nitrate leaching from grazed pastures. Agric. Ecosyst. Environ. 109, 202-212.

Diffenbaugh, N.S., Krupke, C.H., White, M.A., Alexander, C.E. 2008. Global warming presents new challenges for maize pest management. Environ. Res. Lett. 3 (4) doi:10.1088/1748-9326/3/4/044007

Dobes, L. 2008. Getting Real about Adapting to Climate Change: Using 'Real Options' to Address the Uncertainties. Agenda: J. Policy Anal. Reform 15, 55-69.

Doole, G. J., 2014. Least-cost greenhouse gas mitigation on New Zealand dairy farms. Nutr. Cycl. Agroecosys. 98(2), 235-251.

Dovers, S., 2013: How much adaptation: are existing policy and institutions enough? In: Climate Adaptation Futures [Palutikof, J., S.L. Boulter, A.J. Ash, M. Stafford-Smith, M. Parry, M. Waschka, and D. Guitart (eds.)]. John Wiley & Sons, Brisbane, QLD, Australia, pp. 97-102.

Dowd A-M., Marshall, N., Fleming, A., Jakku, E., Gaillard, E., Howden, M. 2014. The role of networks in transforming Australian agriculture. Nat. Clim. Change. 4, 558-563.

Drewry, J.J., Paton, R.J., 2000. Effects of cattle treading and natural amelioration on soil physical properties and pasture under dairy farming in Southland, New Zealand. N. Z. J. Agric. Res. 43, 377–386.

Dynes, R., Payne, T., Brown, H., Bryant, J., Newton, P., Snow, V., Lieffering, M., Wilson, D., Beets, P., 2010. New Zealand's land-based primary industries & climate change: assessing adaptation through scenario-based modelling. In: Nottage, R.A.C., et al. (Eds.), Climate Change Adaptation in New Zealand: Future Scenarios and Some Sectoral Perspectives. NZ Climate Change Centre, Wellington, NZ, pp. 44-55.

Easton, H.S., Lee, C.K., Fitzgerald, R.D., 1994. Tall fescue in Australia and New Zealand. N.Z. J. Agric. Res. 37, 405-417.

Eastwood, C.R., Chapman, D.F., Paine, M.S. 2012. Networks of practice for co-construction of agricultural decision support systems: Case studies of precision dairy farms in Australia. Agricultural Systems 108, 10-18.

Eckert, E., Bell, A. 2005. Invisible Force: Farmers' Mental Models and How They Influence Learning and Actions. Journal of Extension 43,3. Available http://www.joe.org/joe/2005june/a2p.shtml

Edwards, G. R., Clark, H., Newton, P. C. D. 2001. The effects of elevated CO_2 on seed production and seedling recruitment in a sheep-grazed pasture. Oecologia 127(3), 383-394.

Edwards, E.J., Still, C.J. 2008. Climate, phylogeny and the ecological distribution of C4 grasses. Ecol. Lett. 11, 266-276.

Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J., Leemans, R. 2005. Future scenarios of European agricultural land use I. Estimating changes in crop productivity. Agric. Ecosyst. Environ. 107, 101–116.

FAO, 2008. Climate Change and Disaster Risk Management. Food and Agriculture Organization of the United Nations, Rome.

Fariña, S.R., Alford, A., Garcia, S.C., Fulkerson, W.J., 2013. An integrated assessment of business risk for pasture-based dairy farm systems intensification. Agric. Syst. 115, 10-20.

Fauconnier, G., Turner, M., 1998. Conceptual integration networks. Cogn. Sci. 22 (2), 133-187.

Fitzgerald, J.B., Brereton, A.J., Holden, N.M., 2009. Assessment of the adaptation potential of grass-based dairy systems to climate change in Ireland-the maximised production scenario. Agric. For. Meteorol. 149 (2), 244-255.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecol. Soc. 15 (4), 20.

Fowler, H.J., Blenkinsopa, S., Tebaldi, C., 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27, 1547-1578.

Fuller, S. 2007. New frontiers in science and technology studies. Cambridge: Polity

Füssel, H.M., 2007. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustain. Sci. 2, 265-275.

Garrett, K.A., Dobson, A.D.M., Kroschel, J., Natarajan, B., Orlandini, S., Tonnang, H.E.Z., Valdivia, C. 2013. The effects of climate variability and the color of weather time series on agricultural diseases and pests, and on decisions for their management. Agr.Forest Meteorol. 170,216-227.

Gerard, P.J., Barringer, J.R.F., Charles, J.G., Fowler, S.V. Kean, J.M., Phillips, C.B. Tait, A.B., Walker, G.P. 2012: Potential effects of climate change on biological control systems: case studies from New Zealand. BioControl, 58(2), 149-162.

Gray, D.I., 2001. The Tactical Management Processes used by Pastoral-Based Dairy Farmers: A Multiple Case Study of Experts. PhD Thesis, Massey University, Palmerston North, New Zealand.

Gregorini, P., Eirin, M., Refi, R., Ursino, M., Ansin, O.E., Gunter, S.A. 2006. Timing of herbage allocation in strip grazing: Effects on grazing pattern and performance of beef heifers. J Anim Sci 84, 1943-1950.

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Glob. Environ. Chang. 15, 199–213.

Gueringer, A., Rapey, H., Houdart, M., Bigot, G., Josien, E., Landré, F., 2009. Adaptability through spatial management: a case study of livestock farms in the Massif Central, France. Outlook. Agric. 38 (2), 111-118.

Haden, V.R., Niles, M.T., Lubell, M., Perlman, J., Jackson, L.E. 2012. Global and Local Concerns: What Attitudes and Beliefs Motivate Farmers to Mitigate and Adapt to Climate Change? PLoS One 7:e52882.

Halbrendt, J., Gray, S.A., Crow, S., Radovich,T., Kimura, A.H., Tamang, B.B. 2014. Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. Glob. Environ. Chang. 28, 50-62.

Harris, R.J., Barker, G. 2007. Relative risk of invasive ants (Hymenoptera: Formicidae) establishing in New Zealand. N. Z. J. Zool. 34, 161-178.

Hoffmann, V., Probst, K., Christinck, A., 2007. Farmers and researchers: how can collaborative advantages be created in participatory research and technology development? Agric. Human. Values. 24 (3), 355-368.

Igono, M.O., Bjotvedt, G., Sanford-Crane, H.T. 1992. Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. Int. J. Biometeorol 36, 77–87.

IPCC, 2000. Emissions scenarios. Special report of the Intergovernmental Panel on Climate Change. Nakicenovic, N., Swart, R. (Eds.). Cambridge University Press, Cambridge, England, p. 570.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental

Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Model. Softw. 21 (5), 602-614.

Jay, M., 2007. The political economy of a productivist agriculture: New Zealand dairy discourses. Food Policy 32 (2), 266-279.

Jiang, N. 2011. Efficiency analysis of NZ dairy farming and the issue of climate change policy: A Stochastic Frontier Analysis. PhD thesis. University of Auckland, Auckland.

Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila, 2014: Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Johnson, I.R., Chapman, D.F., Snow,V.O., Eckard, R.J., Parsons, A.J., Lambert, M.G., Cullen, B.R. 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. Aust. J. Exp. Agr. 48:621-631.

Johnson, I.R. 2013. DairyMod and the SGS Pasture Model: a mathematical description of the biophysical model structure. IMJ Consultants, Dorrigo, NSW, Australia.

Jones, N.A., Ross, H., Lynam, T., Perez, P., Leitch, A. 2011. Mental Models: An Interdisciplinary Synthesis of Theory and Methods. Ecol. Soc. 16 (1) 46.

Jones, R. N., 2001. An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments. Nat. Hazards. 23**,** 197-230.

Kalaugher E, Beukes P, Bornman JF, Clark AJ. 2012. Adaptation Strategies for New Zealand Dairy Farms under Climate Change Scenarios. In R. Seppelt AAV, S. Lange, D. Bankamp (Eds.) (ed.) International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software: Managing Resources of a Limited Planet, Sixth Biennial Meeting., Leipzig, Germany.

Kalaugher E., Bornman, J.F., Clark, A., Beukes, P., 2013. An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system. Environ. Model. Softw. 39, 176-187.

Källström, H.N., Ljung, M. 2005. Social Sustainability and Collaborative Learning. Ambio 34,376-382.

Kamman, C., L. Grünhage, U. Grüters, S. Janze, and H.-J. Jäger, 2005: Response of aboveground grassland biomass and soil moisture to moderate long-term CO2 enrichment. Basic Appl. Ecol. 6, 351-365.

Kashtanova, E. 2010. Global trends in milk production and trade: the impact on the European milk market. Biotechnol.Anim. Husbandry, 26 (1–2) 129–134.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267-288.

Kennedy, D., Stocker, L., Burke, G. 2010. Australian local government action on climate change adaptation: some critical reflections to assist decision-making. Local Environ.15(9/10), 805-816.

Kenny, G., Fisher, M., 2003. The View from the Ground: A Farmer Perspective on Climate Change and Adaptation. Earthwise Consulting Limited and the Hawke's Bay Climate Change Adaptation Group, Hastings, New Zealand.

Kenny, G., 2010. Adaptation in agriculture: lessons for resilience from eastern regions of New Zealand. In: Nottage, R.A.C., Wratt, D.S., Bornman, J.F., Jones, K. (Eds.), Climate Change Adaptation in New Zealand: Future Scenarios and Some Sectoral Perspectives. New Zealand Climate Change Centre, Wellington, pp. 56-69.

Kenny, G., 2011. Adaptation in agriculture: lessons for resilience from eastern regions of New Zealand. Climatic Change. 106, 441-462.

Klerkx, L., Schut, M., Leeuwis, C., Kilelu, C. 2012. Advances in Knowledge Brokering in the Agricultural Sector: Towards Innovation System Facilitation. IDS Bulletin 43, 53-60.

Knapp, J. R., Laur, G. L., Vadas, P. A., Weiss, W. P., Tricarico, J. M., 2014. Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. J Dairy Sci. In Press, Corrected Proof.

KPMG, 2010. KPMG Agribusiness Agenda: The Big Opportunities and Challenges Facing New Zealand Agriculture: Reflections on the Views of Industry Leaders. Retrieved 5 May 2011 from: http://www.kpmg.com/NZ/en/IssuesAndInsights/ArticlesPublications/Pages/Agribusiness-Agenda.aspx

Kropff, M.J., Bouma, J., Jones, J.W., 2001. Systems approaches for the design of sustainable agro-ecosystems. Agric. Syst. 70 (2,3), 369-393.

Kurihara, M., Shioya, S., 2003. Dairy Cattle Management in a Hot Environment. Department of Animal Feeding and Management, National Insitute of Livestock and Grassland Science, Nishinasuno, Todhigi, Japan.

Kvale, S., Brinkman, S., 2009. Interviews: Learning the Craft of Qualitative Research Interviewing. Sage, Los Angeles.

Lawson, A.R.., Greenwood, K.L., Kelly, K.B., 2009. Irrigation water productivity of winter-growing annuals is higher than perennial forages in northern Victoria. Crop. Past. Sci., 60 (5) 407–419.

Lee, J.M., Clark, A.J., Roche, J.R., 2013. Climate-change effects and adaptation options for temperate pasture-based dairy farming systems: a review. Grass. Forage. Sci. 68, 485-503.

Lee, J., Minnee, E. 2012. Chicory and plantain - your questions answered. DairyNZ Technical Series. DairyNZ, Hamilton, New Zealand. August 2012, pp 11-15.

Le Gal, P. Y., Dugué, P., Faure, G., & Novak, S. 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. Agr. Syst. 104(9), 714-728.

Li, F.Y., Johnston, P.R., Pearson, A., Fletcher, A., Jamieson, P.D., Brown, H.E., Zyskowskia, R.F. 2009. AmaizeN: A decision support system for optimizing nitrogen management of maize. NJAS – Wag. J. Life Sci. 57, 93–100.

Li, F.Y., Newton, P.C., Lieffering, M.2014. Testing simulations of intra- and inter-annual variation in the plant production response to elevated CO2 against measurements from an 11-year FACE experiment on grazed pasture. Glob. Chang. Biol. 20,228–239.

Linnenluecke, M. K., Griffiths, A., Winn, M. 2012. Extreme Weather Events and the Critical Importance of Anticipatory Adaptation and Organizational Resilience in Responding to Impacts. Bus. Strat. Env. 21, 17–32. doi: 10.1002/bse.708

Lobell, D.B., Tebaldi, C. 2014. Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. Environ. Res. Lett 3, 074003. doi:10.1088/1748-9326/3/3/034007

López-Gatius, F., García-Ispierto, I., Santolaria, P., Yániz, J. L., López-Béjar, M., Nogareda, C., Almería, S., 2005. Relationship between rainfall and Neospora caninum-associated abortion in two dairy herds in a dry environment. J. Vet. Med. B 52, 147-152.

Lynam, T., De Jong,W., Sheil, D., Kusumanto, T., Evans, K., 2007. A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. Ecol. Soc. 12 (1), 5.

Macdonald, K.A., Penno, J.W., Lancaster, J.A.S., Roche, J.R. 2008. Effect of Stocking Rate on Pasture Production, Milk Production, and Reproduction of Dairy Cows in Pasture-Based Systems. J Dairy Sci. 91, 2151-2163.

Mackay, M., Perkins, H.C., Espiner, S. 2009. The Study of Rural Change from a Social Scientific Perspective: A Literature Review and Annotated Bibliography. Lincoln University, Lincoln, New Zealand.

MacLeod, C.J., Moller, H., 2006. Intensification and diversification of New Zealand agriculture since 1960: an evaluation of current indicators of land use change. Agric. Ecosyst. Environ. 115 (1-4), 201-218.

Mader, T.L., Johnson, L.J., Gaughan, J.B. 2010. A comprehensive index for assessing environmental stress in animals. J. Anim.Sci. 88, 2153-2165.

Mansilla, V.B., 2010. Learning to synthesize: the development of interdisciplinary understanding. In: Frodeman, R., Thompson Klein, J., Mitcham, C. (Eds.), The Oxford Handbook of Interdisciplinarity. Oxford University Press, Oxford, pp. 288-306.

Martin, G., Magne, M.A. 2015. Agricultural diversity to increase adaptive capacity and reduce vulnerability of livestock systems against weather variability – A farm-scale simulation study. Agric. Ecosyst. Environ 199, 301-311.

Martin, G., Felten, B., Duru, M., 2011. Forage rummy: a game to support the participatory design of adapted livestock systems. Environ. Model. Softw. 26, 1442-1453.

Mastrandrea, M., Heller, N., Root, T., Schneider, S., 2010. Bridging the gap: linking climate-impacts research with adaptation planning and management. Clim. Chang. 100 (1), 87-101.

Mastrandrea, M.D., Schneider, S.H., 2010. Preparing for Climate Change. MIT Press, Cambridge, MA.

McCown, R. L. 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agr. Syst. 74*(1), 179-220.

McCown, R.L., Parton, K.A., 2006. Learning from the historical failure of farm management models to aid management practice. Part 2. Three systems approaches. Aust. J. Agric. Res. 57 (2), 157-172.

McCown, R. L. 2012. A cognitive systems framework to inform delivery of analytic support for farmers' intuitive management under seasonal climatic variability. *Agr. Syst. 105*(1), 7-20.

McKeon, G. M., Stone, G. S., Syktus, J. I., Carter, J. O., Flood, N. R., Ahrens, D. G., Bruget, D. N., Chilcott, C. R., Cobon, D. H., Cowley, R. A., Crimp, S. J., Fraser, G. W., Howden, S. M., Johnston, P. W., Ryan, J. G., Stokes, C. J., Day, K. A., 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: A review of issues. Rangeland J. 31, 1-29.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C. Zhao, 2007: Global climate projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin,M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 747- 845.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Melloy, P., Hollaway, G., Luck, J., Norton, R., Aitken, E., Chakraborty, S. 2010. Production and fitness of Fusarium pseudograminearum inoculum at elevated carbon dioxide in FACE. Glob. Chang. Biol., 16(12), 3363-3373.

Memon, A., Skelton, P., 2007. Institutional Arrangements and Planning Practices to Allocate Freshwater Resources in New Zealand: A Way Forward [online]. N.Z. J. Envtl. L. 11, 241-277.

Miller, T.R., Baird, T.D., Littlefield, C.M., Kofinas III, G., Chapin, F.S., Redman, C.L., 2008. Epistemological pluralism: reorganizing interdisciplinary research. Ecol. Soc. 13 (2), 46.

Ministry of Agriculture and Forestry (2008). Situation and Outlook for New Zealand Agriculture and Forestry (SONZAF). August 2008. MAF Policy, Wellington. Retrieved August 1, 2010 from http://www.maf.govt.nz/mafnet/rural-nz/statistics-and-forecasts/sonzaf/

Ministry of Agriculture and Forestry, 2009. Situation and Outlook for New Zealand Agriculture and Forestry. Ministry of Agriculture and Forestry, Wellington, New Zealand.

Ministry for the Environment, 2009. New Zealand's Fifth National Communication under the United Nations Framework Convention on Climate Change. Wellington, Ministry for the Environment.

Ministry for Primary Industries, 2013. Situation and Outlook for Primary Industries 2013. Ministry for Primary Industries, Wellington.

Ministry for Primary Industries, 2014. Situation and Outlook for Primary Industries 2014. Ministry for Primary Industries, Wellington.

Minnee, E., 2011. An evaluation of tall fescue (Lolium arundinaceum) as an alternative to perennial ryegrass (Lolium perenne) for use on dairy farms in the Waikato. Masters thesis, University of Waikato, Hamilton, New Zealand.

Montealegre, C. M., Kessel, C. V., Blumenthal, J. M., Hur, H.G., Hartwig, U. A., Sadowsky, M. J. 2000. Elevated atmospheric CO_2 alters microbial population structure in a pasture ecosystem. Glob. Chang. Biol. 6, 475-482.

Moss, R.H., Edmonds,J.A.,Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A, Mitchell, J.F.B., Nakicenovic, N, Riahi, K., Smith, S.J, Stouffer, R.J., , Thomson, A.M., Weyant, J.P., Wilbanks, T.J. 2010: The next generation of scenarios for climate change research and assessment. Nature, 463, 747–756.

Mullan, A.B. (1995). On the linearity and stability of Southern Oscillation-Climate relationships for New Zealand. Int. J. Climatol.15, 1365–1386.

Mullan, A.B. (1996). Non-linear effects of the Southern Oscillation in the New Zealand region. Aust. Meteorol.Mag. 45: 83–99.

Mullan, A.B., Wratt, D.S., Renwick, J.A. 2001. Transient model scenarios of climate changes for New Zealand. Weather Clim. 21, 3-43.

Mullan, B., Porteous, A., Wratt, D., Hollis, M., 2005. Changes in drought risk with climate change. NIWA, Ministry for the Environment (NZ Climate Change Office), Ministry of Agriculture and Forestry, New Zealand.

Mullan, A.B., Wratt, D., Dean, S., Hollis, M., Allan, S., Williams, T., Kenny, G. MfE. 2008. Climate Change Effects and Impacts Assessment. A Guidance Manual for Local Government in New Zealand. 2nd Edition. Report prepared for Ministry for the Environment. NIWA Client Report WLG2007/62, 156p.

Mullan, A.B., Carey-Smith, T., Griffiths, G., Sood, A. 2011. Scenarios of storminess and regional wind extremes under climate change. NIWA report WLG2010-31. Prepared for Ministry of Agriculture and Forestry. New Zealand.

Neal, M., Neal, J., Fulkerson, B., 2006. Choosing the best forage species for a dairy farm: The Whole-farm approach. Risk and Sustainable Management Group, University of Queensland.

Neef, A., Neubert, D., 2011. Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making. Agric. Human. Values. 28 (2), 179-194.

Nelson, D. R., de Souza Filho, F. D. A., Finan, T. J., & Ferreira, S. 2014. Trajectories of Adaptation: A Retrospectus for Future Dynamics. In *Social-Ecological Systems in Transition* (pp. 121-136). Springer Japan.

Nelson, D.R., 2011. Adaptation and resilience: responding to a changing climate. WIREs. Clim. Chang. 2 (1), 113-120.

Nelson, D.R., Adger, W.N., Brown, K., 2007. Adaptation to environmental change: contributions of a resilience framework. Annu. Rev. Environ. Resour. 32 (1), 395-419.

New Zealand Government, (2010). New Zealand Government Paper for the European Union High Level Experts Group on Milk, 12 January 2010.

Newton, P.C.D., Clark, H., Bell, C.C., Glasgow, E.M., Campbell, B.D., 1994. Effects of elevated CO_2 and simulated seasonal changes in temperature on the species composition and growth rates of pasture turves. Ann. Bot. 73, 53–59.

Newton, P., Bryant, J., Snow, V., Lieffering, M., 2008. Enhanced Modelling Capability to Conduct Climate Change Impact Assessments. AgResearch, New Zealand.

Newton, P.C.D., Lieffering, M., Parsons, A.J., Brock, S.C., Theobald, P.W., Hunt, C.L., Luo, D., Hovenden, M.J., 2013. Selective grazing modifies previously anticipated responses of plant community composition to elevated CO_2 in a temperate grassland. Glob. Chang. Biol., 20 (1) 158–169.

Nettle, R. Waters, W. Kenny, S. Love, S. 2012. Crisis as an opportunity for change?: A case study of applying resilience thinking to extension responses in dairy industry crisis [online]. Extension Farming Systems Journal, Vol. 8, No. 1, 2012: 21-31. Availability:≤http://search.informit.com.au/documentSummary;dn=699726525674060;res=IELHSS> ISSN: 1833-203X. [cited 22 Mar 15].

Niles, M.T., M. Lubell, V.R. Haden. 2013. Perceptions and responses to climate policy risks among California farmers. Glob. Environ. Chang. 23: 1752-1760.

Niles, M.T., M. Lubell, M. Brown. 2015. How limiting factors drive agricultural adaptation to climate change. Agric. Ecosyst. Environ. 200: 178-185.

Norgaard, R.B., Baer, P., 2009. Collectively seeing climate change: the limits of formal models. BioSci. 55 (11), 961-966.

Nuthall, P. 2009. Managerial Factors in Primary Production: Data from a sample of New Zealand Farmers with an Emphasis on Experience as a Factor in Success. Lincoln University Agribusiness & Economics Research Unit, Lincoln.

O'Kane, M., King, B., O'Brien, G. 2009. Farmer risk perceptions and practice: Utilising notions of risk for extension in Project 3030. Extension Farming Systems Journal 5, 59-69.

Park, S.E., Marshall, N.A., Jakku, E. Dowd, A.M. Howden, S.M. Mendham, E. Fleming, A. 2012. Informing adaptation responses to climate change through theories of transformation. Glob. Environ. Chang, 22(1), 115-126.

Parry, M., Carter, T., 1998. Climate Impact and Adaption Assessment: a Guide to the IPCC Approach. Earthscan Publications Ltd., London.

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), 2007. Climate Change: Impacts, Adaptation and Vulnerability. Contribution of WG II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Patwardhan, A., Downing, T., Leary, N., Wilbanks, T., 2009. Towards an integrated agenda for adaptation research: theory, practice and policy: strategy paper. Curr. Opin. Environ. Sustain 1 (2), 219-225.

Payne, T., White, T.D., 2009. Northland Dairy Farmers: How Resilient are They to Adverse Weather Events? Contract Report by Landcare Trust, Prepared for Ministry of Agriculture and Forestry, New Zealand.

Pearson, L.J., Nelsonc, R., Crimp, S., Langridge, J., 2011. Interpretive review of conceptual frameworks and research models that inform Australia's agricultural vulnerability to climate change. Environ. Model. Softw. 26, 113-123.

Pereira, Â.G., Funtowicz, S., 2006. Knowledge representation and mediation for transdisciplinary frameworks: tools to inform debates, dialogues and deliberations. Int. J. Transdiscipl. Res. 1 (1), 34-50.

Phelan, D.C., Parsons, D., Lisson, S.N., Holz, G.K., MacLeod, N.D., 2014. Beneficial impacts of climate change on pastoral and broadacre agriculture in cool-temperate Tasmania. Crop. Past. Sci., 65, 194–205.

Porteous, A., Mullan, B., 2013. The 2012-13 drought: an assessment and historical perspective MPI Technical Paper No: 2012/18 Prepared for the Ministry for Primary Industries by NIWA.

Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Preston, B., Westaway, R., Yuen, E. 2011. Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations. Mitig. Adapt. Strateg. Glob. Change. 16 (4), 407-438.

Reed, K.F.M., 1996. Improving the adaptation of perennial ryegrass, tall fescue, phalaris, and cocksfoot for Australia. N.Z. J. Agric. Res. 39, 457-464.

Reidsma, P., 2007. Adaptation to Climate Change: European Agriculture. PhD thesis. Wageningen University, Wageningen, The Netherlands.

Reidsma, P., Ewert, F., 2008. Regional farm diversity can reduce vulnerability of food production to climate change. Ecol. Soc. 13 (1), 38-53.

Reisinger, A., R.L. Kitching, F. Chiew, L. Hughes, P.C.D. Newton, S.S. Schuster, A. Tait, and P. Whetton, 2014: Australasia. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Renwick, J., Clark, A., Griffiths, G., Hendrikx, J., Liley, B., Tait, A.,Wood, S., 2010. State of the Climate 2010: a Snapshot of Recent Climate in New Zealand. National Institute of Water and Atmospheric Research, Wellington, New Zealand.

Reynolds, M., Holwell, S. (Eds.), 2010. Systems Approaches to Managing Change: a Practical Guide. Springer, London.

Ripoche, A., Rellier, J.P., Martin-Clouaire, R., Paré, N., Biarnès, A., Gary, C., 2011. Modelling adaptive management of intercropping in vineyards to satisfy agronomic and environmental performances under Mediterranean climate. Environ. Model. Softw. 26, 1467-1480.

Robson, M. 1972. The Effect of Temperature on the Growth the S. 170 Tall Fescue (Festuca arundinacea). I. Constant Temperature. J Appl. Ecol. 643-653.

Roche, J.R., Turner, L.R., Lee, J.M., Edmeades, D.C., Donaghy, D.J., Macdonald, K.A., Penno, J.W., Berry, D.P. 2009. Weather, herbage quality and milk production in pastoral systems. 4. Effects on dairy cattle production. Anim. Prod. Sci. 49, 222–232.

Rodima-Taylor, D., Olwig, M.F., Chhetri, N. 2012. Adaptation as innovation, innovation as adaptation: An institutional approach to climate change. Appl. Geogr. 33,107-111.

Rodriguez, D., deVoil, P., Power, B., Cox, H., Crimp, S., Meinke, H. 2011. The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. Field Crops Res.124,157-170.

Rogers, D. J., Randolph, S. E., 2006. Climate change and vector-borne diseases. Adv. Parasitol. 62, 345-81

Romera, A.J., McCall, D.G., Lee, J.M., Agnusdei, M.G .2009. Improving the McCall herbage growth model. N.Z. J. Agric. Res. 52,477-494.

Romera, A.J., Doole, G.J., Khaembah, E.N. 2014. Value of chicory (Cichorium intybus L.) crops to pasture-based dairy farms in the Waikato region of New Zealand. J. Agr. Sci. (in press).

Romera, A.J., Doole, G.J. 2014. Integrated analysis of profitable stocking-rate decisions in pasture-based dairy systems. Grass and Forage Science.

Rötter, R. P., Carter, T. R., Olesen, J. E., & Porter, J. R. 2011. Crop-climate models need an overhaul. Nature Clim. Chang., 1(4), 175-177.

Sanderson, M. A., 2006. Plant species diversity: Management implications for temperate pasture production.

Saunders, C., W. Kaye-Blake, and J. Turner, 2009: Modelling Climate Change Impacts on Agriculture and Forestry with the Extended LTEM (Lincoln Trade and Environment Model). AERU Research Report No. 316, Prepared for the Ministry of Agriculture and Forestry by the Agribusiness and Economics Research Unit (AERU), Lincoln University, Lincoln, New Zealand, 53 pp.

Sautier, M., Piqueta, M., Durua, M., Martin-Clouaire, R.,2014. A sequential participatory approach to adapt livestock systems to climate change. In Ames, D.P. Quinn N. (Eds.) International Environmental Modelling and Software Society (iEMSs) 7th International Congress on Environmental Modelling and Software, San Diego, California, USA.

Schipper, L. A., Parfitt, R. L., Ross, C., Baisden, W. T., Claydon, J. J., Fraser, S. 2010. Gains and losses in C and N stocks of New Zealand pasture soils depend on land use. Agric. Ecosyst. Environ. 139 (4), 611-617.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. USA 104,19703-19708.

Schneider S, Easterling W, Mearns L (2000) Adaptation: Sensitivity to Natural Variability, Agent Assumptions and Dynamic Climate Changes. Climatic Change 45:203-221.

Scoones, I., 2004. Climate change and the challenge of non-equilibrium thinking. IDS Bull. 35 (3), 114-119.

Sewell, A. M., Gray, D. I., Blair, H. T., Kemp, P. D., Kenyon, P. R., Morris, S. T., & Wood, B. A. 2014. Hatching new ideas about herb pastures: Learning together in a community of New Zealand farmers and agricultural scientists. Agr. Syst. 125, 63-73.

Silungwe, D. 2011. Evaluation of forage yield and quality of sorghum, sudangrass and pearl millet cultivars in Manawatu. Masters thesis. Massey University, Palmerston North, New Zealand.

Sirohi, S., Michaelowa, A., 2007. Sufferer and cause: Indian livestock and climate change. Clim. Chang. 85, 285-298.

Smit, B., Skinner, M.W., 2002. Adaptation options in agriculture to climate change: A typology. Mitig. Adapt. Strateg. Glob. Change., 7, 85–114.

Smith, W., Kelly, S., Rhodes, T., 2008. Information, Decision and Action: The Factors That Determine Farmers Environmental Decision-Making. Ministry of Agriculture and Forestry, New Zealand.

Snow, V.O., Rotz, C.A., Moore, A.D., Martin-Clouaire, R., Johnson, I.R., Hutchings, N.J., Eckard, R.J. 2014. The challenges – and some solutions – to process-based modelling of grazed agricultural systems. Environ. Model. Softw. 62:420-436.

SNZ, 2012: Global New Zealand – International Trade, Investment, and Travel Profile: Year ended June 2012. Ministry of Foreign Affairs and Trade and Statistics New Zealand (SNZ), Wellington, New Zealand, 196 pp.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York.

Sood, A., 2015. Improved Bias Corrected and Downscaled Regional Climate Model Data for Climate Impact Studies: Validation and Assessment for New Zealand. Submitted to J Clim. Available: https://www.researchgate.net/publication/265510643_Improved_Bias_Corrected_and_Downscaled_Regional_Climate_Model_Data_for_Climate_Impact_Studies_Validation_and_Assessment_for_New_Zealand

Soussana, J-F., Graux, A-I., Tubiello, F.N. 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Exp. Bot. 61, 2217–2228.

Stafford-Smith, M. 2013. Scenarios for picturing a future adapted to +4°C. In: Climate Adaptation Futures [Palutikof, J., S.L. Boulter, A.J. Ash, M. Stafford-Smith, M. Parry, M. Waschka, and D. Guitart (eds.)]. John Wiley & Sons, Brisbane, QLD, Australia, pp. 119-125.

Steffen, W., Hughes, L. 2013. The critical decade 2013: climate change science, risks and responses. Climate Commission, Commonwealth of Australia, Canberra, Australia. 112 pp.

Stirling, A., 2010. Keep it complex. Nature 468 (7327), 1029-1031.

Stokes, C. J., Ash, A., Howden, S. M., 2008. Climate change impacts on Australian rangelands. Rangelands. 30, 40-45.

Stokes, C., Howden, M. (Eds.), 2010. Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future. CSIRO Publishing, Collingwood VIC, Australia.

Stokes, C., Marshall, N., MacLeod, N. 2012. Developing improved industry strategies and policies to assist beef enterprises across northern Australia adapt to a changing and more variable climate. Final report B.NBP.0617, Meat & Livestock Australia Ltd, North Sydney, NSW, Australia

Stoorvogel, J.J., Antle, J.M., Crissman, C.C., Bowen, W., 2004. The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. Agric. Syst. 80 (1), 43-66.

Stroombergen, A., 2010. The International Effects of Climate Change on Agricultural Commodity Prices, and the Wider Effects on New Zealand. Motu Working Paper 10-14, Motu Economic and Public Policy Research, Wellington, New Zealand, 27 pp.

Sturman, A.P., Tapper, N.J. (2006). The weather and climate of Australia and New Zealand. 2nd ed. Oxford University Press, Melbourne. 541 p.

Swart, R., Bernstein, L., Ha-Duong, M., Petersen, A., 2009. Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC. Clim. Chang. 92 (1), 1-29.

Tait, A., Baisden, T., Wratt, D., Stroombergen, B., 2008. An initial assessment of the potential effects of climate change on New Zealand agriculture. New Zealand Science Review. 65, 50.

Teixeira EI, Fischer G, van Velthuizen H, Walter C, Ewert F (2013) Global hot-spots of heat stress on agricultural crops due to climate change. Agricultural and Forest Meteorology 170:206-215.

Thornton, P.K., Ericksen, P.J., Herrero, M., Challinor., A.J. 2014. Climate variability and vulnerability to climate change: a review. Glob. Chang. Biol., 20, 3313-3328.

Tozer, K.N.; Cameron CA, Thom ER. 2011. Pasture persistence: farmer observations and field measurements. Pasture Persistence. Grassland Research and Practice Series 15: 25-30.

Turner, L.R., Holloway-Phillips, M.M., Rawnsley, R.P., Donaghy, D.J., Pembleton, K.G., 2012. The morphological and physiological responses of perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinaceae* Shreb.; syn. *Schedonorus phoenix* Scop.) to variable water availability, Grass. Forage. Sci., 67, (4) 507-518.

Verdon-Kidd, D.C., Kiem, A.S., Austin, E.K. 2012. Decision Making Under Uncertainty – Bridging the Gap Between End User Needs and Climate Science Capability. National Climate Change Adaptation Research Facility (NCCARF), Griffith University, Gold Coast Campus, Southport, QLD, Australia, 116 pp.

Vermunt, J. J., West, D. M., Cooke, M. M., Alley, M. R., Collins-Emerson, J. 1994. Observations on three outbreaks of Leptospira interrogans serovar pomona infection in lambs. N.Z. vet. J. 42, 133-136.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Softw. 25 (11), 1268-1281.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R., 2002. Resilience management in socialecological systems: a working hypothesis for a participatory approach. Conserv. Ecol. 6 (1), 14.

Walker, N.J., Schulze, R.E., 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. Agric. Ecosyst. Environ. 124,114-124.

Wall, G.W., Garcia, R.L., Kimball, B.A., Hunsaker, D.J., Pinter Jr, P.J., Long, S.P., Osborne, C.P., Hendrix, D.L., Wechsung, F., Wechsung, G., 2006. Interactive effects of elevated carbon dioxide and drought on wheat. Agron. J. 98, 354–381.

Wallace, N. 2014. When the Farm Gates Opened: The impact of Rogernomics on rural New Zealand. 160 pp.

Wan, S., Norby, R.J., Ledford, J. Weltzin, J.F. 2007. Responses of soil respiration to elevated CO2, air warming, and changing soil water availability in an old-field grassland. Glob. Chang. Biol, 13(11), 2411-2424.

Warrick, R.A., Kenny, G.J., Harman, J.J., 2001. The Effects of Climate Change and Variation in New Zealand: An Assessment Using the CLIMPACTS

System. International Global Change Institute (IGCI), The University of Waikato, Hamilton, New Zealand.

Watanabe, T., Bowatte, S. Newton, P.C.D. 2013: A reduced fraction of plant N derived from atmospheric N (%Ndfa) and reduced rhizobial nifH gene numbers indicate a lower capacity for nitrogen fixation in nodules of white clover exposed to long-term CO2 enrichment. Biogeosciences, 10, 8269-8281.

Waugh, C.D., Clark, D.A., Harris, S.L., Thom, E.R., Copeman, P.J.A, Napper, A.R.1998. Chicory for milk production. Proceedings of the New Zealand Grassland Association, 60, pp. 33–37.

WBGU. 2009. Solving the climate dilemma: the budget approach. Special Report. German Advisory Council on Global Change, Berlin. 124 p.

West, J.W. 2003. Effects of heat-stress on production in dairy cattle. J. Dairy Sci. 86, 2131–2144.

White, T. A., Campbell, B. D., Kemp, P. D., Hunt, C. L., 2001. Impacts of extreme climatic events on competition during grassland invasions. Glob. Chang. Biol. 7, 1-13.

Wiid, N., Ziervogel, G. 2012. Adapting to climate change in South Africa: Commercial farmers' perception of and response to changing climate. S Afr. Geogr. J. 94,152-173.

Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65 (7), 180-185.

Williams, W. M., Easton, H.S., Jones, C.S., 2007. Future options and targets for pasture plant breeding in New Zealand. N.Z. J. Agric. Res., 50, 223-248.

Wilbanks, T.J., Kates, R.W., 2010. Beyond adapting to climate change: embedding adaptation in responses to multiple threats and stresses. Ann. Assoc. Am. Geogr.100,719 – 728

Wilson, E.O., 1998. Consilience among the great branches of learning. Daedalus 127 (1), 131-149.

Windle, G., 2011. What is resilience? A review and concept analysis. Rev. Clin. Gerontol. 21, 152-169.

Wise, R.M.,Fazey, I.,Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M., Campbell, B. 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global. Environ. Chang. 28, 325–336.

Wixon, D.L., Balser, T.C., 2009. Complexity, climate change and soil carbon: a systems approach to microbial temperature response. Syst. Res. Behav. Sci. 26 (5), 601-620.

Woodward, S.J.R., Romera, A.J., Beskow, W.B., Lovatt, S.J., 2008. Better simulation modelling to support farming systems innovation: review and synthesis. N.Z. J. Agric. Res. 51, 235-252.

Woodward, S.L., Waugh, C.D., Roach, C.G., Fynn, D., Phillips, J. 2013. Are diverse species mixtures better pastures for dairy farming? Proceedings of the New Zealand Grassland Association 75. pp. 79-84.

Wratt, D., Mullan, A.B., Tait, A., Woods, R., Baisden, T., Giltrap, D., Hendy, J., Stroombergen, A., 2008. Costs and Benefits of Climate Change and Adaptation to Climate Change in New Zealand Agriculture: What Do We Know so Far? Contract Report by EcoClimate Consortium: Integrated Research on the Economics of Climate Change Impacts Adaptation and Mitigation. Ministry of Agriculture and Forestry, New Zealand. 112.

Yakushev, V.P., 2009. Risk analysis as the basis for evaluating the consequences of climate changes in agriculture. Russ. Agric. Sci. 35 (5), 355-358.

Yeates, G. W., Newton, P. C. D. 2009. Long-term changes in topsoil nematode populations in grazed pasture under elevated atmospheric carbon dioxide. Biol. Fert. Soils. 45:799-808. doi 10.1007/s00374-009-0384-9

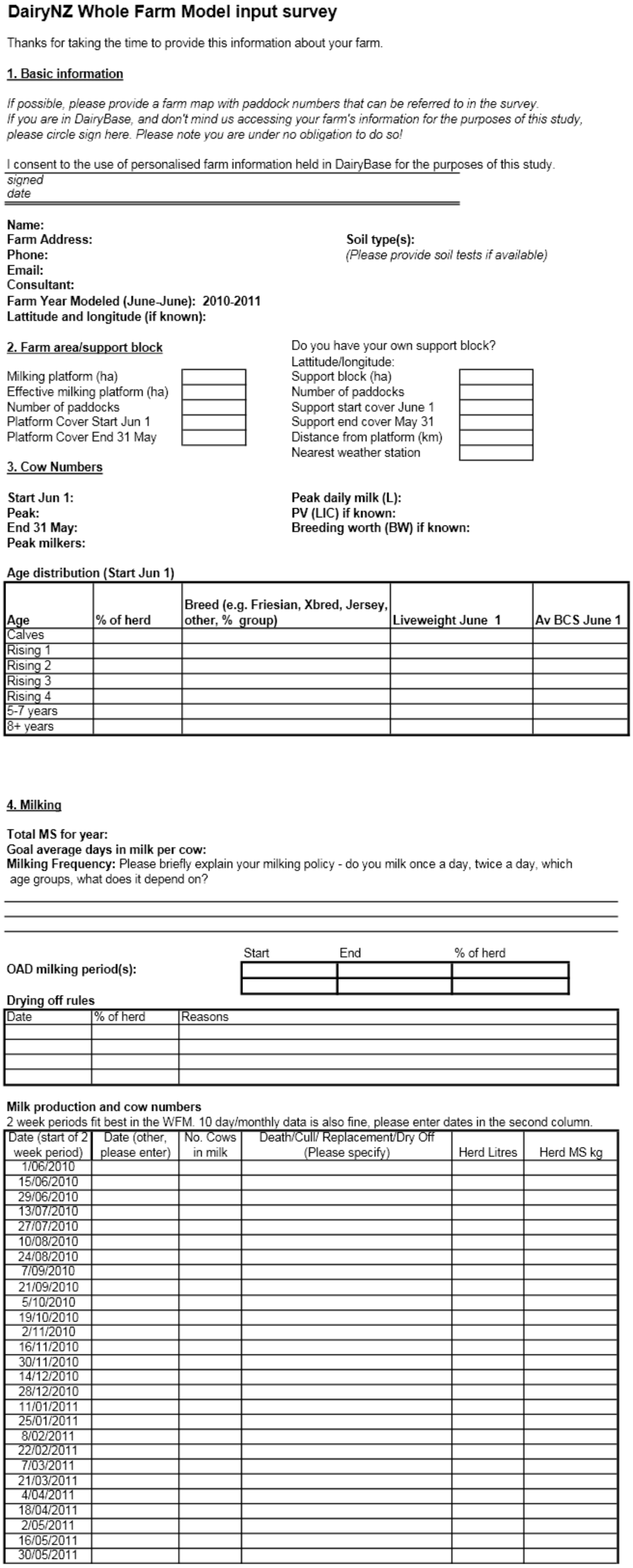
Yuen, E., Jovicich, S., Preston, B. 2012. Climate change vulnerability assessments as catalysts for social learning: four case studies in south-eastern Australia. Mitig. Adapt. Strateg. Glob. Change. 18(5), 567-590.

Zand, E., Soufizadeh, S., Eskandari, A., 2006. Water stress and nitrogen limitation effects on corn (Zea mays L.) competition with a C3 and a C4 weed. Commun. Agric. Appl. Biol. Sci. 71, 753-60.

Zhang, B., Valentine, I., Kemp, P.D., 2007. Spatially explicit modelling of the impact of climate changes on pasture production in the North Island, New Zealand. Clim. Chang. 84 (2), 203-216.

Zhou, X., Weng, E, Luo, Y. 2008. Modeling patterns of nonlinearity in ecosystem responses to temperature, CO2, and precipitation changes. Ecol. Appl. 18(2), 453-66.

Appendix A: Farm management data gathered



DairyNZ Whole Farm Model input survey

Thanks for taking the time to provide this information about your farm.

1. Basic information

If possible, please provide a farm map with paddock numbers that can be referred to in the survey.
If you are in DairyBase, and don't mind us accessing your farm's information for the purposes of this study, please circle sign here. Please note you are under no obligation to do so!

I consent to the use of personalised farm information held in DairyBase for the purposes of this study.
signed
date

Name:
Farm Address:
Phone:
Email:
Consultant:
Farm Year Modeled (June-June): 2010-2011
Lattitude and longitude (if known):

Soil type(s):
(Please provide soil tests if available)

2. Farm area/support block

Milking platform (ha)
Effective milking platform (ha)
Number of paddocks
Platform Cover Start Jun 1
Platform Cover End 31 May

Do you have your own support block?
Lattitude/longitude:
Support block (ha)
Number of paddocks
Support start cover June 1
Support end cover May 31
Distance from platform (km)
Nearest weather station

3. Cow Numbers

Start Jun 1:
Peak:
End 31 May:
Peak milkers:

Peak daily milk (L):
PV (LIC) if known:
Breeding worth (BW) if known:

Age distribution (Start Jun 1)

Age	**% of herd**	**Breed (e.g. Friesian, Xbred, Jersey, other, % group)**	**Liveweight June 1**	**Av BCS June 1**
Calves				
Rising 1				
Rising 2				
Rising 3				
Rising 4				
5-7 years				
8+ years				

4. Milking

Total MS for year:
Goal average days in milk per cow:
Milking Frequency: Please briefly explain your milking policy - do you milk once a day, twice a day, which age groups, what does it depend on?

	Start	End	% of herd
OAD milking period(s):			

Drying off rules

Date	% of herd	Reasons

Milk production and cow numbers
2 week periods fit best in the WFM. 10 day/monthly data is also fine, please enter dates in the second column.

Date (start of 2 week period)	Date (other, please enter)	No. Cows in milk	Death/Cull/ Replacement/Dry Off (Please specify)	Herd Litres	Herd MS kg
1/06/2010					
15/06/2010					
29/06/2010					
13/07/2010					
27/07/2010					
10/08/2010					
24/08/2010					
7/09/2010					
21/09/2010					
5/10/2010					
19/10/2010					
2/11/2010					
16/11/2010					
30/11/2010					
14/12/2010					
28/12/2010					
11/01/2011					
25/01/2011					
8/02/2011					
22/02/2011					
7/03/2011					
21/03/2011					
4/04/2011					
18/04/2011					
2/05/2011					
16/05/2011					
30/05/2011					

5. Calving and mating

Do you rear your own replacement stock?:	Y	N
Target replacement rate:		

If yes, please explain your policy: to what age you rear them, whether or not you keep them, and whether you rear them on a support block? Do you send them to a grazier, if so at what age? What % do you keep, and how do you decide?

Planned start of calving:

Calving Spread	2 wks	4 wks	6 wks	8 wks	10 wks	12 wks	14 wks	16 wks
% of herd								

Mating Policies

Planned Start Mating		No. of weeks AI	
Induction Date (s) and %		PD Dates	
CIDRs Date and %		Metricure No. /Date	
Bull Mating Start		Heat det. method	
Mating End Date		No. bulls	

Expected heat detection efficiency:

	Heifers		Mixed age cows	
	Goal	Actual	Goal	Actual
BCS at mating				
BCS at calving				

Mating Performance

Submission rate 3 wks	
Submission rate 4 wks	
Final empty %	

AI bull name (if known):

	2 wks	4 wks	6 wks	8 wks	10 wks	12 wks	14 wks	16 wks	18 wks
% in calf									

Culling

Please describe your culling policy: What proportion of the herd do you cull and why? When does this take place? Which groups do you cull first - age categories, dries, empties first?

6. Pasture Management

Estimated pasture yield TDM/ha/year:

	Target pasture intake (kg/day)
Milkers at peak	
Dry cows	

Please explain your policy on pasture feeding in your own words. For example, do you always attempt to feed to demand? If not, what are your decision criteria? How do you decide when to start feeding supplements or destock? What does it depend on? Do you feed your milkers and dry cows differently?

Do you have standing off facilities or a use sacrifice paddock?

Stand-off facilities

Date range for standing off	
Hours per day standing off	

Did you graze off part of your herd in a support block during the 2010-2011 season? If so, is the land your own or leased? Do you use a grzier?

Grazing Off

Mob (e.g. young stock, dries)	Owned/leased/grazier?	Start	End	Cost/hd/wk

Do you make pasture silage? Yes No *(Please circle one)*

If yes, please explain your policy: How do you decide when to make it? What are the criteria? What area of the farm do you aim to make silage from and when (e.g. peak spring growth?)

Please provide as much information as you can for the 2010-2011 year:

Date (range)	Rotation (days)	Residuals (kg dm/ha)	Topping

4.5 Which paddocks have you regrassed in the 2010-2011 season?

Date	Paddock no	Pasture variety/mix planted	Reason

Please briefly describe your renovation practice (tillage, herbicides undersowing or oversowing, etc)

7. Supplements and cropping

Feed Pad Used? Y N

Date range	SuppType	Mob	kg DM/ head/ day	Total Fed (T DM)		Bought/ sold (price)	Estimated %	On Hand 1/6 Start	On Hand 31/5 End

Do you grow any crops? Y N

If yes, please provide as much information as you can:

Date planted	Date harvested	Paddock no.(supp. block)	Crop type	Cropping area (ha)	Estimated wastage/ feeding notes

8. Fertilisers, pest and weed control, effluent and irrigation

Date	Paddock no. (or support block)	Fert N (kg/ha, not incl. effluent)	Fert other (kg/ha)	Other (e.g. LessN, DCDs)	Herbicides (Name, Kg/ha)	Pesticide (Name, Kg/ha)

9. Effluent and irrigation

Date	Paddock no(s)	Effluent or non-effluent?	Area (ha)	Irrigation mm/ha

Source of effluent:
Effluent N concentration if known (kg N/m3):
Storage facilities volume (days capacity):

10. Pests and diseases

Has your farm suffered from any pest or disease outbreaks in the 2010-2011 year? Y N

If yes, please describe and estimate losses as far as possible:

Month(s)	Pest or disease	Estimated losses/comment

Has your farm suffered from any other animal health issues in the 2010-2011 year? Y N

If yes, please describe and estimate consequences/losses as far as possible:

Month(s)	Health issue	Estimated consequences/losses

11. Economics

Please check the DairyNZ projections for the year 2010 and note any major differences from your costs

Also, if you are happy to do so, please provide information on the following costs:

			$/cow/year
Feed pad/standoff pad/other facilities			
Irrigation costs			
Labour costs per cow			
Fertiliser costs			
Support block (rented leased?			
Young stock, grazier costs			

Appendix B: Interview schedule

Aims of the interviews:

1) To understand the system perspective (context/goals/values) of the farmer(s)
2) To Identify risks and opportunities from the farmers perspective and how these contribute to decision-making on farm
3) To validate modelling results and identify alternative adaptation options from the farmers' perspective

Interview 1: System perspective, and identification of risks and opportunities

Question	**Theme**
So how long have you been farming, how/why did you get into it? How intensely do you farm, and why? (Dairy NZ levels 1-5). What are the main goals for you – lifestyle, financial, production, social? What are some of the things that are non-negotiable on this farm? What will this farm look like in 10 years and who will be running it? What will your lifestyle be like in 10 years time?	Historical profile of the system Goals of the system and problem identification
Who does the work on farm – family, staff? Who makes the decisions? Who do you supply milk to, what is the arrangement/obligations there?	Key actors and modifying influences
What is the biggest limitation on your farm that you can't control? How might this change over the next 5 years? What are the other external forces that influence what happens on the farm?	Current operational environment & associated constraints
Which best describes your farming situation currently? What are your strengths and weaknesses? What is a critical decision you've made this year? What was the reason? What made you change it and why? Has the farming system changed in the past five years? Why did you make any changes? What were the key drivers for change? What are the main sources of risk to your farming operation/system? Are you planning to change anything next year based on this years' experience? Why?	Identification of risks & opportunities
If you were a consultant, what advice would you give the owner of this farm? What would the key issues be if they were new to the area?	Consideration of uncertainties
What is successful dairy farming for you, and how do you measure that? Which aspects of farm management do you record and discuss together?	Identification of indicators of success

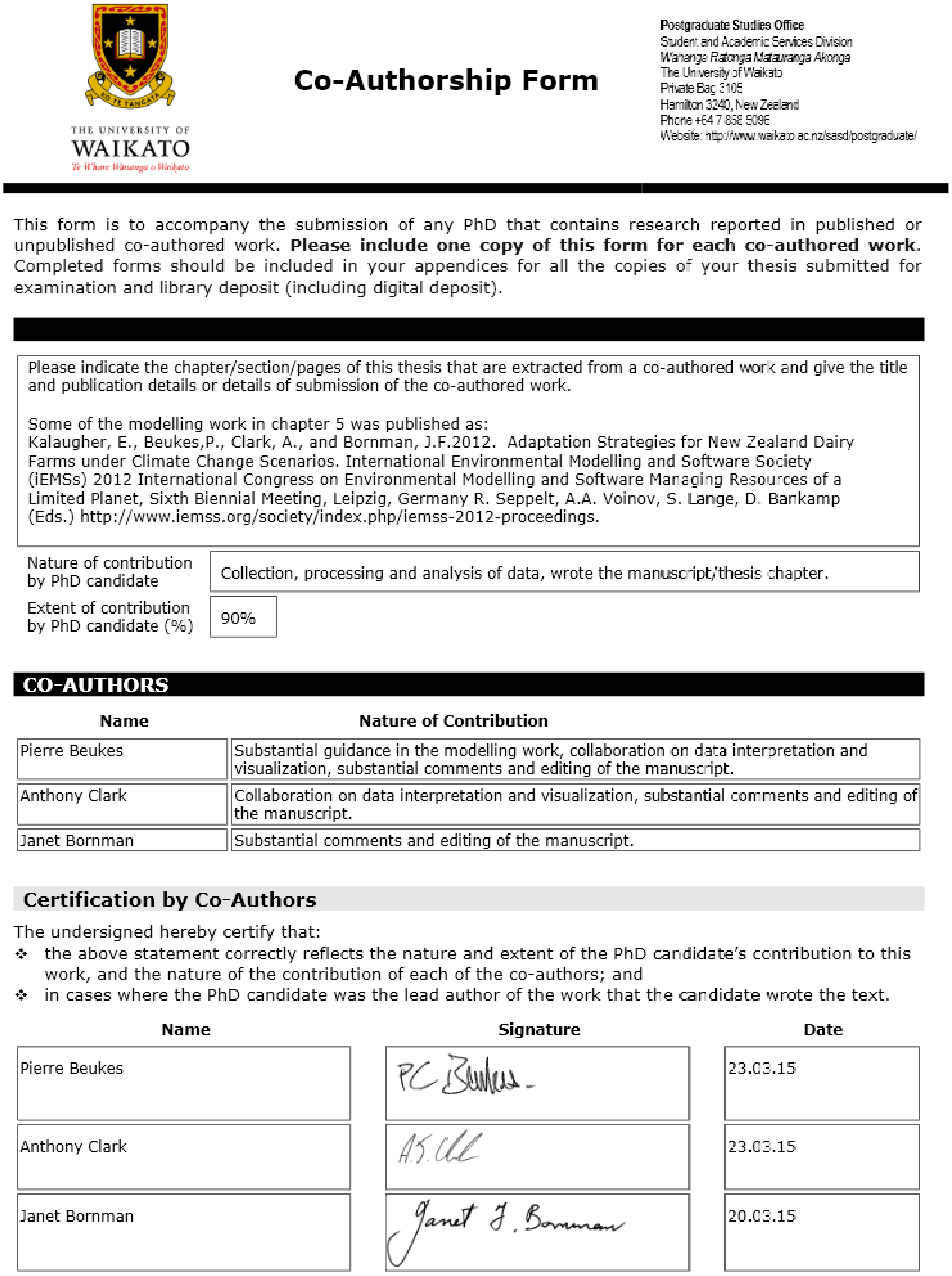
What was the worst extreme weather event to affect your productivity over the past 5 years? When? What happened? Why significant? How did it affect pasture? Stock? Land? Key memories (these may have nothing to do with farm it could be people memories) a. How bad was it? In what sense…lack of rain? Too much rain? Stock losses? Nil production? Nil pasture growth? Etc What affected your ability to manage the event? b. Do you think you were more or less affected than your neighbours? How could you tell? c. How did you cope? In what sense? Family? Decision making? Strategies used – pasture and stock? d. What do you think are the most important factors in surviving an extreme weather event like that? e. What were your economic losses for the year of the event, in terms of % of production lost? How about losses in future – calving rates? Animal health issues? Dry matter production losses? Stock losses? f. Have you changed anything about your farm as a result? Decisions made – tactical and strategic? Management – Business? Family? Stock? Pasture? Land? How resilient is your farm to weather events like that? 1) How much "wriggle room" do you have? long term and short term? 2) In what context? Pasture? Stock? Land? Staff? Infrastructure? On a scale of 0 to 5, how happy are you with the capacity of your farm to cope with the current range of weather? What aspects of the farm system have the most impact on this?	Assessment of current adaptive capacity of farm system: Economic, environmental, social
Have you noticed any changes in seasonality/extreme weather events in your area? Do you attribute this to CC or just normal climate variability? Are you worried about climate change – is it something you think will affect you, your decision making, your farm? Do they think it affects these things now? Long term?	Perspective on climate change

Interview 2: validate modelling results and identify alternative adaptation strategies

Questions	**Themes**
Here is the impact analysis for the two projected climate "scenarios" (high and low CO_2 emissions) for 2030-2050. What's the first thing that springs to mind when you see these projections? Do you think your current farming system would hold up under the high scenario? Low scenario? Would you have enough wriggle room/resilience in the system to cope? Do you think either of these weather scenarios would change the level of risk you'd be prepared to accept?	Validation of modelling results

How would your ideal system look under these scenarios? Would you change anything about the basic structure of your present system? (goals of the system, intensity, diversification, flexibility?) 1) Minor changes within the current system 2) Using new strategies 3) developing a completely new farming system? Can we go back over the table we filled out for the WFM? Realistically, what would you see yourself changing under the CC scenarios?	Identification of feasible adaptation options Matching goals with economic, environmental & social capabilities Identification of adaptation strategies or "Resilience pathways"
Here are the adaptation options that were modelled for your farm already. What do you think? How valuable is this kind of modeling work for you? Out of 5, where 5 is very valuable? What is useful about it? What are the limitations to its usefulness? What do you think of the use of operating profit, pasture growth/ha and milk solids/ha as measures of success? What's missing? What else would you consider? What else would you run in the model if you were doing it yourself? Can you outline 3 different management strategies or combinations of strategies would you like to run?	Highlight gaps & synergies Consideration of options not modelled
Which kind of management strategies can't be modelled, and how important are they? Out of 5? Why? Which parts of the system do you think would be the most sensitive to or affected by these kinds of changes in climate? Temporal? Long/short term Spatial? Flats/hills If you had $100,000 to invest in climate-proofing your farming system, what would you spend it on?	Assessment of trade-offs between soft & hard components of the system Identification of priorities & implementation planning
What would you need to know before changing your system? What would it depend on? What would the risks be? What would the barriers be to making those changes? What pressures/factors from the external environment would be important? What are the most important sources of information for you? How much trust do you have in each of these information sources? On a scale of 1-5? Why?	Analysis of opportunities & barriers

Appendix C: Co-authorship forms



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Co-Authorship Form

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This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. **Please include one copy of this form for each co-authored work.** Completed forms should be included in your appendices for all the copies of your thesis submitted for examination and library deposit (including digital deposit).

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Some of the modelling work in chapter 5 was published as:
Kalaugher, E., Beukes,P., Clark, A., and Bornman, J.F.2012. Adaptation Strategies for New Zealand Dairy Farms under Climate Change Scenarios. International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.) http://www.iemss.org/society/index.php/iemss-2012-proceedings.

Nature of contribution by PhD candidate	Collection, processing and analysis of data, wrote the manuscript/thesis chapter.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Pierre Beukes	Substantial guidance in the modelling work, collaboration on data interpretation and visualization, substantial comments and editing of the manuscript.
Anthony Clark	Collaboration on data interpretation and visualization, substantial comments and editing of the manuscript.
Janet Bornman	Substantial comments and editing of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
Pierre Beukes	PC Beukes	23.03.15
Anthony Clark		23.03.15
Janet Bornman	Janet J. Bornman	20.03.15

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Co-Authorship Form

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Chapter 3: Kalaugher, E., Bornman J.F., Clark, A., Beukes, P. 2013. An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system. Environmental Modelling & Software 39:176-187.

Nature of contribution by PhD candidate	Conceptual development of the framework, collection and processing of data, wrote the manuscript/thesis chapter.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Janet Bornman	Conceptual contribution and guidance, substantial comments and editing of the manuscript.
Anthony Clark	Conceptual contribution and guidance, substantial comments and editing of the manuscript.
Pierre Beukes	Guidance on pilot study, substantial comments and editing of the manuscript.

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

Name	Signature	Date
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