Estimating the Adaptation Deficit

An empirical analysis of the constraints on climate change adaptation in agriculture

The Hikurangi/Upper Wairua Catchment

David Gawith

Gonville and Caius College

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Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text

David Gawith

For my late grandfather, David Gawith (Pa)

Who farmed in the Wairarapa hill country and worked hard to pass on a better environment

Abstract

Agricultural adaptation to climate change is often simulated by changes in land use over time. Land use is commonly optimised in economic models, which rests on the neoclassical economic assumption of rational choice among farmers. A wealth of experimental and empirical evidence demonstrates that rational choice can be a poor approximation of human decision making. Models simulating adaptation by optimising producers' behaviour are in effect simulating adaptive potential. Much evidence demonstrates that adaptive potential does not necessarily translate into adaptation.

This investigation focuses on the ways by which farmers' real-world adaptive behaviours depart from those assumed by the dominant economic models of agricultural responses to climate change. These departures are characterised as adaptation constraints, and they are assessed through an empirical case study of adaptive behaviours in the Hikurangi catchment, New Zealand. Data are collected using a mixed methodology comprising an extensive survey of rural decision making, to which this study contributes, and a suite of semi-structured interviews. The interviews give an understanding of the origins and processes of adaptation constraints, while the surveys provide information about the extent to which they impact adaptive propensity. These adaptation constraints are then formalised as mathematical rules and written into an existing agent-based model of land use change, which is substantially modified for the purposes of this study. Different combinations of constraints are then tested in order to produce estimates of their economic impacts.

The constraints on adaptation are found to significantly reduce profits relative to a specification that assumes rational choice among farmers. This is understood to be the first empirically derived estimate of the extent of the adaptation deficit. The size of the deficit identified in this study implies that current economic models are likely to significantly underestimate the costs of adaptation to climate change, the benefits of climate change mitigation, and the residual loss and damage climate change will cause.

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I hope to live-up to the expectations of all those who have enabled me to take this extraordinary opportunity.

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Chapter 1

Introduction

1.1 Context and Rationale

1.1.1 Vulnerability of Agriculture to Climate Change

Climate change has been described by the World Bank as "the defining development challenge of our generation" (Agrawal, 2008, p.8). Agriculture is among the most important, and most climate sensitive of all human activities (Howden *et al.*, 2007; Meinke *et al.*, 2009; Mendelsohn and Dinar, 2009; Smit and Skinner, 2002; Rosenzweig *et al.*, 2014). Changes in climate will affect the productivity and in some cases the suitability of current crop and livestock choices in many parts of the world (Field *et al.*, 2014; Porter *et al.*, 2014; IPCC, 2014).

Losses in agriculture are likely to be the most important economic impacts of climate change (Dasgupta *et al.*, 2014). A range of studies have estimated these impacts. While results vary between locations, scales, and analytical approaches, the Intergovernmental Panel on Climate Change (IPCC (2014)) conclude with *high confidence* that negative impacts have been more commonly reported than positive ones. Reductions in agricultural yields have implications for food security. The impacts of agricultural fluctuations on global food prices have become clearer in recent years, with a number of price shocks tentatively linked to climatic extremes in major producing regions (Porter *et al.*, 2014). It has been estimated that 60% more food will be needed to meet global demand by 2050 (FAO *et al.*, 2012). The possible impact of climate change on global and regional food security has been identified as one of the IPCC's (2014) key risks under climate change.

The effects of climate change on agriculture are likely to be felt most acutely at the local level. Agriculture is the dominant economic activity in many regions, and the income it generates supports secondary and tertiary industries which are in turn vulnerable to agricultural changes (Dasgupta *et al.*, 2014). Climate change may provide agricultural opportunities in some areas, particularly in cold regions. On balance, however, net losses of rural livelihoods under climate change are anticipated with *high confidence*, and constitute another key risk that the IPCC (2014) has identified.

Linked to economic impacts, there is a growing appreciation of the social impacts of climate change, in particular the impacts of extreme events in rural areas. There is robust and consistent evidence that major floods and persistent drought lead to increases in rural poverty, closure of key services, social isolation, outward migration, and increased off-farm work leading to the separation of families (Reisinger *et al.*, 2014). Furthermore, numerous studies have identified significant emotional and psychological impacts resulting from climatic variability and extremes, including post-traumatic stress disorder, depression, and suicide (Alston, 2012; Doherty and Clayton, 2011).

1.1.2 Mitigation Prospects

There is considerable potential to reduce the speed and degree of climate change through global reductions in greenhouse gas emissions. Projections for changes in temperature for 2081-2100 relative to 1986-2005 range between 0.3°C and 4.8°C depending on the atmospheric concentration of greenhouse gases assumed (IPCC, 2013). There is, however, far less potential to mitigate near-term changes in climate (Klien *et al.*, 2014). Projections using the same range of assumptions about greenhouse gas concentration suggest that global mean surface temperature will increase by 0.3°C to 0.7°C by the period 2016 to 2035 relative to 1986 to 2005 (Kirtman *et al.*, 2013). These increases, added to observed warming of 0.85°C between 1880 and 2012 (IPCC, 2013), indicate that mitigation alone will be incapable of avoiding increases in climate change impacts (Meinke *et al.*, 2009; Howden *et al.*, 2007; Ford and Berrang-Ford, 2011; Field *et al.*, 2014; Porter *et al.*, 2014). These unavoidable impacts provide strong rationale for increasing focus on adaptation (Howden *et al.*, 2007; Berrang-Ford *et al.*, 2011; Wilby and Dessai, 2010; Chhetri *et al.*, 2010; Hallegatte *et al*., 2016).

The degree of climate change and the extent to which the global community will mitigate its impacts remain highly uncertain. It is worth noting that since the first IPCC assessment report in 1991, observed temperature increases have been in the higher portion of model projections (Pielke, 2008; Howden *et al.*, 2007). Furthermore, Anderson and Peters (2016) point out that the integrated assessment models used to form these projections generally assume large-scale anthropogenic carbon sequestration over the coming century, but it is not clear yet whether this will be feasible.

In efforts to mitigate climate change, multilateral negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) reached what has been named the 'Paris Agreement' in December 2015. The framework it laid out aims to "[hold] the increase in the global average temperature to well below 2°C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015, p.3). Current commitments by countries to limit or reduce emissions under this agreement, however, imply a median warming of 2.6-3.1°C by 2100 (Rogelj *et al.*, 2016), and there is substantial doubt as to whether 1.5°C is feasible (Rogelj *et al.*, 2015). Furthermore, in June 2017 the government of the world's second largest emitter, the United States, announced its intention to cease all participation in the Paris Agreement, implying that these estimates may need to be revised upwards. Given increasing annual emissions of greenhouse gas and the inadequacy of current emissions reduction targets, temperature increases at the high end of the IPCC projection ranges appear likely (Mastrandrea *et al.*, 2010; Parry *et al.*, 2009; Berrang-Ford *et al.*, 2011). Adger and Barnett (2009) suggest we need to start accounting for the significant likelihood of warming more than 4°C above pre-industrial levels. This strengthens the case for increasing focus on adaptation to climate change.

With respect to the impacts of climate change, both mitigation and adaptation influence the level of damage incurred. Mitigation and adaptation are complementary, and to some limited extent, substitutable (Klein *et al.*, 2014; Felgenhauer, 2015). Increased mitigation of greenhouse gas emissions can reduce the speed and magnitude of climate change, and hence the level of adaptation required to avoid unacceptable damages (Klein *et al.*, 2014; Field *et al.*, 2014). In many decision making structures, the potential costs of climate change are the dominant consideration in the level of mitigation deemed necessary (Parry *et al.*, 2009; Fankhauser, 2017; Burton *et al.,* 2002). These costs are estimated using integrated assessment models and depend on the assumed cost and effectiveness of adaptation options (de Bruin and Dellink, 2011). If adaptation to climate change is both cheap and highly effective, then the best level of mitigation effort may be low. If, on the other hand, adaptation is costly, difficult, and ultimately unlikely to be successful, the best level of mitigation will be high. The costs and effectiveness of adaptation options are therefore a crucial determinant of how best to respond to climate change in terms of both adaptation and mitigation (Burke and Emerick, 2016).

1.1.3 Adaptation

The potential magnitude of climate change makes the need to adapt agricultural systems clear. Meinke *et al.* (2009, p.74) state that “Adaptation is rapidly emerging as one of the biggest global agenda items for this decade, and possibly the century”. The potential for adapting to changes in climate through adjustments to farming practice and targeted policy responses is considerable (Elliott *et al.*, 2014; IPCC, 2014; Nelson *et al.*, 2013; Fezzi *et al.*, 2014). A number of studies suggest that this potential may exceed the expected negative impacts of climate change, even in highly vulnerable communities (Gawith *et al.*, 2015; Howden *et al.*, 2007; Fitzgerald *et al.*, 2009; Iglesias and Garrote, 2015; Nordhagen and Pascual, 2013; Dynes *et al.*, 2010).

Adaptation to climate change is already occurring in some places and within some communities (Berrang-Ford *et al.*, 2011; Dasgupta *et al.*, 2014). Berrang-Ford *et al.* (2011) and Davidson (2016) point out that increases in awareness about the need to adapt have been matched by an increase in research on adaptation in recent years. This has led to a proliferation of adaptation plans in both developed and developing countries (Jones *et al.*, 2014). Dilling and Moser (2007, p.9) observe that in most developed countries "… a perception prevails supported by much science, and even more political rhetoric, that society will be able to adapt to any adverse changes once they arrive…"

As Adger and Barnett (2009) point out however, adaptive potential does not necessarily translate into adaptation. The national adaptation plans developed to date focus largely on 'capacity building', and despite increases in research and awareness, many studies report a lack of adaptive *action* (Noble *et al.*, 2014; Jones *et al.*, 2014; Ford and Berrang-Ford, 2011; Repetto, 2009; Berrang-Ford *et al.*, 2011; Davidson, 2016). Heyd and Brooks (2009, p.277) suggest that this lack of response reflects "a fundamental and broadly based *cultural inadequacy*, characterised by an inability to fully comprehend or act on certain risks associated with environmental variability and change, even when information on these risks is widely available" (emphasis in original). Repetto (2009) suggests that information about the potential for adaptation dominates information about how adaptation occurs in reality, a situation which he describes as the 'adaptation myth'. He concludes by pointing out that "to say that [we] *can* adapt to climate change does not imply that [we] *will* adapt" (Repetto, 2009, p.20, emphasis in original). The difference between these two scenarios is profoundly important because underestimating the difficulties of adaptation risks forming unreasonably optimistic expectations about the costs of climate change, and hence underestimating the overall scale of the problem (IPCC, 2014; Repetto, 2009; de Burin and Dellink, 2011).

Observations of the gap between adaptive potential and adaptive action demonstrate the existence of an 'adaptation deficit', which the IPCC defines as "the gap between the current state of a system and a state that would minimise adverse impacts from existing climate conditions and variability" (Noble *et al.*, 2014, p. 839). In its original formulation, the adaptation deficit was conceptualised as the gap between current and optimal levels of adaptation when optimal adaptation is considered to be the "gross (or theoretically maximum) benefit of adaptation and risk management" (IPCC, 2012, p. 265; Burton and May, 2004). The term was first used by Burton (2004) to explain the high levels of losses from climatic factors occurring in the absence of significant climate change. In this sense, the adaptation deficit can be understood as inadequate adaptation to current climatic conditions (Burton, 2004; Burton and May, 2004; Noble *et al*., 2014), and the term can be closely linked to a broader 'development deficit' (World Bank, 2010; Hallegatte *et al*., 2016). Burton *et al*. (2002) go as far as suggesting that many aspects of development policy relating to climate vulnerability could be equally termed 'adaptation policy'. Fankhauser and McDermott (2014) suggest that differences in the extent of the adaptation deficit between countries largely explain why poor countries are more vulnerable to climate variability and change than rich countries are. While used infrequently, the term was adopted by the IPCC's fifth assessment report (Noble *et al*., 2014), and is still sometimes employed to describe attempts to address vulnerabilities to the current climate (Simões *et al*., 2017; Asfaw et al., 2018; Fankhauser and McDermott, 2014).

The adaptation deficit is a function of both the climate and the effectiveness of adaptation. Burton and May (2004) suggest that the latter may be the dominant influence in some cases. This implies that analyses of adaptation 'needs' that consider climate change alone may underestimate the challenges of adaptation to climate change and likely impacts it will have. Burton and May (2004) and Parry *et al*. (2009) stress that the current adaptation deficit needs addressing before credible estimates of the additional costs of climate change adaptation can be formed.

While the adaptation deficit is seen to be large in specific sectors and places, there is no consensus as to how large it is globally (Ford and Berrang-Ford, 2011; de Bruin and Dellink, 2011). As the ever-increasing impacts of climate change outstrip the implementation of adaptation, however, it is clear that this deficit is growing (Burton, 2004; Burton and May, 2004; IPCC, 2012; Eisenack *et al.*, 2014). This growth has spurred increasing global concern. The failure of climate change mitigation and adaptation has been ranked among the top five global risks in four of the last five annual Global Risk Reports from the World Economic Forum (2017). In 2016 the failure of climate change mitigation and adaptation was ranked as the highest global risk in terms of impact and the third highest risk in terms of likelihood, behind the closely connected risks of large scale involuntary migration and extreme weather events. Simões *et al*. (2017, p.1740) stress that it is "critically important to reduce the "adaptation deficit" between the implementation of adaptation with the ever increasing need for it".

The adaptation deficit is likely to result in considerable residual damages under climate change, and understanding these residual damages has been highlighted as an important area for future research (Parry *et al.*, 2009; Noble *et al.*, 2014). While our understanding of the physical science of climate change has improved, and indicates a significant chance that warming will exceed 4°C, Adger *et al.* (2009a, p. 20) point out that "… in effect, there is no science on how we are going to adapt to 4°C warming". Moser (2009, p.10) claims that "… an honest discourse and more critical examination of our true ability to adapt to climate change is warranted and overdue, including for highly developed countries". Howden *et al.* (2007) call for structured approaches to assessing the likely adoption of adaptation options, accounting for constraints that are important to the adapting actors.

Efforts to understand the adaptation deficit have focused on adaptation constraints (Fankhauser, 2017; Simões *et al*., 2017). Broad definitions describe adaptation constraints as factors, processes, or challenges that make adaptation more difficult, but that can be overcome (Klein *et al.*, 2014; Moser and Ekstrom, 2010). While a large number of adaptation constraints have been identified in recent years (Biesbroek *et al.* 2013), there remains what de Bruin and Dellink (2011, p.34) describe as "a significant gap in the literature regarding the effects of restrictions on adaptation". There is a need to move beyond the identification of constraints to assess how these constraints are likely to affect the adaptation process (Biesbroek *et al.,* 2013; Masud *et al*., 2017). Adger *et al.* (2009a, p.3) suggest that analyses that overlook factors such as adaptation constraints "may present a dangerously misleading understanding of the consequences of climate change". Despite this, adaptation constraints are generally ignored in studies seeking to assess the economic impacts of climate change.

While a small number of studies have sought to assess the impacts of adaptation constraints, most have done so using theoretical exogenous restrictions (see for example de Bruin and Dellink (2011), Chhetri *et al.* (2010), and Moore and Lobell (2014)). Despite this, de Bruin and Dellink (2011, p.42) acknowledge that "Understanding what adaptation restrictions are actually being faced or are likely to arise is an important issue that direly needs more attention." A similar research gap is highlighted by Cinner *et al*. (2015) in relation to applied research on adaptive capacity. Specifically, at the end of their assessment of adaptive capacity among finishing communities in Kenya, they acknowledge that "we have used theoretically informed indicators, but there are limitations to this approach and further work is needed to empirically test the relationship between these indicators and actual adaptive behaviour" (Cinner *et al*., 2015, p.874). Developing empirical understanding of the possible impacts of the constraints on adaptation to climate change constitutes the research gap that this study seeks to address.

1.2 Research Objectives

This study investigates the most important ways by which farmers' real-world adaptive behaviours depart from those that would maximise monetary benefit. The aim is then to quantify these departures by constraining adaptation within an Agent-Based Model (ABM) in order to form an estimate of the potential scale of the adaptation deficit. This constitutes the first empirically-based estimate of the economic impacts of adaptation constraints.

The study first seeks to identify known adaptation constraints in agriculture through a review of the literature. The saliences of these constraints are then evaluated through an empirical case study of the constraints on adaptation to climate change in the Hikurangi catchment in New Zealand. The empirical investigation comprises an extensive survey of rural decision makers and a suite of semi-structured interviews with farmers and industry professionals in the study region. The qualitative interviews explore how and why farmers' adaptive behaviours depart from economic optimality. The quantitative surveys assess whether the hypothesised constraints correlate with farmers' adaptive propensities, and if so, how strong these correlations are. The qualitative findings are used to inform the construction of mathematical constraints, a number of which are quantified using the results of the quantitative assessment. These mathematical constraints are then added to an empirically based, spatially explicit ABM of land use change in the Hikurangi catchment. Climate change forcing from the most recent yield-change projections, and socioeconomic variables calculated using data from the empirical case study are also added to the ABM. The study compares model outputs under a specification in which adaptation is optimised economically, with those under a range of specifications in which adaptation is constrained using the constraints specified in the empirical investigation. Figure 1.1 shows the structure of the approach taken in this study.

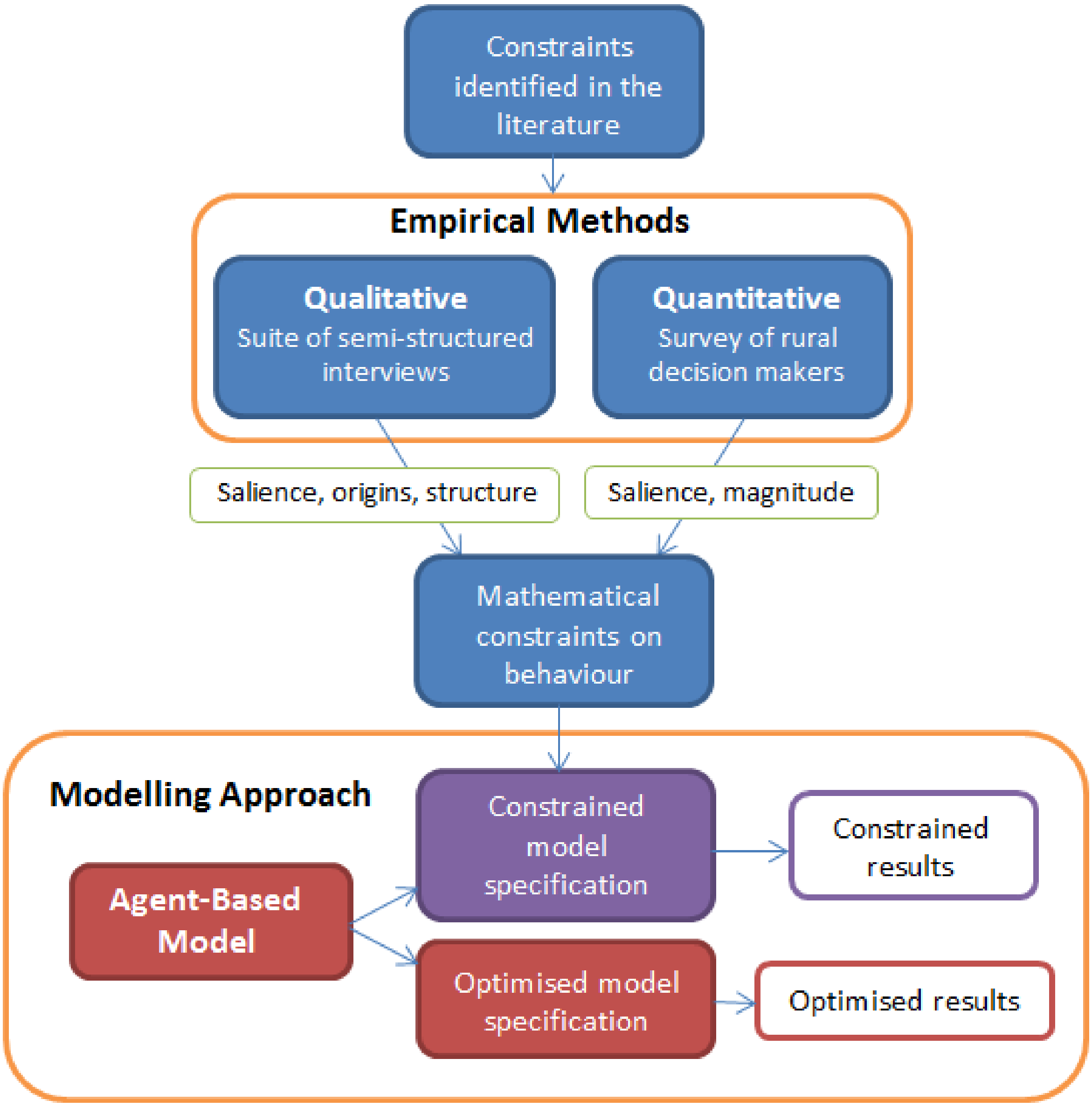

Figure 1.1: Flowchart of the research approach taken in this study.

The central research question of this thesis is:

Does including empirically derived constraints on adaptation produce significantly different economic outcomes?

The hypothesis in conducting this research is that:

Including empirically derived constraints on adaptation does significantly affect economic outcomes.

If there is evidence to support this hypothesis it would suggest that constraints on adaptation may significantly affect future patterns of production, and should be accounted for in policy formulation. It would also suggest that the extent to which people will adapt to climate change will be below the level at which individual and collective monetary benefit would be maximised. Further to this, it would demonstrate that existing impact assessment models can be improved upon by including empirically derived adaptation functions. It would also make it possible to experiment with various policy interventions to understand whether specific constraints on adaptation can be ameliorated.

If there is little evidence to support this hypothesis, it would strengthen the foundations for basing policy decisions on the findings of current impact assessment models. It would also present quantitative evidence that constraints on farmers' adaptive behaviours have negligible impacts on future economic performance in agriculture.

As acknowledged in the previous section, a small number of studies have compared scenarios relating to model treatment of adaptation constraints. The current study will move beyond these initial investigations by pursuing five key objectives. Firstly, it will use empirical evidence to construct adaptation constraints, rather than rely on arbitrarily weighting theoretical constraints. Secondly, it will assess a broader range of constraints within a more defined context than the aforementioned studies. Thirdly, it will use a modelling technique (ABM) that has not been used before to assess a broad suite of constraints on adaptation to climate change, but that explicitly accounts for adaptive behaviour. Fourthly, it will assess these constraints both quantitatively and qualitatively in order to understand the processes that result in adaptation constraints and the impacts these constraints may have. Fifthly, it will assess constraints in combination with one another in order to account for interactions and feedbacks, which are thought to be of considerable importance (Eisenack *et al.*, 2014). Integrating these five objectives, this study aims to demonstrate a method for empirically estimating the economic impacts of adaptation constraints.

1.3 Thesis Structure

The objectives of the study are addressed in the following nine chapters. Chapter Two details the research gap that this work seeks to address, explains how this work relates to the concepts of adaptation, adaptive capacity, and resilience, and describes the overall theoretical framework of the thesis. Chapter Three justifies focusing the assessment on the Hikurangi catchment, and describes the social, economic, institutional, and environmental context of the area. Chapter Four describes previous work assessing suboptimal adaptation, and identifies a range of known adaptation constraints through a review of the literature. Chapter Five then describes how the saliences of these constraints are investigated empirically in this study. The qualitative results of this empirical work are presented in Chapter Six, while the quantitative results are presented in Chapter Seven as part of a broader explanation of the modelling approach used. The results of the modelling analysis are presented in Chapter Eight and discussed in relation to previous knowledge on the subject in Chapter Nine. Finally, Chapter Ten provides conclusions which link the findings of this investigation to its objectives, summarises the wider implications of these findings, and highlights important areas for further research.

Chapter 2

Theoretical Framework

2.1 Overview

This chapter defines the terms and describes the theoretical framework on which the rest of the thesis builds. It starts by describing the social-ecological system on which the research focuses. It then introduces, defines, and relates the system characteristics of adaptation and resilience. Section 2.4 describes the two dominant methods used to model the economic impacts of climate change on agriculture, and highlights shortcomings in their treatment of adaptation. Section 2.5 explains how these shortcomings are explored in this study, describing the overall structure and focus of the research, as well as its limitations. Finally, Section 2.6 describes the overarching epistemology adopted in this study.

2.2 Social-ecological Systems

Before describing the research approach it is important to clarify and define the system on which this research focuses. In its simplest terms, this study focuses on the agricultural economy of the Hikurangi catchment. Understanding this as purely an economic system would, however, be inappropriate. The economy of the Hikurangi catchment depends on the highly complex interplay between social and ecological systems. For example, ecological processes such as species competition and nutrient cycling affect economic performance, which in turn affects land use and management, altering the ecological processes themselves. These interactions and feedbacks can dominate the overall system behaviour, such that focusing on individual components of the system may be inappropriate (Dynes *et al.*, 2010). Furthermore, the complexity of these types of interactions means that such systems cannot be understood using a reductionist analytical approach (McGowan *et al.*, 2014; Gallopín, 2006). It is important to consider both social and ecological aspects as part of an overall social-ecological system that generates the agricultural economy in question (Nelson *et al.*, 2007; Redman and Kinzig, 2003; McGowan *et al.*, 2014; Gallopín, 2006; Whitney *et al.*, 2017).

Social-ecological systems (SES) are defined by the Resilience Alliance (in Cradock-Henry *et al.*, 2015) as:

> "A multi-scale pattern of resource use around which humans have organized themselves in a particular social structure (distribution of people, resource management, consumption patterns, and associated norms and rules)."

In this study, agriculture exists as a multi-scale pattern of resource use in the Hikurangi catchment, around which farmers and other stakeholders interact within dynamic social structures. The conceptualisation of the agricultural economy of the Hikurangi catchment as a SES allows a broader understanding of what determines the system's behaviour. It must be acknowledged, however, that our understanding of this system is only partial. We remain ignorant of many important processes, dynamics, and interactions, and the system's actual behaviour will likely bring surprises (Darnhofer, 2014).

2.3 Adaptation and Resilience

Adaptation is considered particularly important for agricultural systems (Martin *et al.*, 2011; Porter *et al.*, 2014), and is likely to be the key way to reduce climate change vulnerability in New Zealand this century (Fitzharris, 2007). This study focuses on adaptation as the operational determinant of resilience. This section describes the variable, and at times inconsistent, ways that the terms adaptation and resilience have been used in the literature. It then defines these two terms as they apply to this study and as they relate to each other within the framework used.

2.3.1 Adaptation

The term 'adaptation' as it is commonly used in the climate change literature has developed from its use in evolutionary biology where it refers to genetic or behavioural changes that allow organisms or species to survive within changing and competitive environments (Smit and Wandel, 2006). Adaptation in social systems differs from adaptation in ecological systems in the way that information and change propagate. In ecological systems, change largely occurs on evolutionary timescales as a result of mutation and information provided by natural selection (Redman and Kinzig, 2003). Social systems, by contrast, have the ability to share information rapidly, and new behaviours and system traits can develop within a single generation (Redman and Kinzig, 2003). In the case of human understanding and foresight, adaptation can even be anticipatory (Redman and Kinzig, 2003; Galopin, 2006; Nelson *et al.*, 2007; Adger *et al.*, 2009a).

The distinction between proactive and reactive adaptation is commonly cited in taxonomies of social system adaptation (Porter *et al.*, 2014; Smit and Wandel, 2006; Grothmann and Patt, 2005; Mendelsohn and Dinar, 2009). Berrang-Ford *et al.* (2011) find that while human systems are capable of proactive adaptation, the majority of adaptive activity remains reactive. Mendelsohn and Dinar (2009) suggest that this is because of difficulties in forecasting changes in local conditions, and suggest that as long as actions are short-lived, most actors are better off reacting to climate change rather than anticipating it. They do, however, stress the importance of proactivity in long-lasting investments such as land use planning.

Adaptation rarely occurs in response to climate drivers alone (Rickards and Howden, 2012; Smit and Wandel, 2006; Dessai and Hulme, 2007; Berrang-Ford *et al.*, 2011). In an agricultural context, a variety of non-climate factors influence adaptation actions, including economic and regulatory conditions, social and technological pressures, changing labour and commodity prices, and globalisation (Klein *et al.*, 2014; Smit and Skinner, 2002; Cradock-Henry, 2011; Adger and Barnett, 2009; Darnhofer *et al.*, 2010; Ford and Berrang-Ford, 2011; Reed *et al.*, 2013). These non-climate factors are likely to interact with and dominate the influence of climate change in many cases (Beijeman *et al.*, 2009; Burton and Peoples, 2008; Field *et al.*, 2014). This complicates the definition of adaptation to climate change (Dessai and Hulme, 2007).

There have been many different definitions for adaptation proposed in the climate change literature, with varying degrees of reference to climate change. At the broadest level, adaptation can be defined as encompassing both ecological and social systems. For example, Adger *et al.* (2009b. p. 337) state that:

> "In essence, adaptation describes adjustments made to changed environmental circumstances that take place naturally within biological systems and with some deliberation or intent in social systems"

A number of other definitions include possible opportunities. For example the IPCC definition, which is commonly adopted in the climate change field, states that adaptation is "adjustment in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities" (McCarthy *et al.*, 2001, p.928).

Moser and Ekstrom (2010), propose a more detailed definition which they suggest builds on a number of weaknesses in the IPCC's definition. They acknowledge that adaptation may be justified by conditions or opportunities other than climate change. They further point out that while the IPCC's definition assumes effectiveness, well intended adaptations may fail. Their definition acknowledges that adaptation can range from coping strategies to system transformation, which, as

Section 2.3.3 explains, links it to the concept of resilience. Finally, while the IPCC's definition separates human and natural systems, Moser and Ekstrom (2010) suggest that SES are the systems of concern, a focus that fits with the current study. In light of these points, they propose the following definition:

> "Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting nonclimatic changes. Adaptation strategies and actions can range from short-term coping strategies to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not be successful in moderating harm or exploiting beneficial opportunities." (Moser and Ekstrom, 2010, p.22026).

Because of its breadth, appreciation of context, and links as a determinant of resilience, this definition is adopted by the current study.

With adaptation defined, it is important to explore what could be considered 'good' or 'desirable' adaptation (Adger *et al.*, 2005). Adaptations that could be viewed as successful in monetary terms can have more complex social, cultural, or environmental impacts that make them undesirable from the perspective of the people they affect. Central to understanding what constitutes 'good' or 'desirable' adaptation, is understanding what people and societies value (Klein *et al.*, 2014; Adger *et al.*, 2005,2009). Values define the goals of adaptation. However, as Ford and Berrang-Ford (2011, p.19) note: "there is surprisingly little research about what these values are, indeed, whose values they are and what they imply for adaptation outcomes". These values are highly context specific (Dessai and Hulme, 2007) and they differ between agents, meaning that the goals of adaptations relating to shared contexts are often contested (Adger *et al.*, 2009b; Dessai and Hulme, 2007). Furthermore, successful adaptation can differ between scales, such that successful private adaptation may not assist with collective adaptation (Adger *et al.*, 2005). Put simply, "The goal of adaptation will likely depend on who or what is adapting." (Adger *et al.*, 2009b, p.341).

Despite this understanding, conceptual, methodological, and practical challenges to assessing these goals mean that non-market impacts remain invisible to the vast majority of adaptation planning and assessment (Adger *et al.*, 2009b). Having an appreciation of the diversity of values held by actors, and the adaptation goals these values shape, is a crucial component of investigating adaptation. While these values and goals are difficult to quantify (Stern, 2007), they are considered in this study through an investigation of farmers' motivations and aspirations as described in Sections 4.9.1.1 and 6.3.1.1.

2.3.2 Adaptive Capacity

While adaptation is the act of change, adaptive capacity determines whether adaptation can occur (Adger *et al.*, 2011). Adaptive capacity is one of three components of the IPCC's vulnerability framework; the other two being exposure and sensitivity (Cinner *et al*., 2013, 2015). Within this framework, Cinner *et al*. (2013, p.9) suggest that adaptive capacity "is perhaps the component of vulnerability most amenable to influence, and may be a useful focus for adaptation planning". Adaptive capacity differs between people and over time (Cinner *et al*., 2015). Extensive evidence demonstrates that within all societies there are individuals and groups that lack adaptive capacity (IPCC, 2012; Noble *et al*., 2014).

Adaptive capacity is conceptualised in the literature as a latent characteristic of individuals and groups that determines their abilities to anticipate and respond positively to change (Burton *et al*., 2002; Marshall *et al*., 2013; Cinner *et al*., 2015; Whitney *et al*., 2017). More specifically, it is defined by Nelson (2011) and Cinner *et al*. (2015) as the sets of preconditions that enable adaptation to take place. While these preconditions are often conceptualised as different forms of capital, people's capacities to adapt often depend on characteristics beyond those generally understood to be 'capitals' (Mortreux and Barnett, 2017; Nelson, 2011). For example, Mortreux and Barnett (2017) reviewed the development of the concept of adaptive capacity in the literature, and noted a clear extension of the concept into the behavioural and psycho-social sciences, including a developing awareness of the importance of aspects such as risk attitudes, trust, and place attachment. Whitney *et al*. (2017) reviewed a wide range of approaches to the assessment of adaptive capacities within SESs. They found large variations in the approaches used, concluding that "The variety of ways in which adaptive capacity is defined, applied, assessed, and measured reflect a diversity of interests, areas of expertise and rationales" (Whitney *et al*., 2017, p.2). They also noted that, while certain characteristics can be seen to enhance adaptive capacity in a general sense, many aspects of adaptive capacity relate specifically to the change in question.

Among assessments focussing on social adaptive capacity, researchers have tended to explore people's access to assets, diversity and flexibility, institutions, governance, and knowledge (Whitney *et al*., 2017). Research by Marshall *et al*. (2013) and Cinner *et al*. (2013) on adaptive capacities among primary resource users has identified four essential and measurable dimensions of adaptive capacity: the management of risk; the ability to plan, learn, and reorganise; financial and psychological flexibility, and; interest in undertaking change.

The various dimensions and characteristics of adaptive capacity identified in this section can be seen as the *enablers* of adaptation (Simões *et al*., 2017). Like these previous pieces of work, the current study assesses adaptive capacity. However, instead of focussing on the characteristics that enable adaptation to occur, it explores the factors that make adaptation more difficult. In the context of this study, farmers' adaptive capacities are determined by a broad range of adaptation constraints, which are described in Section 4.9. These constraints determine the extent to which farmers are likely to adapt in response to changes in climate.

2.3.3 Resilience

The term 'resilience' is commonly used in the climate change literature, however there have been inconsistencies in how it is defined (Nelson, 2011; Smit and Wandel, 2006; Darnhofer, 2014; Gawith *et al.*, 2016). The term originated in the physical sciences to describe a material's ability to store strain without breaking (Klein *et al.*, 2003). It was subsequently applied to ecology by Holling (1973) who used it to describe the capacity of ecosystems to endure and recover from stress. This metaphorical usage has since been extended to a wide range of systems including SES (Klein *et al.*, 2003; Folke, 2006). According to Darnhofer (2014), the extension of the concept of resilience to SES reflects a paradigmatic shift in understanding to a greater appreciation of complexity. The concept of resilience acknowledges our inability to optimise complex systems and is conscious of deep uncertainties and the likelihood of surprises within these systems (Noble *et al.*, 2014; Darnhofer, 2014; Adger *et al.*, 2011).

In a farming context, Darnhofer (2014) proposes that resilience can be broken into three separate capabilities: buffer capability, adaptive capability, and transformative capability. Buffer capability describes the ability for a system to absorb disturbance and return to its original structure and function. Adaptive capability describes the ability of a system to adjust to changing external conditions in order to develop while maintaining the same basic structure. Transformative capability describes the potential for re-organisation of a system into a new configuration. Darnhofer (2014) suggests that resilient farm management requires each of these three capabilities. With these three capabilities in mind, the current study adopts the definition of resilience put forward by the IPCC (2014, p.5) which states that resilience is:

> "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."

This definition acknowledges both social and ecological systems, which matches the framing of this study and has been seen as central to the assessment of resilience (Nelson *et al.*, 2007).

A critical link in the framework of this study is that resilience can be enhanced or diminished through adaptation. Nelson (2011) suggests that adaptation encompasses actions that determine overall resilience. A subtly different outcome of adaptation is 'system adaptedness', which describes "the level of effectiveness in the way a system relates with the environment and meets the normative goals of system managers and stakeholders" (Nelson *et al.* 2007, p400). System adaptedness describes the extent to which a system makes 'optimal' use of current conditions. System adaptedness is the objective of most economic models of adaptation based on optimisation.

In contrast to system adaptedness, the objective of resilience explicitly includes maintenance of the capacity for further adaptation, learning, and transformation. Darnhofer (2014) points out that elements of uncertainty and surprise mean that farmers recognise a trade-off between their adaptedness and their ability to respond to changes. Farmers generally work towards *resilience.* By using empirical data on the priorities, aspirations, and behaviours of farmers, therefore, the constrained specification of the model used in this study (described in Section 2.6) implicitly incorporates resilience as its objective. By ignoring these constraints, the optimised specification of the model used in this study (also described in Section 2.6) maximises system adaptedness.

It must be acknowledged that using resilience as an organising concept has been criticised on some grounds. Contested definitions and meanings make the concept of resilience vague, undermining its value for practical policy or management advice (Darnhofer, 2014). Resilience has also proven particularly difficult to measure, making it hard to apply in practice (Noble *et al.*, 2014). Furthermore, resilience focuses explicitly on the state of the overall system, and pays little attention to individuals within that system, their needs, and their objectives (Nelson *et al.*, 2007; Eakin *et al.*, 2009). Despite these drawbacks, the concept of resilience allows for a more holistic understanding of the process and objectives of adaptation to climate change (Nelson *et al.*, 2007; Darnhofer, 2014). In the context of this study, its flexibility is an advantage because it can be moulded to match the focus of the research question posed in Chapter One.

2.3.4 Trade-off between Adaptation and Resilience

While adaptation can increase resilience, it can also work to undermine it (Nelson, 2011). Walker *et al.* (2006) identified three ways in which adaptation has been seen to undermine resilience. The first of these relates to adaptation externalities, in which adaptation in one place or time diminishes resilience in another location or period. For example, Nelson (2011) pointed out that adaptations such as flood defences could increase flood risk in adjacent regions.

The second way that adaptation can diminish resilience is through a loss of response diversity caused by sunk costs - a phenomenon which has variously been described as 'lock in' or 'path dependency' in other literatures (Chhetri *et al.*, 2010). In this case, past adaptation investments, particularly large investments, make people less able or less inclined to consider new approaches, even when change may be beneficial (Nelson, 2011).

The third way that adaptation can reduce resilience is when a system becomes over-adapted to a certain range of conditions or opportunities and becomes vulnerable to other hazards as a consequence. For example, Adger (2000) showed that, while specialising in a single type of production can increase income, it can also increase income variability and decrease social resilience. Basset-Mens *et al.* (2009) argued that, while intensification of dairy farming in New Zealand has increased production, it has also undermined efficiency relative to European systems, leaving farmers vulnerable to fluctuation in the world dairy price. These examples demonstrate that system adaptedness can be a poor measure of success and may not be a desirable objective (Nelson *et al.*, 2007). The broader concept of resilience avoids these drawbacks.

In all systems, there is a balance that must be met between the degree of adaptedness to current conditions and the degree of flexibility should these conditions change (Nelson *et al.*, 2007). The extent of variability in the conditions that influence agriculture suggests that this trade-off may be particularly important for farmers. Darnhofer (2014) suggests that *less* time and effort should be spent on improving the efficiency of current farming systems and more on maintaining a diversity of response options. Based on these findings, the current study recognises resilience, rather than system adaptedness, as the goal of adaptation.

2.4 Modelling of Adaptation in Economic Impact Studies

Studies that model the economic impacts that climate change may have on agriculture are numerous, and date back a number of decades. These studies have informed assessments of the global costs of climate change, and have in turn provided information upon which global responses, in the form of both adaptation and mitigation, are designed (Gsottbauer and van den Bergh, 2011; Burke and Emerick, 2016). A major limitation of these studies has been their incomplete treatment of the dynamics of adaptation and their neglect of adaptation constraints (Nelson *et al.*, 2013; Bateman *et al.*, 2011; Fezzi *et al.*, 2014; Nolan *et al.*, 2009; Gsottbauer and van den Bergh, 2011; Burke and Emerick, 2016).

Economic assessments of the impacts that projected climate change may have on agriculture commonly follow either an econometric or a Ricardian approach (Dasgupta *et al.*, 2014; Mendelsohn and Dinar, 2009; Burke and Emerick, 2016). Both of these approaches model adaptation exogenously. Econometric approaches, labelled 'first generation' approaches by Smit and Skinner

(2002), dominated the literature during the late 1980s and early 1990s (Kelly *et al.*, 2005). Econometric approaches use time-series data on the impacts of climatic variation on productivity and agricultural revenue in order to model the impact of future climate change. These approaches consider only short-term responses to climatic stress enacted under the expectation of a stable climate (Mendelsohn and Dinar, 2009; Moore and Lobell, 2014). They do not consider the possibility for adaptation spurred by changed expectations under long-term changes, and they have been labelled the 'dumb farmer' approach as a consequence (Kelly *et al.*, 2005; Kenny, 2011; Smit and Skinner, 2002; Mendelsohn and Dinar, 2009; Parry *et al.*, 2009). Econometric approaches are likely to overstate the economic impacts of climate change because they overlook long-term adaptation[1] (Nelson *et al.*, 2014; Wratt *et al.*, 2008).

Alternative 'second generation' or 'smart farmer' approaches model a theoretical equilibrium adaptation through adjustments in management practices and land use under changing conditions (Kenny, 2011; Parry, 2009; Berger and Troost, 2014; Smit and Skinner, 2002). These commonly follow a 'Ricardian approach' - named after David Ricardo (1772-1823). This approach uses cross-spatial data on land-use and management covering a range of environmental conditions to infer optimal responses to changes in climate (Mendelsohn and Dinar, 2009; Wratt *et al.*, 2008; Berger and Troost, 2014; Baisden *et al.*, 2010; Bateman *et al.*, 2013). By controlling for unwanted variables this approach can, in principle, determine the impact of climatic conditions on agricultural production (Mendelsohn and Dinar, 2009; Burke and Emerick, 2016). The Ricardian approach assumes that farmers maximise their profits subject to the climatic conditions they experience. When these conditions change, farmers are assumed to adjust their land use perfectly, instantaneously, and without cost, in order to emulate those who experienced their new climatic conditions under the baseline climate (Seo *et al.*, 2009; Mendelsohn and Dinar, 2009; Bateman *et al.*, 2013). This describes how agricultural systems would change if they had sufficient time to reach equilibrium under new conditions (Kelly *et al.*, 2005). In reality, agriculture is unlikely to ever be in equilibrium (Beijeman *et al.*, 2009), and the Ricardian approach can be seen to produce lower bound estimates of the costs of adaptation as a result (Kelly *et al.*, 2005; Wratt *et al.*, 2008; Burke and Emerick, 2016).

The optimisation of decision making has become the dominant approach to assessing the economics of climate change adaptation. However there is considerable reason to expect that agricultural adaptation will not take place in an optimal manner (Chhetri *et al.*, 2010; de Bruin and Dellink, 2011; Marshall, 2013; Gsottbauer and van den Bergh, 2011). The optimisation of land use and management

[1] This overestimation may, however, be modest. Recent work by Burke and Emerick (2016) explored the possible bias contributed short-term responses in econometric models by using data on the response of farmers to longer term changes in climate. They found that adaptation to observed changes in temperature between 1980 and 2000 in the central and eastern United States offset less than 50% of the negative short-run impacts of fluctuations in temperature, and may have even be indistinguishable from short-run adjustments.

assumed in the Ricardian approach rests on a narrow concept of economic rationality and ignores the adaptive constraints that farmers face. Economic rationality differs from other broader conceptualisations of rationality in that it focuses exclusively on maximising monetary benefit. It is equivalent to the assumption of 'rational choice' in neoclassical economics. Economically rational agents are solely concerned with maximising their financial wellbeing, have infinite analytical ability, and base their decisions on perfect information about their alternatives (Parker *et al.*, 2003). The approximation of human decision makers as economically rational agents, often termed 'Homo Economicus', is of some use in the modelling of impersonal and competitive markets. It is, however, far less appropriate for modelling agricultural adaptation to climate change (Heckbert *et al.*, 2010a; Parker *et al.*, 2003; Schreinemachers & Berger, 2011).

A wealth of experimental and empirical evidence demonstrates that the assumptions of economic rationality underlying Homo Economicus are inappropriate (Heckbert *et al.*, 2010a; Parker *et al.*, 2003; Gsottbauer and van den Bergh, 2011). While many people behave in economically rational ways in some situations (Janssen and Ahn, 2006), human behaviour is characterised by numerous behavioural anomalies (Tversky and Khaneman, 1986; Pike, 2008; Gowdy, 2008; Gintis, 2000; Chambwera *et al.*, 2014; Gsottbauer and van den Bergh, 2011), and people's decisions are subject to many constraints (Kenny, 2011; Klein *et al.*, 2014; Grothmann and Patt, 2005). Multiple laboratory and field scale social experiments have shown people to be boundedly rational and to have limited self-interest (see Gsottbauer and van den Bergh (2011) for a review of seminal work).

Examples of adaptive behaviour in agriculture departing from that assumed under rational choice are common (Gifford *et al.*, 2011). In a laboratory experiment comparing agricultural land use choices under changing land rents, Manson and Evans (2007) found that the majority of participants persisted with their original land use for numerous rounds after the alternative land use became more profitable. In the eastern United States, Nelson *et al.* (2014a) found that a lack of diversity in farmers' social networks worked against potentially profitable land use change, favouring current land uses. Cradock-Henry and Mortimer (2013) investigated climate resilience amongst dairy farmers in New Zealand. They found that adaptation decisions depended on conditions such as the extent to which farmers were aware of the risks associated with climate change, whether they thought that adaptation strategies were able to mitigate those risks, and whether they felt confident in their capacity to undertake such strategies. They demonstrated that the majority of farmers surveyed lacked critical awareness of the risks that climate change poses, and were therefore unlikely to change their production strategies in anticipation of climate change alone. These examples demonstrate that the rational choice assumptions underpinning the dominant Ricardian approach poorly approximate farmers' adaptive behaviours. There is an urgent need to investigate how, and to what extent, actual adaptive behaviour departs from this assumed ideal (Brown *et al.*, 2013).

2.5 Framework

The ordering framework of this study compares two alternative scenarios for climate change adaptation: one in which adaptation is optimised to achieve the highest possible monetary benefit, and one in which it is constrained based on empirical information about the major constraints farmers face. The optimised scenario represents the prevailing Ricardian approach, and assumes that farmers work to achieve system adaptedness. The constrained scenario rejects the rational choice premise, treats farmers' behaviour as constrained, and implicitly assumes resilience as the objective of adaptation.

The differences between these two scenarios will be assessed both qualitatively and quantitatively. The qualitative assessment will explore how and why farmers' adaptive behaviours depart from those assumed under rational choice. The quantitative assessment will compare the outputs of an agent-based model in which adaptation is optimised against a range of specifications in which adaptation is constrained. The findings of the qualitative assessment are used to inform the construction of adaptation constraints that are then programmed into the agent-based model. This overall framework is shown in Figure 2.1.

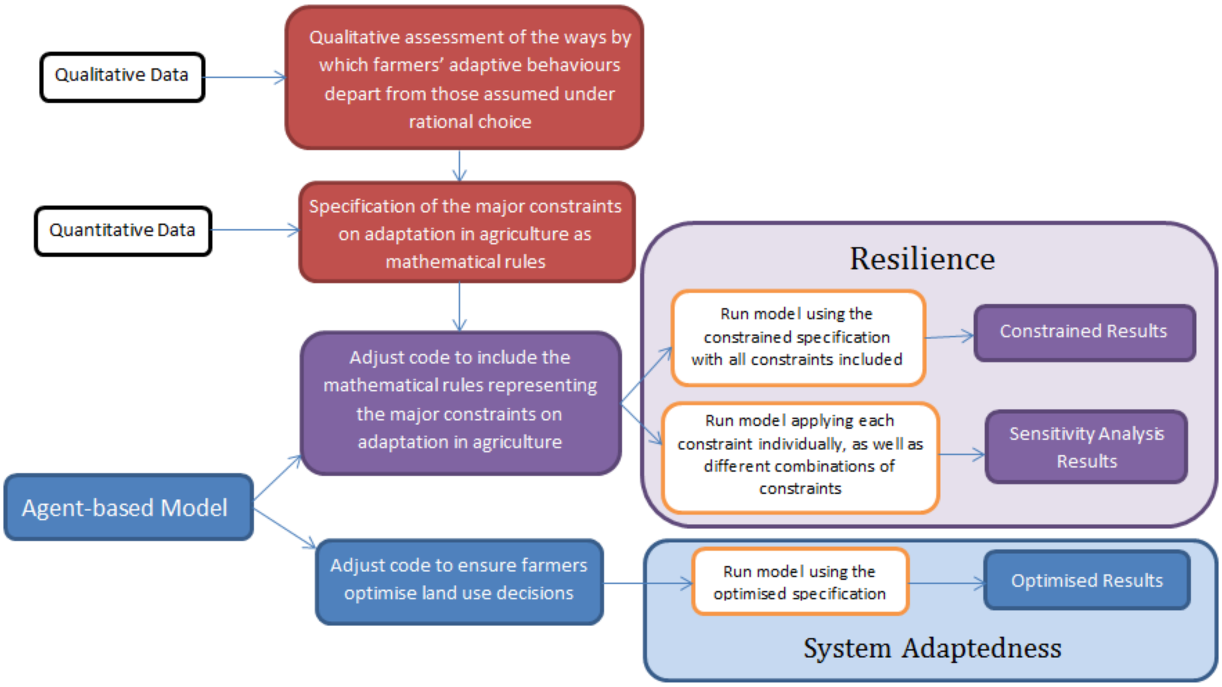

Figure 2.1: Overall framework of this study.

This overall framework adheres to the recommendations of Moser and Ekstrom (2010, p.22027), who suggest that, given the broad influence of climate change and the multitude of complex adaptive decisions it affects, investigations should be "principled but not overly confining". Relating to their four guiding principles, this framework is focused on the social and economic impacts of climate change, but constrained by ecological parameters. It focuses on the farmers in the catchment, but includes contextual considerations such as climate change and market growth. It focuses on the process of adaptation but is concerned primarily with the macro-scale impacts of this process. Finally, the analysis is iterative and considers complex influences, but follows a linear framework, as shown in Figure 2.1, for tractability.

Similar to their use by the IPCC (Field *et al.*, 2014), the scenarios used in this study are not synonymous with predictions. Rather, they are used as tools to answer the question 'how might agricultural adaptation depart from optimised adaptation assumed under the prevailing Ricardian framework?' The optimised scenario is used to highlight the impacts of adaptation constraints because it reflects the treatment of adaptation in the dominant Ricardian approaches. It is well-known and widely acknowledged that the optimisation of adaptation is unrealistic, however it is still widely used as a simplification (Adger *et al.*, 2009a; Seo *et al.*, 2009; Mendelsohn and Dinar, 2009; Wratt *et al.*, 2008; Berger and Troost, 2014). Optimised adaptation scenarios are commonly used as a benchmark to compare alternative hypotheses about adaptation, and this is how the optimised scenario is used in this study (Kelly *et al.*, 2005; Morgan *et al.*, 2015; de Bruin and Dellink, 2011).

2.5.1 Important Actors

In investigating adaptation to climate change, it is vital to outline which actors are the focus of the study and why. Approximately half of all farms in New Zealand are still owner operated or owned in a single family trust (Nuthall, 2006; Brown *et al.*, 2013). Owner operators are therefore the primary actors of concern in this study.

A number of other actors, including ownership partners, private sector support services, and local government are also important (Davidson, 2016). Large areas of New Zealand's farmland are leased, and sharemilking is common (Brown *et al.*, 2013), while a small number of farms (less than 3%) are corporate owned (Brown *et al.*, 2013). For farms that are owned in partnerships or businesses, owned as part of a corporate portfolio, or leased, farmers' decisions may be influenced by others (Brown *et al.*, 2013). The extent of this influence is complex, and depends on the nature of the ownership structure and the relationships and trust between parties (Parker *et al.*, 2007). It is clear, however, that external partners or landlords are likely to be important actors in adaptation decision making, and their influence is therefore considered in this study.

Where farms are owned by their operators, farmers may be able to act with a high degree of autonomy. Many owner operated farmers are, however, to some extent influenced by external capital. For example, in many cases farm ownership and farm development and infrastructure projects are financed by banks. As Brown *et al.* (2013, p. 37) point out, “In effect, an ‘owner occupied’ farm can be owned to varying degrees by other organisations that are then able to influence decision-making on the farm.” Jack (2006) found that banks, financial managers, and accountants can hold considerable power in farm decision making processes, particularly for farm businesses under financial pressure. As Noble *et al.* (2014) note, the private and financial sectors are likely to become increasingly important in translating specialised and technical risk information into farm-scale adaptation pressure. These pressures and influences are highly complex and variable; however financial services, banks, and private-sector extension services are likely to be important actors in adaptation decision making, and are also considered in this study.

Relating mainly to problems of collective action, local government has also been identified as critical to successful adaptation in agriculture (Noble *et al.*, 2014). Local governments are often responsible for setting local resource management policies and undertaking infrastructure developments. They are commonly mandated to consider climate change as a long-term threat in their decisions (Ford and Berrang-Ford, 2011). Local governments therefore provide another linkage by which climate change projections are translated into local scale adaptation, and comprise another group of actors considered in this study.

2.5.2 Limitations

While agricultural adaptation to climate change includes a broad range of actions, in the simplified framework of this study the only adaptation available to farmers is land use change. While this is similar to the treatment of adaptation in Ricardian studies, it ignores more subtle management adaptations such as irrigation, fertiliser use, or altering the timing of operations (Daigneault *et al.*, 2012; Smit and Skinner, 2002; Burton and Peoples, 2008). Lieffering *et al.* (2012) calls these ‘tactical’ adaptations, whereas land use change can be thought of as a ‘strategic’ adaptation. Focusing on land use does not, however, consider the full range of strategic adaptations, and more radical transformational changes such as a shift away from agriculture into tourism are also possible (Nelson, 2011).

In addition, while this study focuses on adaptation to climate change, it is widely recognised in the literature that climate change exists as one of many influences that farmers must adapt to – and is often not the most pressing (Cradock-Henry, 2011; Adger *et al.*, 2009a). Contextual factors including international trade, population, and technological development are likely to greatly influence the economics of agriculture in the future. However, many of these factors are poorly understood and unable to be predicted (Bateman *et al.*, 2013; Field *et al.*, 2014; Daigneault *et al.*, 2012; Iglesias and

Garrote, 2015) meaning that including them would quickly make the analysis infeasible. This study will therefore assess adaptation to climate change *ceteris paribus.* While ignorance of stressors beyond climate change can be criticised, particularly in applied vulnerability research (see for example Cradock-Henry, 2011), it is a common approach in more targeted theoretical work (Reed *et al.*, 2013; Reisinger *et al.*, 2014; Daigneault *et al.*, 2012; Gawith *et al.*, 2015; Iglesias and Garrote, 2015). By ignoring important contextual factors such as trade liberalisation and technological development, however, it is acknowledged that this approach may overestimate the importance of climate change impacts in the future (Iglesias and Garrote, 2015).

2.6 Overall Epistemology

There are a number of possible epistemologies under which the framework of this study could be applied. For example, framing the study as an exercise in behavioural economics would make use of a common language between the economic, social, and behavioural aspects of the research (Pike, 2008). Furthermore, it would align the findings with the language of policy-making while moving beyond traditional approaches based on neoclassical economic assumptions (Pike, 2008). The behavioural economics lens can, however, be criticised for its emphasis on individual motivations, and there is some suggestion that its reductionist treatment of these motivations may provide oversimplified results (Gifford *et al.*, 2011).

Alternatively, focusing on the *process* of adaptation has the potential to identify more nuanced features of the behaviour of the system in question. For example, evolutionary theory can be used to explore the forces driving, and the mechanisms facilitating, changes in social-ecological systems over time (Darnhofer *et al.*, 2010). Gowdy (2008) notes that there appears to have been a shift towards an overall framework called general Darwinism. In broad terms, this framework understands adaptation as the result of variation, inheritance, and selection of certain behaviours and traits (Gowdy, 2008). Through mechanisms of reward and punishment, behaviours repeat and become widespread when they are considered to be beneficial and socially acceptable at the time in their context (Gowdy, 2008). This approach recognises that people's responses to stimuli are socially mediated, and are generally affected by influences that are beyond monetary or political control (Gowdy, 2008). While this provides a promising approach to understanding adaptation in broad terms, it is less useful under the framework of this study. As explained in the previous section, this study focuses exclusively on land use change as an adaptation to climate change. In this sense, the forces driving adaptation are pre-defined, and the mechanisms facilitating adaptation are greatly limited relative to those possible in practice. Evolutionary theory and general Darwinism are, therefore, not considered appropriate overall epistemologies for this study.

A small number of epistemologies have been developed to explicitly integrate interdisciplinary research. Mansilla (2010) critiques two such approaches: logical positivism and consilience. According to this critique, logical positivism elevates propositional knowledge that can be tested formally, and therefore cannot integrate more emotive forms of understanding. While consilience does include these forms of knowledge, it does so from a biological standpoint – seeking psychological explanations for our aesthetic preferences. Instead, Mansilla (2010) suggests the use of a *pragmatic constructionist* epistemology which aims to combine different disciplinary knowledge to produce new knowledge, and does so in a way that puts a premium on the purpose for which the knowledge was collected. This results in what Mansilla (2010) calls a 'reflective equilibrium' of knowledge in which informed theories and explanations can be put forward and accepted, but they remain open to change as disciplines evolve.

In light of the complexities and deep uncertainties inherent to this study, a pragmatic constructionist epistemology is adopted. This acknowledges the pragmatic simplifications used in the framework and methods applied. The constructionist aspect emphasises that these pragmatisms were adopted in a targeted way for the purpose of further understanding the constraints on agricultural adaptation to climate change. Most importantly, adopting a pragmatic constructionist epistemology means the results presented in Chapter 8 and discussed in Chapter 9 are understood to stem from limited knowledge of the systems to which they relate. This understanding is expected to develop and change over time.

Chapter 3

Study Site

While climate change is a global problem, its impacts vary at local scales and require local adaptive solutions. This mismatch of scales has been called the "adaptation paradox" (Jones *et al.* 2014, p.207), and it implies that studies on climate change adaptation should focus on local level adaptive responses while remaining conscious of the drivers of climate change at the global level. With this in mind, the current study makes use of climate change projections based on analysis at the global level, but focuses the assessment of adaptive responses on a single case study catchment in New Zealand, called the Hikurangi/Wairua catchment (henceforth referred to simply as the Hikurangi catchment).

This chapter outlines the rationale for focusing on the Hikurangi catchment. Section 3.1 highlights the importance of agriculture in New Zealand before noting the vulnerability of the country to climate change and acknowledging salient economic, social, and institutional characteristics. Section 3.2 then justifies studying the Hikurangi catchment before Section 3.4 summarises these rationales.

3.1 New Zealand Agriculture

New Zealand's economy is the most highly dependent on land based industries of any developed country (MPI, 2013). Agriculture, food, and forestry exports make up 70% of New Zealand's merchandise export revenue, and contribute around 12% of the nation's Gross Domestic Product (GDP) (MPI, 2013; Dynes *et al.*, 2010). Beyond their importance for the national economy, land based industries employ large numbers of people. From a population of 4.5 million, more than 200,000 people are employed in land based industries, both directly and indirectly (Dynes *et al.*, 2010). While many developing countries are similarly dependant on agriculture, basing this study in New Zealand takes advantage of relatively abundant and robust data for modelling social, environmental, and economic conditions (Cradock-Henry *et al.*, 2015).

The dominant land use in New Zealand is pastoral farming. More fertile and productive land with high average rainfall tends to be used for dairying, while less productive hill country is often used for drystock[2] farming or forestry. Figure 3.1 shows the mixture of dairy, drystock, forestry, and scrubland across New Zealand in 2001-2002, as reported by Wratt *et al.* (2008).

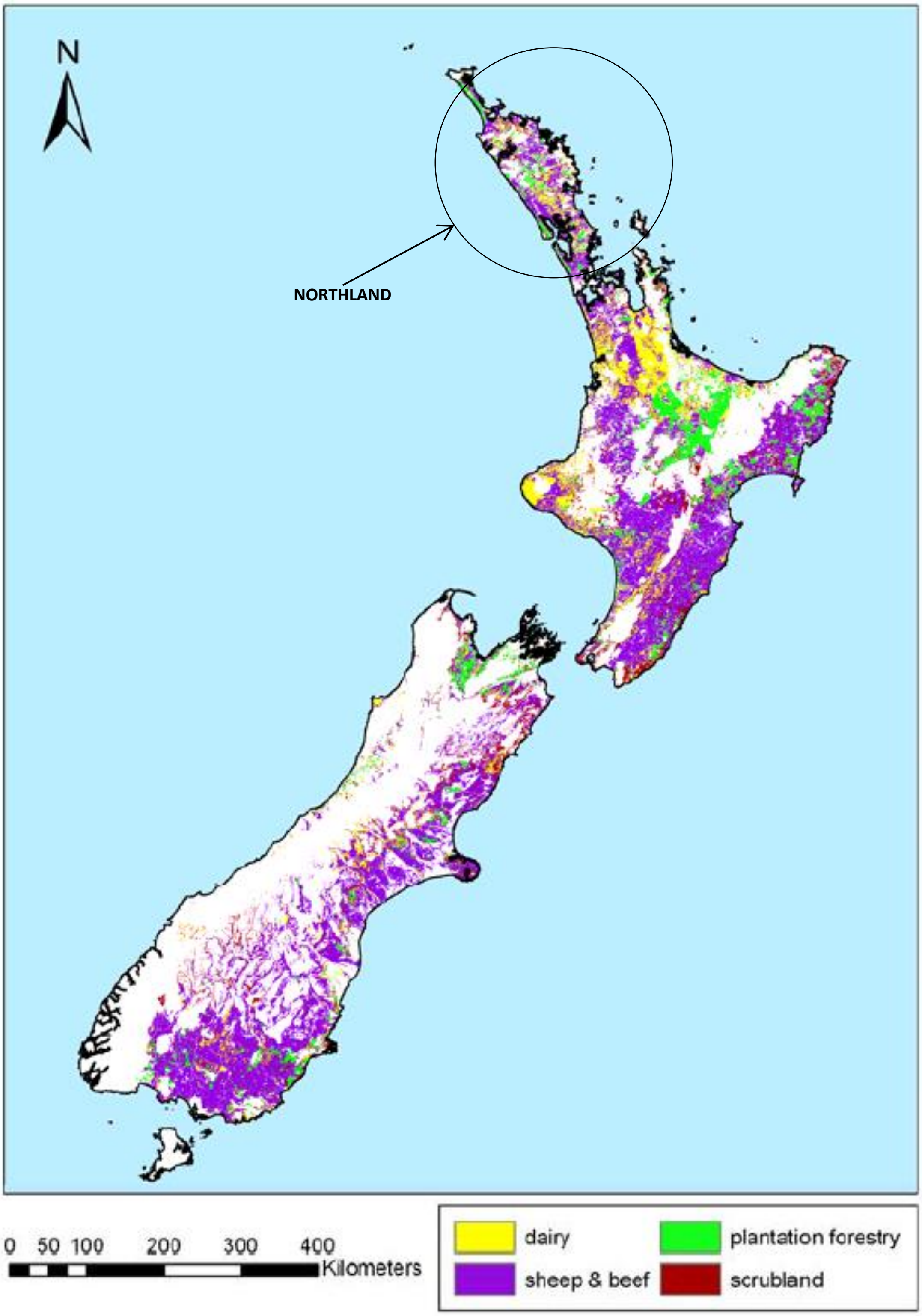

Figure 3.1: Land use map taken from Wratt *et al.* (2008) of New Zealand in 2001-2002.

[2] Drystock farming is also commonly referred to as 'sheep and beef' farming in New Zealand. Conditions in the Hikurangi catchment mean that the majority of drystock farming is beef, hence the term drystock is used instead of sheep and beef in this thesis.

3.1.1 Climate Vulnerability

The vulnerability of New Zealand's agriculture to climate extremes is widely recognised (Reisinger *et al.*, 2011, 2014). As explained in the previous section, farming in New Zealand is predominantly pastoral, and relies on a small number of pasture, plant, and animal species (Cradock-Henry & Mortimer, 2013). Pastures in New Zealand are vulnerable to successive droughts (Wedderburn *et al.*, 2010), flooding, waterlogging (Nie *et al.*, 2001), and competition from low-nutrient subtropical grasses (Crush & Rowarth, 2007; Zhang *et al.*, 2007). Pastoral farming systems in New Zealand are predominantly rain-fed and low-input. These systems are particularly vulnerable to climate fluctuations because feed supply is heavily reliant on climatic conditions (Dynes *et al.*, 2010; Cradock-Henry, 2011; Kalaugher *et al.*, 2013).

3.1.2 Economic Conditions

Unlike many developed countries, New Zealand's agricultural sector is not protected by high import tariffs or supported by large-scale production subsidies (Beijeman *et al.*, 2009; Daigneault *et al.*, in review). This makes New Zealand's agriculture a particularly appropriate case-study because the economic impacts of climate change (or any other stressor for that matter) are not distorted by large agricultural subsidies or pay-outs (Beijeman *et al.*, 2009; Daigneault *et al.*, 2014; Basset-Mens *et al.*, 2009). Given the lack of state protection, the agricultural sector must compete in global markets, making it particularly vulnerable to cost increases and price decreases. This vulnerability means that farmers in New Zealand must be highly adaptive. In the words of Beijeman *et al.* (2009, p.386), "Family farms… in New Zealand… have to be adaptive systems if they are to progress successfully to the next generation. Equilibrium is not an option and, if achieved, is short-lived." The long history of exposure to shifting economic conditions gives reason to expect that farmers in New Zealand may be, on average, more adaptable than farmers elsewhere.

3.1.3 Institutional Context

Agriculture in New Zealand is strongly influenced by various formal and informal institutions. The most important institutions with respect to agriculture are often those associated with local government (Noble *et al.*, 2014; Klein *et al.*, 2014; Reisinger *et al.*, 2014; Wratt *et al.*, 2008; Cradock-Henry, 2011; Smith *et al.*, 2008). For example, in New Zealand the responsibility for the management of water resources and the development and implementation of adaptation policy falls largely with local councils (Reisinger *et al.*, 2014; Wratt *et al.*, 2008; Daigneault *et al.*, in review).

In addition to local government, the private sector has substantial influence on the selection and delivery of adaptations in agriculture. The private sector is particularly important in New Zealand, where agricultural extension work supported by the government ceased in the late 1980s, leaving the private sector to promote inputs, services, and technologies to farmers based on their economic advantages (Smith *et al.*, 2008). While there is some evidence to suggest that allowing the private sector to promote products aimed at improving profitability has been effective, the promotion of technologies, practices, or approaches that contribute to or safeguard public goods such as environmental amenities remains problematic (Smith *et al.*, 2008). Climate change adaptations that rely on the provision or safeguarding of public goods are therefore unlikely to be assisted by the private sector.

3.2 Regions at Risk from Climate Change

The risks that climate change poses to agriculture are uneven across New Zealand. While some regions may benefit from climate change (Fitzharris, 2007; Daigneault *et al.*, 2012), others are both particularly dependent on agriculture and particularly vulnerable to climate change. Figures 3.2 and 3.3 show ensemble model projections for changes in temperature and precipitation across New Zealand between 1995 and 2090 under the IPCC's Representative Concentration Pathways (RCPs) 2.6 and 8.5, calculated by Tait *et al.* (2016). Fitzharris (2007) identified Northland, Bay of Plenty, and the eastern lowlands of both islands as 'hotspots' of climate vulnerability in New Zealand.

Among the vulnerable regions identified by Fitzharris (2007), Northland has the greatest mixture of New Zealand's four main land uses: drystock, dairy, forestry, and cropping of arable land (as shown by Figure 3.1). Northland has been shown to be vulnerable to floods and droughts, both of which are expected to increase in magnitude and frequency under climate change.

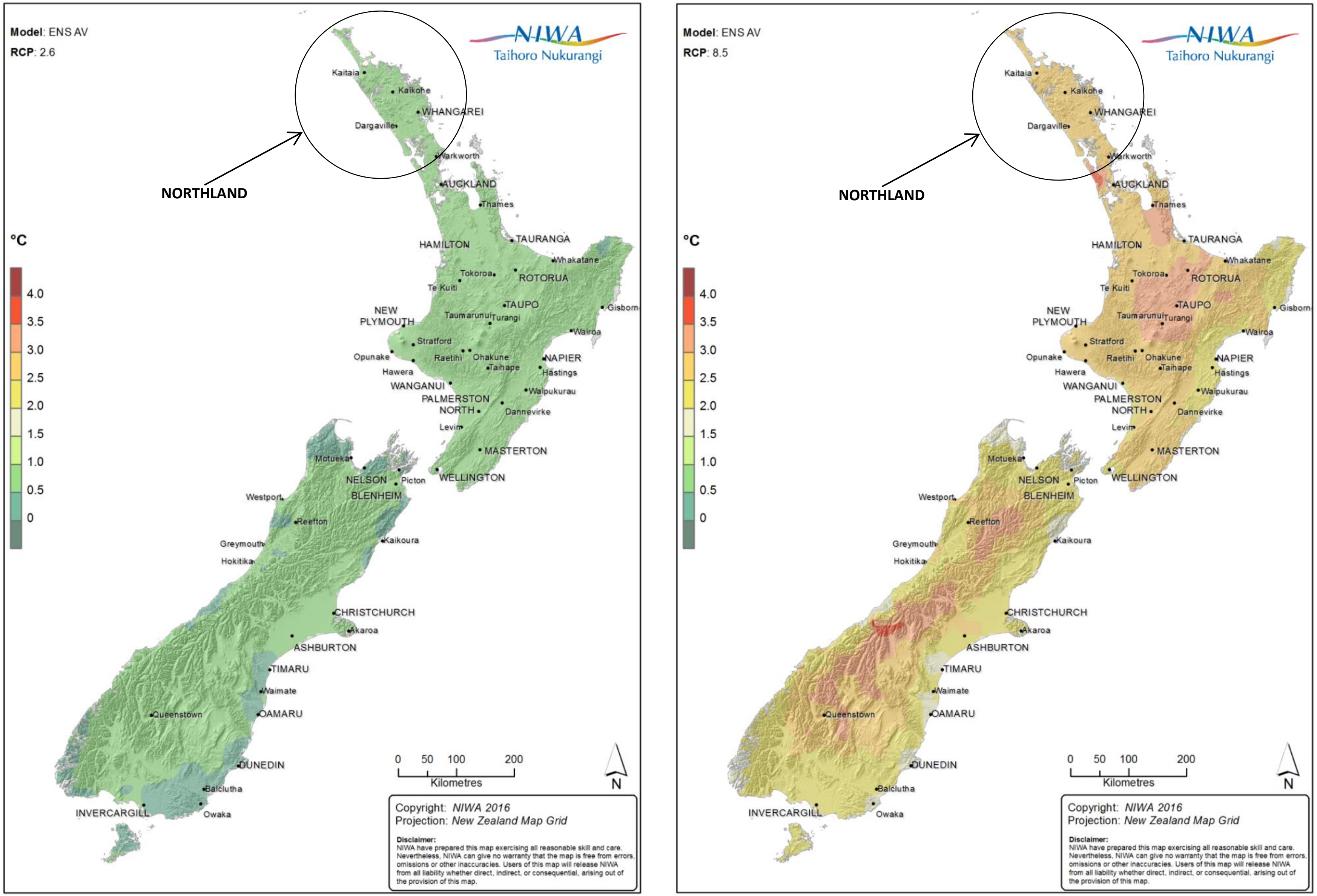

Figure 3.2: Ensemble mean projections for annual mean temperature change between 1995 and 2090 under RCPs 2.6 and 8.5. Source: Tait *et al.* (2016).

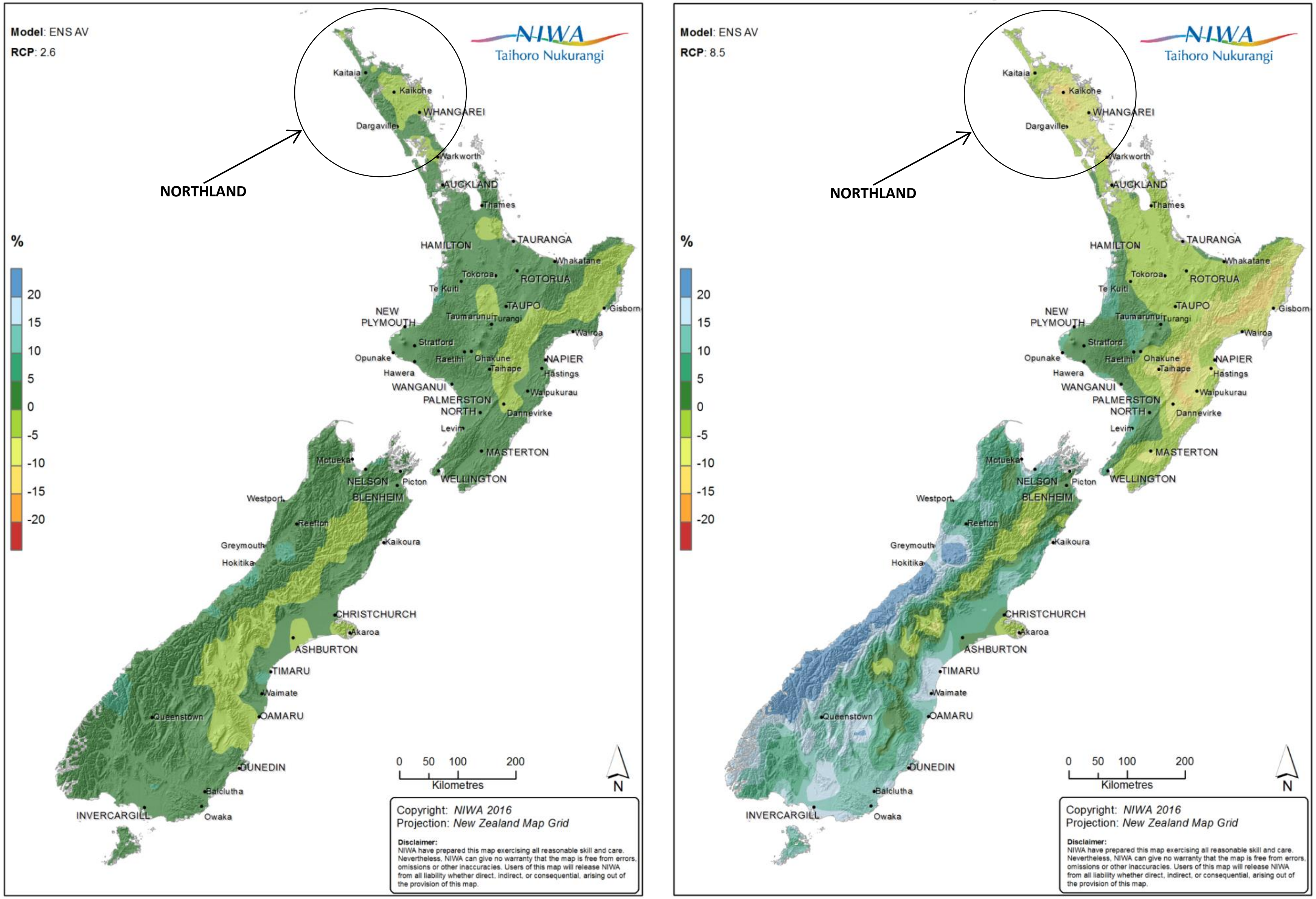

Figure 3.3: Ensemble mean projections for annual mean precipitation change between 1995 and 2090 under RCPs 2.6 and 8.5. Source: Tait *et al.* (2016).

3.3.1 Study Site Resolution

Questions about climate change and adaptation constraints span multiple and interconnected temporal and spatial scales (Klein *et al.*, 2014; Cradock-Henry, 2011; Adger *et al.*, 2005b). With respect to vulnerability, Adger *et al.* (2008) refer to this complex connectedness as 'nested and teleconnected vulnerability'. Because of the complexity of the relationships and interactions within social-ecological systems, characteristics can be highly variable across time and space, and these variations can be obscured by broad scale analysis (Cradock-Henry, 2011).

In the case of this study, an important determinant of the benefits of adaptation is the regional pattern of climate change. While changes in temperature are expected to be reasonably similar across broad scales, changes in precipitation are likely to be more variable (Sturman and Tapper, 2006; Porter *et al.*, 2014). Changes in water availability explain around 60% of annual variation in pasture production in New Zealand (Radcliffe and Barrs, 1987 in Zhang *et al.*, 2007), therefore it is important to focus on a scale at which these changes occur. Given the aims of this study it makes sense to focus on an agricultural area small enough that changes in precipitation across the area are likely to be reasonably homogenous. With this consideration in mind, this study focused on the Hikurangi catchment in central Northland, shown in Figure 3.4.

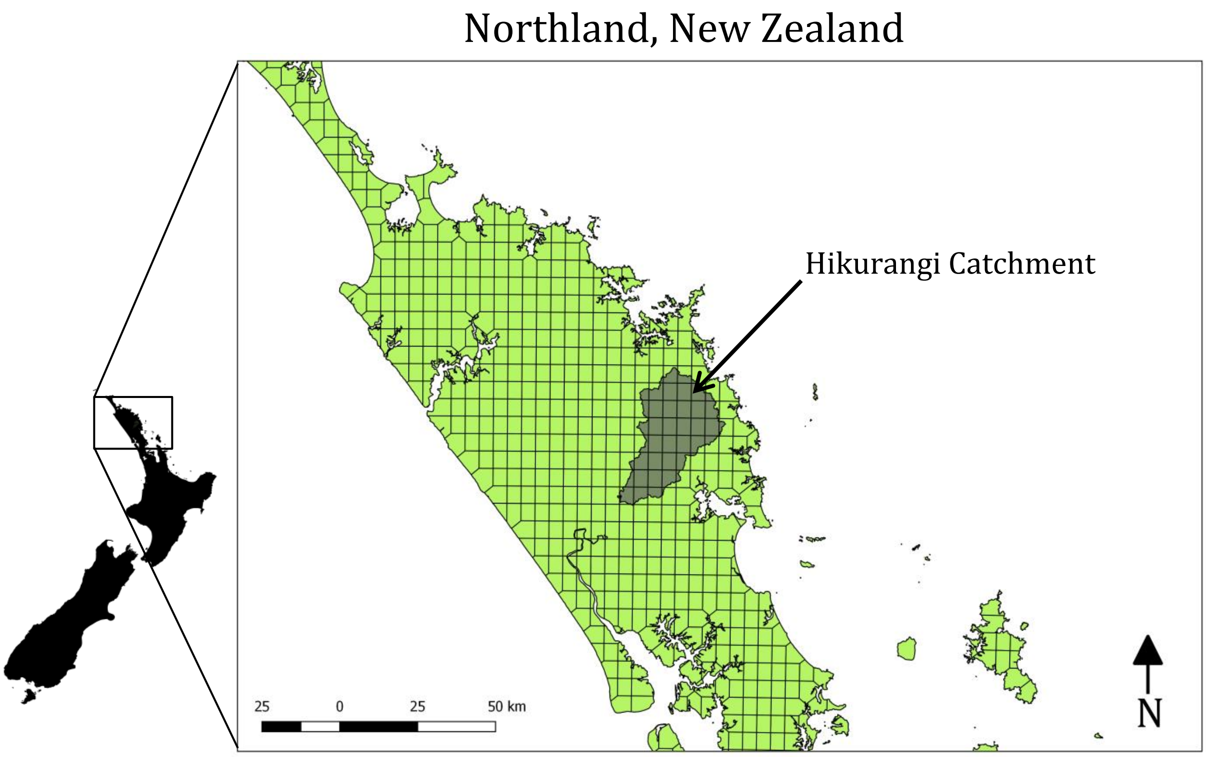

Figure 3.4: Location of the Hikurangi catchment in Northland, New Zealand. Land is shown with a 0.05 degree grid square which represents the level to which climate change projections were

downscaled to form the projections shown in Figures 3.2 and 3.3 (Tait *et al.*, 2016)

The Hikurangi catchment covers an area of approximately 84,000 hectares. Of that total area, 41% is currently used for drystock farming, 38% for dairy farming, 9% for plantation forestry, and 1% for horticulture. Figure 3.5 shows the spatial distribution of these main land uses within the catchment.

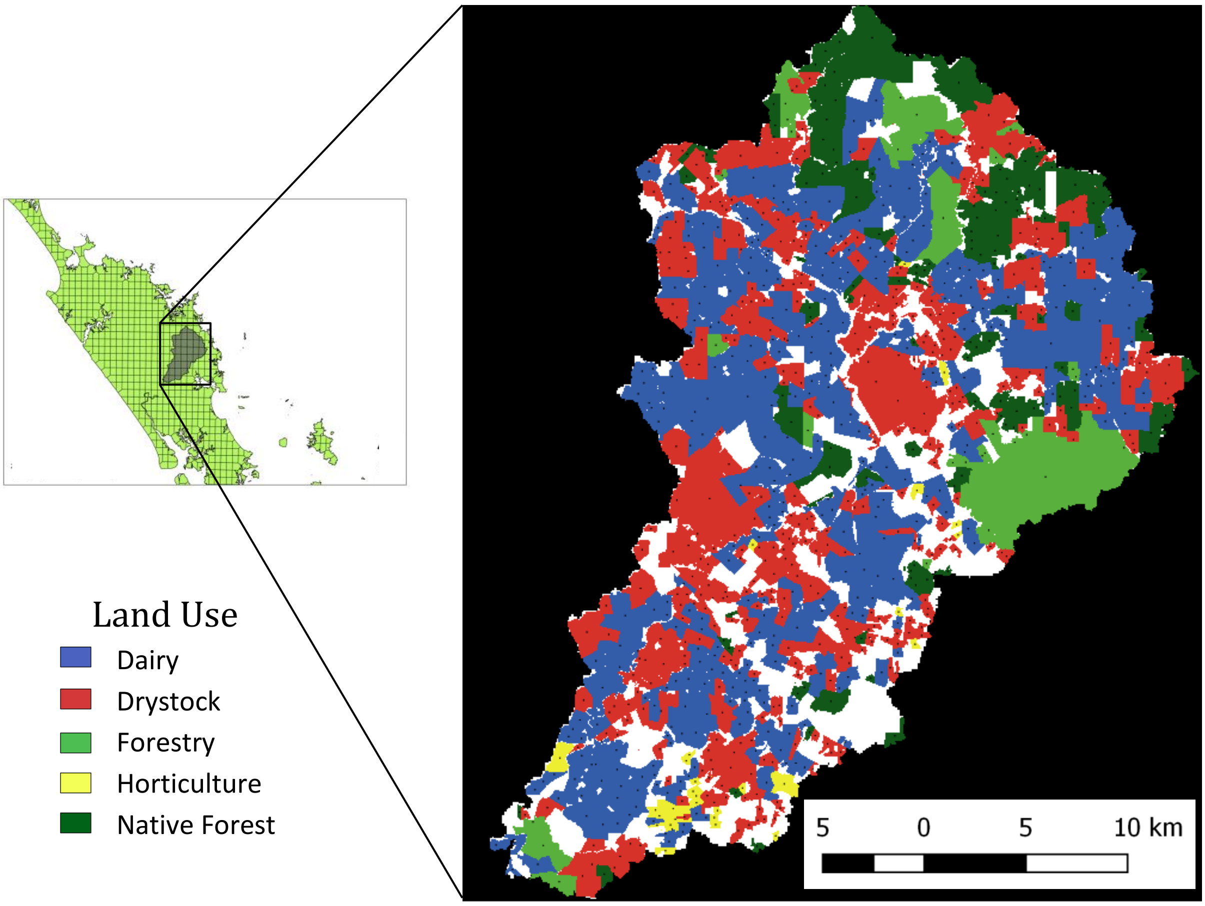

Figure 3.5: Land use in the Hikurangi catchment in 2010 taken from Land Information New Zealand (2015). Area that is not farmed commercially under one of the four main land uses indicated, or not covered by native forest is coloured white.

3.3 Summary

This chapter has put forward the following rationales for focusing this study on the Hikurangi catchment. New Zealand has the most agriculturally dependent economy of any developed country. As developed country, New Zealand has robust social, economic, and environmental information, however unlike most developed countries agriculture is relatively free from government support and trade protection. These characteristics allow for a clear assessment of the possible impacts of climate change on land use. They also give reason to expect that farmers in New Zealand may be more adaptive than farmers elsewhere (Fitzharris, 2007).

A number of regions in New Zealand are likely to be particularly vulnerable under climate change because of reductions in precipitation. Of these vulnerable regions, the mix of land uses in Northland most closely matches the rest of the country, allowing a greater potential to generalise research findings. Within Northland, the Hikurangi catchment covers an area which, because of its size, can be expected to experience near spatially homogenous changes in climate.

Chapter 4

Literature Review

This chapter reviews the literature relevant to the constraints on agricultural adaptation to climate change in New Zealand. It begins by outlining what is known about agricultural vulnerability to climate change in New Zealand. Sections 4.4 and 4.5 describe current observations of agricultural resilience and adaptation to climate change, respectively. Section 4.6 reviews a range of projections for agricultural responses to climate change. Section 4.7 reviews literature on the challenges of climate change adaptation, while Sections 4.8 to 4.10 explore literature on the constraints on adaptation in agriculture. Finally, Section 4.11 reviews the existing literature on the economic impacts of adaptation constraints in agriculture.

4.1 Climate Change in New Zealand

According to the fifth Assessment Report (AR5) of the IPCC (2013) "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia." Temperature in the New Zealand region is expected to increase more slowly than the global average because of the large thermal inertia of the Southern Ocean (MfE, 2001; Tait *et al.*, 2016). Substantial increases in precipitation are projected for the south and west of the South Island, and some western parts of the North Island, while decreasing precipitation is projected for eastern parts of the country in the rain shadow of the main mountain ranges (Reisinger *et al.*, 2014; Tait *et al.*, 2016)

The changes projected for temperature and precipitation in New Zealand are expected to greatly increase the prevalence of droughts (Wratt *et al.*, 2008; Mullan *et al.*, 2005; Clark *et al.*, 2011) and floods in many areas of the country (McMillan *et al.*, 2010; Reisinger *et al.*, 2014; Gawith *et al.*, 2012; Poyck *et al.*, 2011). These changes have serious implications for agriculture (IPCC, 2012; Porter *et al.*, 2014; Chhetri *et al.*, 2010; Nelson *et al.*, 2014b; Rosenzweig *et al.*, 2014; Seo *et al.*, 2009; Mandelsohn and Dinar, 2009; Reisinger *et al.*, 2014).

4.2 Climate Vulnerability in New Zealand Agriculture

Agriculture in New Zealand is vulnerable to climate change in a number of important ways. Spring and summer rainfall has been reported as explaining around 60% of annual variation in pasture production (Radcliffe and Barrs, 1987 in Zhang *et al.*, 2007). Recurring drought either already is, or is expected to become, a problem in many areas (Dynes *et al.*, 2010; Fitzharris, 2007).

Pastoral farming systems in New Zealand are predominantly rain-fed and low-input, making them heavily reliant on local climatic conditions (Dynes *et al.*, 2010; Cradock-Henry, 2011; Kalaugher *et al.*, 2013). Pastoral farmers in New Zealand are also vulnerable to flooding which can cause soil erosion and waterlogging (Cradock-Henry, 2011). Horticulturalists in New Zealand are found to be particularly sensitive to change in average climatic conditions, because fruit development depends on climatic conditions on a seasonal basis, and variables such as winter chilling hours and spring and summer sunshine hours influence fruit quantity and quality (Cradock-Henry, 2011).

4.3 Climate Change Impact Projections

Conditions contributing to a number of New Zealand's key agricultural vulnerabilities are expected to change under climate change. As temperatures rise, the annual number of growing degree days is estimated to increase by 500-800 over much of the North Island from a current total of around 3,000 (Wratt *et al.*, 2008). Changes in precipitation, temperature, and evapotranspiration are expected to increase water security problems, particularly in the northern and eastern areas of both islands (Fitzharris, 2007). Increases in CO_2 concentrations in the atmosphere could have a fertilising effect; however increases in fire risk, extreme winds, and the impacts of pests, weeds, and diseases are also expected (Dynes *et al.*, 2010; Reisinger *et al.*, 2014; Fitzharris, 2007).

4.4 Observed Resilience

The risks and opportunities posed by climate change described in the previous sections demonstrate the importance of farm resilience. Studies assessing resilience among farmers in New Zealand demonstrate that it is a complex condition and is both economically and environmentally determined. Farming in New Zealand has demonstrated its resilience to the absence of government support and trade protection since neo-liberalisation in the 1980s. However Basset-Mens *et al.* (2009) suggest that focusing on increasing dairy production and profit has left farmers in New Zealand more exposed to these fluctuations as the comparative advantage of highly efficient grass-based systems is eroded. They suggest that low-input grass based dairy systems are likely to be more resilient than those dependent on supplemental feed. These findings were echoed by Cradock-Henry and Mortimer (2013) who found that in eastern New Zealand, low-input grass based systems are more resilient than high-input intensive farming systems across a range of resilience indicators. The resilience of low-input knowledge intensive systems was also demonstrated by Kenny (2011), who found that farmers in eastern regions are already acting to enhance resilience to climate fluctuations, and that this has been an important objective for many farmers for a long time.

4.5 Observations of Adaptation

While worldwide research into climate change adaptation has expanded in recent years, there remains a lack of observations of adaptation actually occurring. In a meta-analysis of more than 1,700 studies into climate change adaptation, Berrang-Ford *et al.* (2011) found only 87 papers (roughly 5%) that described adaptation that was occurring at the time. The number of papers reporting adaptive activity was, however, increasing rapidly, from 12 in 2006 to a projected total approaching 50 in 2009. More recent work by Lesnikowski *et al*. (2016) identified an 87% increase in reported adaptation policies among high-income countries between 2010 and 2014. This progress was, however, highly variable between countries, and the prevalence of adaptation policies even reduced in some countries. Policy insufficiencies were identified in all but two of the analysed countries. The authors also cautioned that increases in adaptation policies did not imply that countries had taken or will take adequate steps to adapt to climate change. Indeed, much of the increase reported by Lesnikowski *et al*. (2016) reflects the development of policies to expand adaptation research and institutional preparation, rather than actions taken to implement adaptation projects directly. Importantly, they noted little progress on including the needs of vulnerable populations in adaptation policy design.

The empirical econometric work of Burke and Emerick (2016) found that in the 20 years from 1980 to 2000, adaptation among farmers in the United States avoided less than half, and possibly none, of the impacts of higher temperatures on crop yields relative to short-run responses. They further found that farmers did not appear to have adjusted their inputs or land uses over the period, despite temperature changes of as much as 1.5°C in some areas. They concluded by suggesting that the lack of observed adaptation might imply either a lack of adaptation options, or their prohibitive cost. These findings demonstrate that while some adaptation is occurring in some communities, there exists a global adaptation deficit which may be increasing under climate change, particularly for those most vulnerable.

4.6 Projections for Adaptation

4.6.1 Global Responses

A small number of studies have estimated the possible costs of adaptation to climate change. Chambwera *et al.* (2014) compiled a table summarising the estimates that have been formed to date

(Table 4.1). Parry *et al.* (2009) suggest that many of the estimates leading up to and including the UNFCCC estimate are likely to be substantial underestimates for the true costs of adaptation due to a range of methodological oversights. According to Chambwera *et al.* (2014), the World Bank estimate is the most comprehensive, suggesting that annual adaptation costs could be between US$70 billion and US$100 billion globally by 2050.

Table 4.1: Estimates of the global costs of adaptation reviewed by Chambwera *et al.* (2014).

Study	Results (billion US$ per year)	Time frame	Sectors	Methodology and comments
World Bank (2006)	9–41	Present	Unspecified	Cost of climate proofing foreign direct investments, gross domestic investments, and Official Development Assistance
Stern (2007)	4–37	Present	Unspecified	Update of World Bank (2006)
Oxfam (2007)	>50	Present	Unspecified	World Bank (2006) plus extrapolation of cost estimates from national adaptation plans and NGO projects
UNDP (2007)	86–109	2015	Unspecified	World Bank (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC (2007)	28–67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and financial flows required for the international community
World Bank (2010a)	70–100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement on UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea level rise and storm surges

Source: Modified from Agrawala and Fankhauser (2008) and Parry et al. (2009) to include estimates from World Bank (2010a).

4.6.2 Projections for Adaptation in New Zealand

A small number of studies have explicitly included adaptation in projections for the impacts of climate change on agriculture in New Zealand. Dynes *et al.* (2010) modelled the impacts of climate change on the outputs of a Manawatu dairy farm, both prohibiting and allowing for management adjustments. They found that management adjustments enabled a 1% increase in cow numbers between 2000 and 2080. They also found that the production of milk solids increased in both 2030 and 2080 as a result of increased lactation seasons and increased summer feeding levels, resulting in increased profitability.

The potential for land use change in response to climate was assessed by Daigneault *et al.* (2012) using the New Zealand Forest and Agriculture Regional Model (NZFARM). In the Manawatu catchment, model simulations suggested that more than 20% of land would change use under climate change relative to the current pattern. The specifics of these changes are shown in Figure 4.1. The largest increases were seen for arable land, which allowed for increases in grain production of more than 2,300%. Large areas of land were taken out of pastoral agriculture, while areas of scrubland were converted to arable cropping.

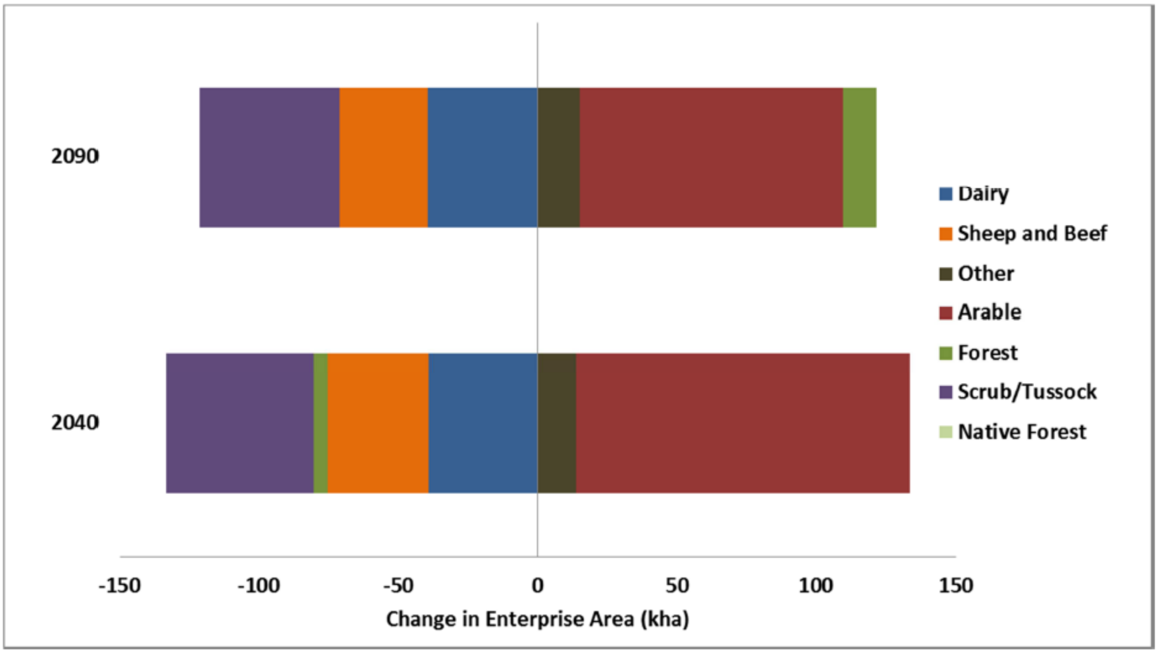

Figure 4.1: Modelled changes in land use area (in thousands of hectares) in the Manawatu catchment under climate change. Source: Daigneault *et al.* (2012).

In the Hurunui-Waiau catchment, land use change was modelled under two scenarios – one considering the impacts of climate change alone, and one simulating the implementation of a proposed irrigation development called the Waitohi Irrigation Scheme. Similar to findings for the Manawatu catchment, considerable changes in land use were simulated for the Hurunui-Waiau catchment under climate change. However the Waitohi Irrigation Scheme would reduce the amount of land use change by about 50%. The specifics of these changes are shown in Figure 4.2. Forestry expanded by the greatest area, followed by arable land, while pastoral agriculture contracted. The model also suggested that some land will become unproductive and may be retired to scrub and tussock. The Waitohi Irrigation Scheme was found to greatly reduce the impacts of climate change on productivity in the catchment, particularly for dairy production which could see a 68% loss in revenue without the scheme, reduced to a 9% loss in revenue with the scheme.

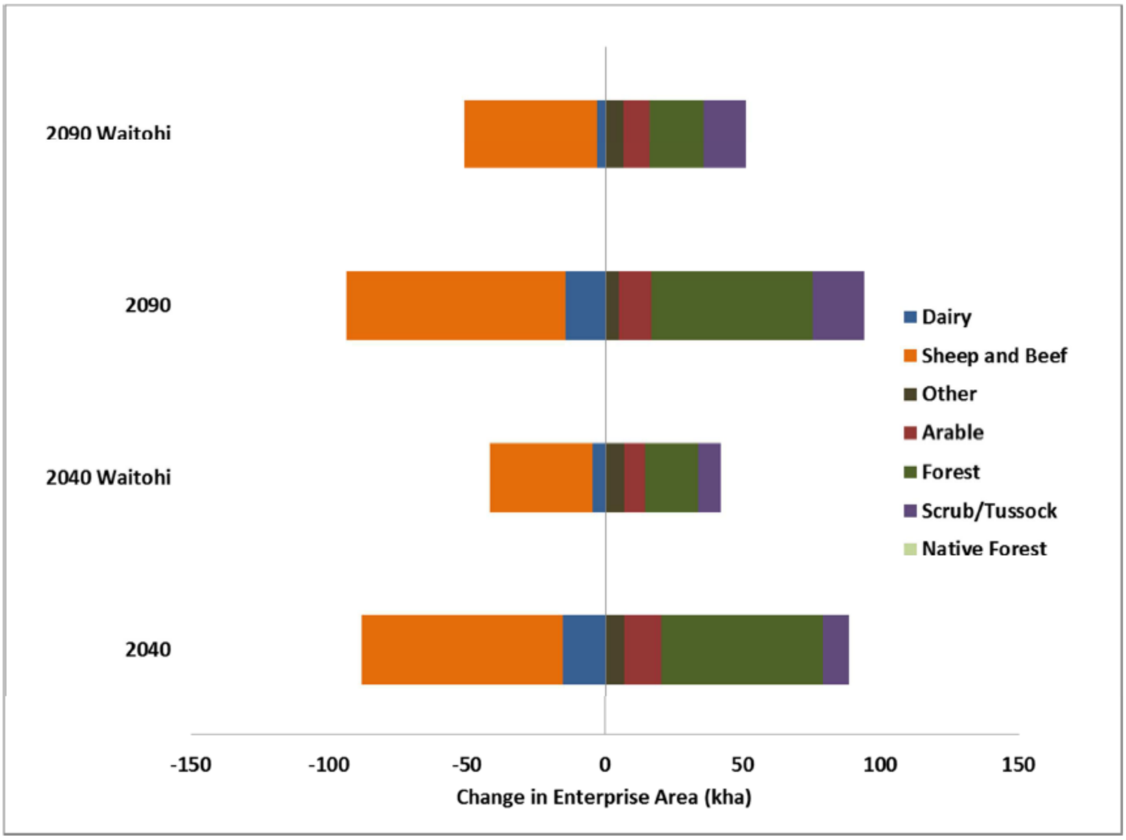

Figure 4.2: Modelled changes in land use area (in thousands of hectares) in the Hurunui-Waiau catchment under climate change, with and without the Waitohi Irrigation Scheme. Source: Daigneault *et al.* (2012).

4.7 Challenges of Climate Change Adaptation

Agricultural adaptation to climate change faces considerable challenges relating to both the farming context and the nature of the climate change problem. Adger and Barnett (2009) highlight four reasons for concern. The first is that, because of uncertainties and ignorance in our understanding of climate change and its impacts, the window of opportunity to implement adaptation may be narrower than we realise. Secondly, constraints on adaptation mean that our assumed ability to adapt may greatly exceed our actual ability to adapt, and these constraints may tighten under climate change. Thirdly, undesirable or detrimental adaptation consequences, termed maladaptation, presents a widespread risk and is already occurring in a number of places (Barnett and O'Neill, 2010). Finally, our current assumptions about what constitutes successful adaptation and what constitutes loss are generally inadequate, as described in Section 2.3.1 (Adger *et al.*, 2009b).

A number of climate change adaptation challenges are particularly relevant for agriculture (Masud *et al.*, 2017). Farmers often learn and adapt through experimentation and observation. This informal research is generally reactive rather than proactive and is therefore insensitive to future risks

(Hoffmann *et al.*, 2007). Moreover, unlike other new approaches or technologies which generally provide rapid benefits to farmers, climate change adaptations may be costly in the short to medium-term, and their longer-term benefits may be uncertain (Smith *et al.*, 2008). Large-scale adaptation of farming systems to climate change, therefore, entails substantial financial risk (Smith *et al.*, 2008).

The challenges described in this section contrast with what Adger and Barnett (2009, p.2804) point out is “a widespread belief that adaptation will be smooth, cheap, and easy to implement”. In reality, adaptation is likely to entail substantial costs, both monetary and relating to non-monetised values, and may require wholesale transformations, some of which will be painful and risky (Adger *et al.*, 2009a,c; Adger and Barnett, 2009; Smith *et al.*, 2008). Importantly, these challenges impose costs both when climate change poses risks and when it provides opportunities (Kelly *et al.*, 2005). Adaptation will also have to contend with the need to mitigate climate change, and may be slowed by the massive economic and institutional inertia of the carbon economy, which can be seen in an economic sense as a formidable market failure (Adger *et al.*, 2009a). These challenges are currently being unpacked in the growing literature on limits to adaptation and constraints on adaptation.

4.7.1 Limits to Adaptation

There is a growing acknowledgement that there are likely to be limits to climate change adaptation. According to the IPCC’s AR5, “Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor’s objectives or for the needs of a system are not possible or are not currently available” (IPCC, 2014, p.28). The broadly held understanding that intolerable risks will arise in certain places and among certain communities, and that the needs of some systems will not be met under climate change, imply that adaptation limits are likely to be reached in the future (Klein *et al.*, 2014). At these limits, “an intolerable risk must be accepted; the objective itself must be relinquished; or some adaptive transformation must take place to avoid intolerable risk” (Klein *et al.*, 2014, p.609).

The reference to ‘intolerable risks’ means that the degree to which there are limits on adaptation depends on the goals of those in the system (Field *et al.*, 2014). If the goal is to maintain the status quo then there may well be limits in a changing climate. If the goal is continued functioning in some form or other then there are unlikely to be limits to achieving this. As Adger *et al.* (2009b) point out, the objectives of societies and those who make up societies are generally diverse, meaning that limits to adaptation are similarly diverse. Historically, values relating to culture and place have been undervalued, and we are only beginning to understand the possible limits to adaptation they engender (Adger *et al.*, 2009b). What are seen as limits to adaptation today, may not be viewed as such in the future (Adger *et al.*, 2009b). Equally, however, as society develops, some risks or inequities that are viewed as 'tolerable' today may not be so in the future. Human slavery is an obvious example of this sort of social transition in the past. It is possible, or perhaps likely, that the myriad of social justice issues associated with climate change adaptation will also become less 'tolerable' over time, imposing new limits to adaptation in the future. Conversely, some changes may be seen as more tolerable as their necessity becomes clearer.

Discussions in the literature demonstrate that there are both 'soft' and 'hard' limits to adaptation (Adger *et al.*, 2009b; Field *et al.*, 2014; Felgenhauer, 2015). 'Hard' limits are those for which there are no ways to avoid intolerable risks, while for 'soft' limits, opportunities to avoid intolerable risk may emerge with new technologies or changes in social values (Field *et al.*, 2014). Klein *et al.* (2014) propose water supply from fossil aquifers, species extinction, and flooding of low lying islands as examples of hard limits to adaptation. Adger *et al.* (2009b) highlight soft limits to adaptation including risk perception and behavioural characteristics that exist at the individual level and combine to limit adaptation at more aggregated levels. While these limits are both "subjective and mutable", they may still "preclude adaptation at societal scales" (Adger *et al.*, 2009b, p.339).

4.8 Constraints on Adaptation

Adaptation constraints[3] are distinct from adaptation limits in that the former can, in theory, be avoided or overcome, while the latter are either unavoidable, or require new technologies to emerge or the goals and values of society to change (Aalbersberg, 2011; Ekstrom *et al.*, 2011; Klein *et al.*, 2014; Simões *et al*., 2017). Despite this distinction, Ekstrom *et al.* (2011) point out that the line between constraints and limits is blurry in practice, while others stress that major constraints, and combinations of multiple constraints are likely to create adaptation limits (Klein *et al.*, 2014; Eisenack *et al.*, 2014; Adger *et al.*, 2009b).

Adaptation constraints stem from the actors involved, their governance systems, and their environments and relate to behavioural, social, economic, and environmental characteristics (Biesbroek *et al.*, 2013; Howden *et al.*, 2007; Herrmann and Guenther, 2017; Masud *et al*., 2017; Simões *et al*., 2017). Constraints apply to both incremental and transformational adaptation, and

[3] The term 'adaptation constraint' has been used interchangeably with the terms 'adaptation barrier' and 'adaptation obstacle' in the literature (Klein *et al.*, 2014; Biesbroek *et al.*, 2013). While in their AR4, the IPCC switched between using the term 'constraints' and 'barriers', the AR5 consistently used the term 'constraints' (Klein *et al.*, 2014). For consistency with the IPCC usage, this study uses the term 'constraints' throughout, even when describing the findings of others who used the terms 'barriers' or 'obstacles' (see for example Biesbroek *et al.*, 2013; Eisenack *et al.*, 2014; Ekstrom *et al.*, 2011; Gifford *et al.*, 2011; Greiner and Gregg, 2011; Moser and Ekstrom, 2010; Ekstrom *et al.*, 2011; Wolf *et al.*, 2009; Hermann and Guenther, 2017; Simões *et al*., 2017).

may be particularly challenging to the latter because of the greater adjustments, investments, and risks involved (Klein *et al.*, 2014; Ekstrom *et al.*, 2011). Biesbroek *et al.* (2013, p.1119) reviewed 81 academic papers about the constraints on adaptation to climate change and found that a vast and increasing number of distinct constraints have been identified, noting that "the list of possible [constraints] is seemingly endless."

Eisenack *et al.* (2014) stress that constraints should not be understood or assessed in isolation because the combination of, and interactions between different constraints can either amplify or dampen their impacts. An obvious example of the interaction of adaptation constraints is the impact that acute poverty has on access to beneficial technologies and information and *vice versa* (Klein *et al.*, 2014; Eisenack *et al.*, 2014).

Despite the fact they have been discussed quite consistently (Biesbroek *et al.*, 2013), adaptation constraints have been poorly defined in the literature. Of the 81 studies assessed by Biesbroek *et al.* (2013), only seven gave clear definitions of adaptation constraints, while the remaining papers were either abstract in their definition, or treated it as implicit. As explained in Section 1.1, broad definitions describe adaptation constraints as factors, processes, or challenges that make adaptation more difficult, but that can be overcome (Klein *et al.*, 2014; Eisenack *et al.*, 2014; Moser and Ekstrom, 2010). More specific definitions emphasise that constraints are specific to the adaptation options they affect (Eisenack *et al.*, 2014), and are determined relative to the interpretation and values of the actor(s) they impede (Biesbroek *et al.*, 2013). Taking these considerations into account, Eisenack *et al.* (2014, p. 868) propose the following expanded definition which is adopted by the current study:

> "[An adaptation constraint] is (1) an impediment (2) to specified adaptations (3) for specified actors in their given context that (4) arise from a condition or set of conditions. A [constraint] can be (5) valued differently by different actors, and (6) can, in principle, be reduced or overcome."

Within this definition, the conditions from which constraints arise are the characteristics of the adaptations, the actors themselves, and the context in which they are applied.

It should be acknowledged that Biesbroek *et al.* (2015) have questioned the value of the concept of adaptation constraints. They suggest that the linear and functionalist treatment of constraints, coupled with the black-box treatment of decision making, have provided little insight useful for policy. Their comment, however, assumes that the sole purpose of research in this field is to provide information for policymakers that explores the workings and challenges of the implementation of adaptation. In the current study, the ambition is to explore the extent to which a number of important constraints inhibit adaptation. While it is hoped that this information will be policy relevant, if only to underscore the need to further support adaptation efforts, this study does not focus on putting forward specific policy prescriptions for how these constraints can be overcome. Therefore, while acknowledging its weakness for in-depth and applied research, the concept of constraints is used as an ordering heuristic in this study.

4.8.1 Categories of Constraints

The current study adopts a broad classification proposed by Arnell and Charlton (2011) that separates constraints into two classes: 'generic constraints' and 'specific constraints'. A third category is added to these called 'transaction costs'. Generic constraints arise from the agents or institutions of interest. They apply to the adaptation challenge itself and are likely to influence a wide range of specific adaptation options. Specific constraints apply to individual adaptation options, and determine the feasibility of each option for the agent of concern. These constraints may effectively preclude one adaptation option while having little influence on another. Transaction costs are presented as a third category of adaptation constraints identified in the literature as being relevant to climate change adaptation in agriculture. Transaction costs are defined by Kolstad (2000, p.92) as "the costs of entering into a transaction, over and above the exchange of money for a good." These costs comprise the use of mental, social, financial, and physical resources in the process of identifying and implementing the adaptation in question (Rickards and Howden, 2012; Marshall, 2013).

This broad categorisation is designed specifically to suit the framework of the current study. There is no consensus about how adaptation constraints should be classified or assessed, and many constraints that operate in the real world do not fit neatly within a single category, but may apply to many (Biesbroek *et al.*, 2013). The classification of generic constraints, specific constraints, and transaction costs is therefore used only as a structuring heuristic, while the likelihood of crossover between categories and constraints is acknowledged.

4.9 Constraints Modelled in This Study

In light of the number of possible influences, Whitney *et al*. (2017, p.2) emphasised the need to understand the dynamics of adaptation "of what to what". A review of the literature was therefore undertaken to scope the range of adaptation constraints that were likely to apply to agriculture in New Zealand in the context of climate change. The following sections describe the current understanding of 13 adaptation constraints that were included in the modelling performed in this study. The inability of Ricardian assessments to account for each constraint is highlighted by a description of how they would apply to an economically rational being, referred to as 'Homo

Economicus'. Evidence of how these constraints apply to actual populations is then presented in order to highlight the differences that form the focus of this study.

While a number of other constraints were described in the literature and considered in this study, they found little empirical support in the case study catchment. These constraints are not described in detail in this section, but they are mentioned briefly in Section 4.12 so that their consideration and removal is clear.

4.9.1 Generic Constraints

4.9.1.1 Farmer Motivation and Aspiration

Models of adaptation based on Homo Economicus assume that profit maximisation is farmers' only motivation and that they pursue profit to the greatest extent possible. In reality, farmers have a wide range of motivations, and they pursue these to varying degrees. Where motivations depart from profit maximisation, adaptation can be constrained. For example, a farmer who is motivated by the lifestyle of running a drystock farm may be reluctant to change to forestry even if conditions change to make forestry the most profitable land use. In reality, the difference in profit potential between the two land uses may have to be large before the farmer will be prepared to forfeit his or her lifestyle to secure higher profits.

There is considerable variation in the extent to which financial incentives influence human decision making. For example, while Daigneault *et al.* (2012) found that financial viability and increasing income were important motivators of 95% and 85% of farmers in New Zealand, respectively, Gowdy (2008) and Gsottbauer and van den Bergh (2011) report a variety of experiments in psychology and behavioural economics that suggest other-regarding motivations are more important influences in decision making than profit maximisation. In some cases, money can even act as a deterrent. For example, blood donations have been found to decline when monetary incentives are offered (Titmuss, 1971).

It is clear that motivations vary by context and by group. For example Bartolini *et al.* (2007) found that profit was commonly the most important motivation in decisions about irrigation management in Italy. However the strength of this motivation was seen to vary between different farm types. Burges and Smith (2008) found similar variation in New Zealand, where profitability was seen as the most important motivator among wheat farmers in Canterbury, while farmers of Maori descent in the East Cape region were more motivated by social and community outcomes.

For many farmers, the most important goal is maintaining a lifestyle they enjoy, and making money from farming is simply a means to that end (Kalaugher *et al.*, 2013). Greiner and Gregg (2011) found that graziers in northern Australia were more motivated by lifestyle goals than by maximising their profits. Similarly, Bartolini *et al.* (2007) found that the minimisation of time spent working was an important motivator among farmers in Italy. Many studies also demonstrate that people are not purely self-motivated, and most decisions are socially influenced (Gowdy, 2008; Janssen and Ahn, 2006; Heckbert *et al.*, 2010).

Environmental concern can be both self and socially motivated, and a number of studies have identified environmental stewardship as an important objective held by farmers (Greiner and Gregg, 2011). On a par with financial objectives, Daigneault *et al.* (2012) found that 85% of farmers in New Zealand reported improving water quality as an important objective. Greiner and Gregg (2011) also found that environmental stewardship was a more important objective than financial success among the above group of graziers in northern Australia.

Motivations are also mediated by levels of aspiration. People generally do not work to fulfil their objectives to the greatest possible extent, rather they work to achieve a satisfactory outcome (a phenomenon called 'satisficing') (Reed *et al.*, 2013; Larcom *et al.*, 2015). For example, when profit is the most important motivator, an agent may pursue this objective vigorously up to a point where they are satisfied with the profit they have made, and further profit ceases to elicit the same motivation. Importantly for this investigation, Homo Economicus is assumed to have infinite aspiration such that no amount of profit would diminish the motivation for more.

4.9.1.2 Behavioural Constraints

Models of adaptation based on Homo Economicus also assume that agents are economically rational and consistent in their decision making. Homo Economicus judges each decision based on its costs and benefits, and its decision is unaffected by how choices are framed (Gowdy, 2008; Pike, 2008 Gsottbauer and van den Bergh, 2011). Empirical evidence shows that, while many people do behave in economically rational ways in some situations (Janssen and Ahn, 2006), human behaviour is characterised by numerous behavioural anomalies (Tversky and Kahneman, 1986; Pike, 2008; Gowdy, 2008; Gintis, 2000).

Behavioural anomalies are seen to affect a wide range of common decisions. Experimental and empirical studies have consistently shown that people evaluate choices in terms of a reference point, tend to be risk averse, and tend to lament losses more than they value gains (Tversky and Kahneman, 1986; Heckbert *et al.*, 2010; Chambwera, *et al.*, 2014; Gintis, 2000; Gsottbauer and van den Bergh, 2011). People assess decisions within the context of other decisions, and tend to be influenced by previous expenditure known as sunk costs (Gifford *et al.*, 2011). People also assess choices in social terms, are other-regarding in their decisions, form reciprocal relationships, and are highly averse to inequality and free-riding behaviour among others (Gintis, 2000; Heckbert *et al.*, 2010; Gsottbauer and van den Bergh, 2011).

With particular relevance to adaptation, people are often found to act habitually and to systematically favour the *status quo* (Gifford *et al.*, 2011; Chambwera *et al.*, 2014; Larcom *et al.*, 2015). For example, in a laboratory experiment relating to the choice between agricultural land use and reforestation under changing land rents, Manson and Evans (2007) found that the majority of experiment participants persisted with their original land-use for numerous rounds after alternative land-uses became more profitable. This stability can be related to a number of behavioural traits. For example, people tend to under-experiment when the outcomes of repetition are satisfactory (Larcom *et al.*, 2015). People also tend to have an optimism bias and generally underestimate environmental risks (Gifford *et al.*, 2011; Grothmann and Patt, 2005). People generally defer making decisions with uncertain outcomes (Spence *et al.*, 2012; Chambwera *et al.*, 2014). People are often firmly resistant to feelings of guilt, and strong emotional responses to information, such as powerlessness and fear are found to inhibit further proactive thinking (Dilling and Moser, 2007). Furthermore, people tend to value future costs and benefits inconsistently depending on the framing of the choice, and hold considerably less concern for long term outcomes (Gintis, 2000; Chambwera *et al.*, 2014).

Grothmann and Patt (2005) demonstrated the benefits of considering behavioural anomalies using a process model of adaptation to flood risk in Cologne, Germany, that included elements of risk perception and perceived adaptive capacity. They showed that this socio-cognitive model was more able to simulate adaptive action than a traditional socio-economic model. They supplemented these findings with qualitative evidence that highlighted the importance of risk perception and perceived adaptive capacity in determining crop selection among subsistence farmers in Zimbabwe in light of seasonal forecasts. With reference to the pervasiveness and influence of behavioural anomalies, Gowdy (2008) suggests that they should be the starting point for designing economic policy.

4.9.1.3 Cultural Constraints

Models of adaptation based on Homo Economicus are also blind to the effects of culture on adaptive propensity. As an acultural being, Homo Economicus would be indifferent about where it lives, who it is surrounded by, what it does, and who its actions affect. These traits depart considerably from the culturally mediated behaviour of people in practice.

In relation to climate change adaptation, Adger *et al.* (2013, p.112) define culture as “the symbols that express meaning, including beliefs, rituals, art and stories that create collective outlooks and behaviours, and from which strategies to respond to problems are devised and implemented.”

Culture is seen to determine environmental values and norms, and shape the decisions and actions of individuals and societies in response to climate change (Adger *et al.*, 2009b; Jones *et al.* 2014; Klein *et al.*, 2014; Moser and Ekstrom, 2010). Cultural pressure is both individually and socially derived, of which the latter is particularly important in this study because adaptation strategies are often highly visible to others in society (Gifford *et al.*, 2011). Adger *et al.* (2013) suggest that, with respect to evaluating adaptation options, cultural values may be more important than economic values in some contexts.

The influence of culture has been demonstrated by examples of societies responding differently to similar challenges (Adger *et al.*, 2013). De Monocal (2001) found that some pre-modern societies collapsed when faced with multi-decade to multi-century droughts, while others were able to reorganise and adapt. In northern Burkina Faso, Nielsen and Reenberg (2010) showed that culture within the Fulbe ethnicity constrained the adoption of a number of important adaptation measures, while these options remained available to other ethnicities. Heyd and Brooks (2009) demonstrated that agricultural practices following a western 'productive' culture similarly failed to adapt in response to drought in the Sahel because of their narrow production objectives and the erosion of cultural ties.

Cultural values relating to place and occupation may result in particularly strong constraints on climate change adaptation. Personal and collective cultures are often closely linked to the places and environments in which they exist (Adger *et al.*, 2013; Barnett and O'Neill, 2012; Mortreux and Barnett, 2009). While labour migration or relocation may be effective adaptations to local risks in financial terms, place attachment and cultural loss often make these options maladaptive (Barnett and O'Neill, 2012; Adger and Barnett, 2009; Mortreux and Barnett, 2009; Adger *et al.*, 2013). Place attachment is likely to lead to adaptation that is sub-optimal in monetary terms, as people resist relocation, endure worsening local conditions, and decline opportunities for economic advancement elsewhere.

Occupations also become entwined with people's identities and cultures, and alternative ways of earning a living may clash with people's principles (Coulthard, 2009; Acosta-Michlik and Espaldon, 2008). For example, Rickards and Howden (2010) point out that some Australian farmers are strongly attached to their farming profession and are prepared to go to great lengths in order to continue practicing it. Coulthard (2009) points out a similar resistance to livelihood transformation among fishing societies. Brown *et al.* (2013) found tradition to be an important motivator among some farmers in New Zealand, while Daigneault *et al.* (2012) found that many are primarily interested in farming animals, and respond negatively to the prospect of converting land to forestry.

Adger *et al.* (2013) point out that while cultures impose a number of constraints on adaptation, culture is itself dynamic and can adapt to changing external conditions. Often, however, cultural change is slow and difficult to accept for many (Adger *et al.*, 2013; de Bruin and Dellink, 2011). Culture is therefore likely to impose substantial and persistent constraints on climate change adaptation.

4.9.1.4 Perception of Climate Risk

Risk perception is a major determinant of adaptive behaviour, and where perception deviates from reality, it can constitute a formidable constraint on adaptation (Niles *et al.*, 2013; de Bruin and Dellink, 2011; Grothmann and Patt, 2005; Gsottbauer and van den Bergh, 2011; Masud *et al*., 2017; Simões *et al*., 2017). According to Protection Motivation Theory (Rogers, 1975), the higher risk a person perceives, the more motivated they are to adapt to that risk. In the climate change context, Grothmann and Patt (2005, p.202) define risk perception relative to other concerns as "the perceived probability of being exposed to climate change impacts and the appraisal of how harmful these impacts would be to things an actor values…", and describe it as the "main determinant of motivation to adapt". In models of adaptation based on rational choice, Homo Economicus is risk neutral, and is able to perceive the objective risk from all hazards to all the things it values. Actual human risk perception departs from this simplification.

There are a number of reasons why people over or underestimate risks. People do not generally use all the information available on risks when making decisions (Chambwera *et al.*, 2014). Furthermore, people often reject information on risk when it contradicts their preconceptions or ideologies (Adger *et al.*, 2009b.c; Moser and Ekstrom, 2010). This form of psychological filtering may be particularly prevalent with respect to climate change information, given the emotive and political discourses that frame the scientific information.

With respect to climate change, Spence *et al.* (2012) suggest that psychological distance constrains risk perception across geographical and temporal dimensions. The geographical dimension dictates that impacts that are spatially distant induce lower levels of concern. In developed countries in particular, the impacts of climate change are often seen as distant (Adger *et al.*, 2009a, Wolf *et al.*, 2009; Moser and Ekstrom, 2010). Separation from impacts through time also reduces concern. People are most responsive to immediate problems, and many see climate change as a problem likely to affect people in the future rather than one that can cause loss and damage now (Adger *et al.*, 2009a). On average, Grothmann and Patt (2005) suggest that these biases are likely to reduce perceived climate change risk, lowering people's propensity to adapt as a consequence.

People have also been found to display an optimism bias, in which they perceive risk to themselves as being lower than the average risk across the population (Grothmann and Patt, 2005; Weinstein, 1980). For example, in a study of the perceived risk from heat waves among the elderly in the UK, Wolf *et al.* (2009) found that elderly individuals who identified the elderly as particularly vulnerable to heat stress, did not see themselves as vulnerable personally. This failure to perceive threat on a personal level is likely to constrain adaptive effort (Wolf *et al.*, 2009).

Many studies have investigated various aspects of climate change concern in a wide range of contexts. Some studies report broad acknowledgement that climate change is a problem in a general sense. For example, the Farming Futures survey of British farmers in 2009 found that 50% of farmers thought that they were already being affected by climate change, while 63% though that they would experience the impacts of climate change within the next decade (Ford and Berrang-Ford, 2011). A similar survey carried out in 2008 by the UK's Department for Environment, Food and Rural Affairs (DEFRA) found similar levels of concern (Ford and Berrang-Ford, 2011).

The perception that climate change poses risks is, however, not universal. For example Simões *et al*. (2017) found a lack of perceived risk to be one of the most important constraints on adaptation to climate change among organisations and businesses in Brazil. Niles *et al.* (2013, p.1755) pointed out that "there is a perception among many agricultural producers in the United States that agriculture has not and will not be affected by climate change." Many people in developed countries do not expect climate change to impact them personally (Ford and Berrang-Ford, 2011). O'Brien *et al.* (2006) found that high national levels of adaptive capacity can lead to ignorance of adaptation constraints leading to the underestimation of climate change risk, particularly among those most vulnerable. This complacency has been seen to limit adaptive action in many developed countries (O'Brien *et al.*, 2006; Ford and Berrang-Ford, 2011).

Estimates of concern about climate change in New Zealand vary. Estimates of the proportion of the population who think climate change is occurring range from 33% (NZIER, 2008) to 80% (Stuart, 2009). A national survey of 2,851 people (NZBCSD, 2009) found that three quarters of respondents think climate change is a problem, while a smaller survey of 752 people (Hughey *et al.*, 2008) found that about a third of respondents see climate change as the single biggest problem facing the world. These numbers suggest that, while most New Zealanders perceive some degree of risk from climate change, substantial segments of the population either do not believe climate change is occurring, or do not believe it poses a threat (Reisinger *et al.*, 2011, 2014).

Despite concern among some farmers in some regions, Smith *et al.* (2008) found that as little as 17% of farmers in New Zealand think that climate is becoming more variable or extreme. Reisinger *et al.*

(2011) point out that some farmers, collectives, and rural councils remain sceptical about climate change science. This is supported by anecdotal evidence from a Waikato farmer studied by Kalahuger *et al.* (2013), who was not convinced climate change was anthropogenic in nature, and did not expect it to have an appreciable influence on his farm over his working life. Further anecdotal evidence suggests that many farmers believe that climate change will result in little departure from current farming conditions (Dynes *et al.*, 2010). This lack of perceived risk may limit the abilities of governing bodies to implement adaptation policies, as perceptions of climate change risk are known to affect farmers' responses to policy (Niles *et al.*, 2013; Reisinger *et al.*, 2011).

4.9.1.5 Disaster Experience

Past experiences of climate related stress, particularly extreme weather events, are known to influence adaptive behaviour. In a review of studies documenting adaptation to climate change, Berrang-Ford *et al.* (2011) suggest that past experiences of floods and droughts were the dominant stimulants for adaptive response. Using survey data on risk perceptions in Fiji, Brown *et al*. (2018) found that exposure to Cyclone Evan substantially increased individuals' risk perceptions and expectations about the likelihood of climate related disasters in the future. Extreme climatic events may trigger transformational adaptation (Darnhofer, 2014), and are seen as more important motivators than long-term or gradual changes in climate (Berrang-Ford *et al.*, 2011). Tompkins (2005) described exposure to impacts as one of the two most important factors contributing to social resilience, and equated it in a medical sense to the use of inoculation, where the exposure to mild impacts makes the body better able to respond to infection in the future. Grothmann and Patt (2005, p.205) stress that "Nearly all studies on effects of personal experiences on self-protective behaviour regarding natural hazards show preparedness increasing with the severity of past damage." The link between extreme events and adaptation is not automatic, and in some cases, people's views and behaviour may be unaffected by the experience of climate-related stress (see for example Whitmarsh (2008) and Brown *et al*. (2018)). However, the weight of evidence suggests that in many circumstances, extreme events are a powerful motivator of adaptation (Burton and Peoples, 2008; Niles *et al.*, 2013; Reisinger *et al.*, 2014; Haden *et al.*, 2012; Ford and Berrang-Ford, 2011).

Climate related stress has been seen to increase adaptation intent (Reisinger *et al.*, 2014). For example, from a survey in rural California, Haden *et al.* (2012) found that farmers who perceived decreases in water availability over time were more likely to believe in global climate change and had significantly greater intentions to implement adaptation strategies. The influence of climate related stress on adaptive behaviour may also extend to farmers who are not directly affected if they are socially or geographically close to those who are (Niles et el., 2013; Spence *et al.*, 2012). At an institutional level, environmental crises may lead to the development of collective management

(Tompkins, 2005). For example, Nelson *et al.* (2007) reported a case in the Okanagan Basin, British Columbia, where the occurrence of a severe drought helped to coalesce water management bodies in the region and led to improved water management strategies.

In New Zealand, the influence of extreme weather events on farm management has been recognised. For example, many of the farmers in the Hurunui-Waiau catchment interviewed by Daigneault *et al.* (2012) reported lowering their stocking rates in response to recent droughts and floods, and maintaining these low rates because they proved to be beneficial. Drought in the Waikato in 2008 was also seen to lead to management changes including the reduction of stock numbers, earlier calving, holding of additional supplementary feed, and the consideration of irrigation (Smith *et al.*, 2008).

4.9.1.6 Social Information

Social networks strongly influence the dispersal of information and innovation that contribute to adaptation. In many situations, social connections can encourage adaptation and increase resilience, however they can also do the opposite (Adger, 2003; Wolf *et al.*, 2009). Social networks are not considered in models of adaptation that assume rational choice. Homo Economicus is assumed to have perfect access to information regardless of where it is generated, or by whom. In the context of agricultural adaptation to climate change, this assumption is inappropriate for a number of reasons.

Social learning is an important component of adaptation. In a farming context, the benefits of new technologies, management approaches, and land uses are often uncertain (Parker *et al.*, 2003). Some farmers, through their risk tolerance, inquisitiveness, or financial position, are more likely to trial new approaches than others (Parker *et al.*, 2003). When trials occur, they allow other farmers to gather information about the strategy or technology without having to risk an unsuccessful trial themselves (Pandel *et al.*, 2006). This information can be exchanged through direct social interaction or from passive observation, which lead to its diffusion across the landscape and across society (Parker *et al.*, 2003; Brown *et al.*, 2013). Brown *et al.* (2016) report evidence from a number of studies suggesting that successful demonstration of innovations by well-respected farmers is the most important way to facilitate the diffusion of new ideas among farmers in New Zealand.

Social learning depends on the characteristics of people's social networks. For example, in their assessment of adaptation to climate shocks in Malawi, Nordhagen and Pascual (2013) found that having close family members working outside the household and holding a diverse livelihood portfolio significantly increased adaptation through the use of local seed markets. They noted that kinship ties have also been seen to play a facilitative role in informal seed distribution. Thompson (2004) suggests that social networks can build on themselves through social learning, as positive experiences can encourage further exchanges in the future. Despite this, certain conditions can also hinder social learning. For example, social networks may inhibit the diffusion of innovations that are seen as inappropriate or culturally unacceptable, even if they could provide financial benefits (Reed *et al.*, 2013).

4.9.1.7 Institutional Constraints and Governance

There is a growing recognition that many adaptation strategies require institutional guidance and collective action (Rickards and Howden, 2012; Marshall, 2013; Jones *et al.*, 2014; Ignaciuk, 2015; Hotte *et al*., 2016; Oberlack, 2017). Institutions are defined as "rules and norms held in common by social actors that guide, constrain, and shape human interaction" and can be either informally constructed by social cooperation, or formally defined by governing bodies (Jones *et al.*, 2014, p.206). As the number of actors involved, and scale of collective action problems increase, formalised governance becomes important in adaptation decisions (Adger, 2003; Adger *et al.*, 2009a; Ignaciuk, 2015).

The simulation of collective action in adaptation models based on rational choice depends on the level at which revenue is optimised. If optimisation is sought at the level of individual agents, collective action would be non-existent and collective action problems such as resource depletion may emerge. If optimisation occurs across a landscape or population, collective action would maximise the revenue generated by that landscape or population – as if Homo Economicus were a GDP-focused leader with complete authority, perfectly managing a complex set of actors. The outcome of optimisation at these two levels can be very different, but neither reflects the complex potentials and limitations of human cooperation particularly well.

Public policy interventions in adaptation are appropriate in a wide range of situations (Ignaciuk, 2015). Often, individuals' actions (and inactions) relating to climate change adaptation impact other people of groups. When the interests of these people or groups do not align with the person considering adaptation, principal-agent problems may arise (Hotte *et al*., 2016). Institutions are particularly important when adaptation involves the management of public goods which are not provided efficiently by markets because their costs and benefits are not appropriated by those responsible for them (Kolstad,, 2000; Marshall, 2013; Ignaciuk, 2015). This results in the commonly cited tragedy of the commons (Hardin, 1968), which dictates that even when people anticipate resource depletion, they are unlikely to reduce their resource use because they cannot rely on the same restraint on the part of others. Commons dilemmas and principal-agent problems are, however, manageable through the development of social and formal institutions (Ostrom, 2012; Pike, 2008; Hotte *et al*., 2016).

Moser (2009) suggests that governance is a particularly important aspect of climate change adaptation that receives less attention than it should. National governments are seen as fundamental for broad scale adaptation strategy and for setting mandates and prioritising funding for local level governance (Noble *et al.*, 2014). Local government is likely to be the most important level in climate change adaptation because of the local scale of many climate change impacts (Jones *et al.*, 2014). Reisinger *et al.* (2014) argue that private sector organisations are also likely to be important drivers of adaptation, however they acknowledge other work showing that the private sector varies in terms of appreciation of and preparedness for climate change. Finally, boundary organisations that act as intermediaries between science and policy, and facilitate communication with the public, are likely to be important in facilitating effective governance (Jones *et al.*, 2014).

A number of institutional constraints on climate change adaptation stem from inadequacies of governance. For example, in a review of institutional adaptation constraints, Oberlack (2017) identified a lack of coordination between different levels of authority as a particularly common problem. They also found that there was often confusion about which levels of government were responsible for managing adaptation. Related literature has identified the perceived lack of a mandate for climate change adaptation across a number of levels of government (Ford and Berrang-Ford, 2011; Reisinger *et al.*, 2011; Few *et al.*, 2007). In many places, democratic pressure to address climate change, while vocal, is not widespread. In some cases, local governments and planners are not required to consider long term climate change in their management decisions (Few, 2007). Even when impetus to address climate change does exist, it may be difficult to determine what the goals of action are or should be (Moser and Ekstrom, 2010).

Jones *et al.* (2014) point out that, while developed countries are often seen to have institutions capable of adapting to climatic threats, a number of recent disasters such as Hurricane Katrina and the European heat wave of 2003, have revealed institutional inadequacies. Resource constraints are frequently observed among governing bodies (Ford and Berrang-Ford, 2011; Few *et al.*, 2007; Klein *et al.*, 2014). In the United States for example, Ebi *et al.* (2009) estimate that US$200 million each year would be required to adequately manage public health challenges related to climate change, but these currently receive only US$3 million per year. Resource constraints are seen as particularly limiting for the science-heavy tasks of planning and managing adaptation strategies (Moser and Ekstrom, 2010). These challenges apply especially to developing countries (Agrawal, 2008; Smit and Wandel, 2006; Chambwera *et al.*, 2014) and commonly result in a bias towards short term planning, even among planners aware of and concerned about the impacts of climate change (Few *et al.*, 2007; Moser, 2009).

Many adaptation options require co-ordination between multiple levels of government (Chambwera *et al.*, 2014). Multi-level approaches contribute complexity to initiatives that may already be highly complex and divisive (Klein *et al.*, 2014). Adger *et al.* (2009a) cite research by McIntosh *et al.* (2000) suggesting that as societies become more complex, the management of natural resources becomes disproportionately challenging.

Climate change governance is also challenging because long timeframes conflict with short term political priorities. Investments in climate change adaptation often entail considerable cost and produce minimal short term benefits. Short-term political cycles make justifying such expenditure both politically difficult and risky (Few *et al.*, 2007; Ford and Berrang-Ford, 2011; Simões *et al*., 2017).

A number of specific institutional barriers to climate change adaptation have been identified in New Zealand. The market-led approach to decision making that has become dominant in New Zealand over the last few decades has placed considerable focus on private property rights, meaning that developments and policies that impinge on these rights are rigorously scrutinised (Reisinger *et al.*, 2011). Under the Resource Management Act (1991), the onus falls on local councils to demonstrate the harmful impacts of land uses or activities that they wish to limit (Reisinger *et al.*, 2011). While the Act has been amended to require councils to consider climate change in their assessments, this burden of proof, coupled with the limited resources of local authorities, is likely to constrain effective climate change adaptation planning (Reisinger *et al.*, 2011; Cradock-Henry *et al.*, 2015).

4.9.1.8 Response Lags

The responses of social systems lag environmental changes to some extent. Understanding of these lag effects is growing, and they are thought to have appreciable impacts on resilience (Moser, 2009; Redman and Kinzig, 2003). Barnett and O'Neill (2010) argue that the mismatch between requirement and action means that response lags increase the likelihood of maladaptation in response to climate change. Response lags are generally non-existent in models of adaptation based on rational choice. Homo Economicus is assumed to have perfect, objective, and instantaneous understanding of changes in its environment, and is able to adjust resource allocations, management, and infrastructure immediately in response to these changes. This assumption departs from reality in a number of ways.

People generally do not respond to true or current environmental conditions, rather environmental perceptions are constructed based on observation and memory (Redman and Kinzig, 2003; Kelly *et al*., 2005; Burke and Emerick, 2016). These perceptions are also seen as "the product of tradition, which can have elements of denial, or misinformation intended for purposes of political manipulation" (Redman and Kinzig, 2003, p.10). While perceptual inertia may be useful when changes from a long-term average are short-lived, it constitutes an important constraint on responses to long term 'hidden' or 'creeping' challenges such as climate change (Berrang-Ford *et al.*, 2011; Redman and Kinzig, 2003). Even when changes are rapidly perceived, responses to these changes may take considerable time to implement (de Bruin and Dellink, 2011).

4.9.2 Specific Constraints

4.9.2.1 Financial Constraints

Adaptation is frequently constrained when adaptation options are too expensive for individuals or governing bodies to implement. Models of adaptation based on optimisation vary in the extent to which they consider financial constraints. Some econometric studies include financial constraints by simulating the costs and benefits of adaptation options (see for example Schreinemachers *et al.* (2007)). Many, however, largely disregard the costs of changing between management practices and land use, only modelling the changes in long-run costs and revenue associated with each configuration.

Financial constraints are among the most commonly reported constraints on adaptation (Ekstrom *et al.*, 2011; Acosta-Michlik and Espaldon, 2008; Grothmann and Patt, 2005; de Burin and Dellink, 2011; Klein *et al.*, 2014; Hallegatte *et al.*, 2016; Masud *et al.*, 2017; Simões *et al.*, 2017). Despite this, a number of studies highlight the lack of specific information on the nature of financial constraints. Chambwera *et al.* (2014) report only limited evidence that there is a gap between adaptation needs and financial capacity at the global level. Despite this, they point out that aversion to the cost of adaptation means that autonomous adaptation will be below optimal levels, implying the need for public investment.

At an individual level, farmers' financial positions are known to affect adaptive propensity. For example, Masud *et al*. (2017) found that the high cost of agricultural inputs was the most critical impediment to climate change adaptation among farmers in Malaysia. Schreinemachers *et al.* (2009) combined econometric approaches with an ABM to simulate the effects of access to finance on the adoption of greenhouse agriculture in Northern Thailand. They found that when access to finance was extended to all households, the likelihood of adopting greenhouse agriculture increased by 18% in the wealthier central part of the watershed, and by up to 52% in the poorer upper part of the watershed.

Farmers' financial positions have also been found to influence their risk tolerance. The benefits of adaptation are often uncertain, which means that farmers with greater financial resources are better placed to trial adaptations than those with less (Parker *et al.*, 2003; Brown *et al.*, 2013; Brown *et al.*, 2016). In an example of this phenomenon, Bharwani *et al.* (2005) used an ABM to assess the benefits of seasonal climate forecasts for smallholder farmers in South Africa. They found that rich farmers could afford to take advantage of these forecasts and determine their cropping strategies, using them when the accuracy of seasonal forecasts was only 65%. At this level, however, forecasts were simply too risky for poorer farmers who chose to maintain high diversity in their cropping strategies to ensure resilience. Only when certainty grew to 85% did forecasts assist poorer farmers.

In New Zealand, financial constraints have been found to limit the adoption of sustainable farming practices in Waikato (Jay, 2005). Farmers also reported financial constraints when considering sustainable practices in the Hurunui-Waiau Catchment. Daigneault *et al.* (2012) used an ABM to simulate a range of policy strategies to support sustainable farming, one of which included financial support. They found that providing financial support, as well as time and advice, were the most effective policy strategies for reducing land tillage. This implies that in the absence of support, farmers face financial constraints in adopting new practices.

4.9.2.2 Scale Constraints

It is widely understood that the scale of the farming enterprise, both in terms of area and output, affect its ability to adapt (Brown *et al.*, 2013). For example, Lambert *et al.* (2007) investigated the influence of farm characteristics on the adoption of conservation practices. They found that smaller farms split the fixed costs of conservation practices over smaller areas and fewer production units. The same applies to the fixed costs of adaptation to climate change, where investments such as the time spent learning about adaptation options and securing the appropriate support are likely to have greater payoffs on lager farms than smaller ones. Farm size also affects farmers' risk calculations. In his critique of the analysis of risk in agricultural economics, Just (2003) suggests that small farms are more risk-averse than large farms and that this may substantially affect decision-making. In New Zealand, farm scale has been found to be significantly positively correlated with risk tolerance, with a 10% increase in farm size correlating with a 0.03 point increase in risk tolerance on an 11 point Likert scale (Brown *et al.*, 2013).

4.9.2.3 Path Dependence

Climate change adaptation is likely to be heavily influenced by historical conditions – a phenomenon called path dependence. Models of adaptation based on rational choice are not affected by path dependence. Homo Economicus ignores sunk-costs and evaluates each decision on its costs and benefits in the future. In reality, path dependence may be particularly prevalent in agriculture (Nelson *et al.*, 2014; Dasgupta *et al.*, 2014; Chhetri *et al.*, 2010) and is likely to affect climate change adaptation (Klein *et al.*, 2014; Ekstrom *et al.*, 2011).

Understandings of path dependence developed substantially in the 1980s after David's (1985) seminal paper explaining the continued dominance of the QWERTY keyboard despite the well-known existence of more efficient configurations. David (1985) identifies three mechanisms that contribute to path dependence: synergies between technologies and their uses, incremental development leading to economies of scale, and sunk costs.

Sunk costs constitute a primary cause of path dependence. Put simply, Nelson (2011, p.115) describes sunk costs as "the phenomenon in which past investments, rather than future opportunities, weigh more heavily in decisions, reducing the perceived response options." A relevant example used by Nelson (2011) is that of large-scale irrigation infrastructure in agriculture, which, once constructed, may make farmers reluctant to consider rain-fed production alternatives even when they are more suitable. Sunk costs are likely to be particularly influential in the large-scale structural decisions associated with agricultural adaptation to climate change (Gifford *et al.*, 2011; Chhetri *et al.*, 2010; Rickards and Howden, 2012).

Path dependence can also emerge when incremental development or adaptation becomes self-reinforcing and precludes potentially beneficial larger scale transformation (Darnhofer, 2014; Chhetri *et al.*, 2010). Incremental adaptation is likely to be particularly common in response to gradual climate change, and will advantage certain industries and systems – although not necessarily the most productive or desirable ones (Chhetri *et al.*, 2010). For example, the productivity of many staple crops is the result of centuries of formal scientific work and millennia of informal scientific development (Chhetri *et al.*, 2010). While alternative plant species may hold the potential to become more productive in certain areas under climate change, without such a strong scientific legacy they may continue to be out-performed by traditional crops.

Chhetri *et al.* (2010) modelled path dependence in agricultural adaptation to climate change in the south-eastern United States using a logistic model of innovation adoption in which some farmers adapt early, and some late, with the majority adapting sometime around the mean. They compared this to a scenario in which adaptation is optimised to estimate the economic effects of path dependence. They found that productivity was significantly lower in the logistic adaptation scenario during the first 20 year period. However differences were not significant in the second and third 20 year periods. They concluded that path dependence is likely to constrain adaptation under climate change, however the economic impact of this constraint may diminish over time.

4.9.2.4 Perceived Self-Efficacy

Adaptation may also be constrained when people's perceived abilities to manage the impacts of climate change differ from their objective abilities to do so. Perceived self-efficacy is a key determinant of adaptive behaviour (Burnham and Ma, 2017; Moser, 2009; Gifford *et al.*, 2011; Brown *et al.*, 2013; Grothmann and Patt, 2005; Ford and Berrang-Ford, 2011; Wolf *et al.*, 2009). Even when people view an adaptation positively and have a desire to implement it, they will not generally do so if they do not think themselves capable of attaining the desired outcome (Brown *et al.*, 2013). Furthermore, even when people perceive climate change as a risk, their adaptive intent may remain low because of a perceived lack of self-efficacy in responding to this risk (Burnham and Ma, 2017). Grothmann and Patt (2005) suggest that, in many cases, people's perceived ability to adapt may be more important than objective physical or financial constraints. Despite this, models of adaptation based on rational choice consider only objective efficacy. Homo Economicus perfectly understands its own capacity to implement adaptation options.

A number of studies have found a lack of perceived self-efficacy inhibiting adaptive action among certain populations. For example, through their study in the United Kingdom, Wolf *et al.* (2009) found that many elderly people believed that they were incapable of responding to heat waves, and they were unlikely to take action to avoid heat stress as a consequence. Grothmann and Patt (2005) demonstrated that including perceived self-efficacy within a socio-cognitive model of adaptive responses to flooding in Cologne, Germany, improved the model's performance relative to a more traditional socioeconomic model. Burnham and Ma (2017) found that perceived self-efficacy was strongly positively correlated with the adaptive intent of smallholders in the Loess Plateau region in China.

Among New Zealanders, age has been found to have an inverse relationship with perceived self-efficacy in responding to climate change, while knowledge about the problem of climate change was found to increase perceived self-efficacy (Milfont, 2012). When combined with perceptions of impending threats, a lack of perceived self-efficacy can lead to particularly strong psychological and emotional responses including denial, rejection, and fatalism (Grothmann and Patt, 2005; Milfont, 2012; Ekstrom *et al.*, 2011).

Adaptation may also be constrained when perceived self-efficacy is higher than objective self-efficacy. When people overestimate their abilities to manage problems, they are less likely to take preventative or preparatory measures (Wolf *et al.*, 2009). In the same study of elderly residents in the United Kingdom, Wolf *et al.* (2009) found that people often saw themselves as capable of responding to heat stress alone, and rejected the need for assistance from caregivers. High levels of perceived self-efficacy have been found among farmers in California, where 76% are confident that they will adapt to climate change (Niles *et al.*, 2013). Similar confidence was found among a group of environmentally engaged 'smart' farmers in New Zealand, who participated in the work of Kenny (2011).

4.9.3 Transaction Costs

4.9.3.1 Information Constraints

Information constitutes an important constraint on agricultural adaptation to climate change (Gsottbauer and van den Bergh, 2011). Model studies of adaptation based on optimisation assume that Homo Economicus has perfect information on environmental change and the potential costs and benefits of every possible adaptation option. Importantly, Homo Economicus faces no financial, time, or cognitive burdens in accessing and comprehending this information.

In reality, farmers do not have perfect information about their environments, how these environments may change under climate change, or the ways by which they could reduce harm or exploit opportunities (Janssen, 2004; Masud *et al*., 2017). Rather, people make adaptation decisions based on incomplete, and at times inaccurate information (Janssen, 2004). The costs of improving the coverage and accuracy of this information are often substantial, and these costs are factored in to the decision making process (Chambwera *et al.*, 2014). Ignaciuk (2015) suggests that the public sector should be responsible for the generation and provision of broad information on the risks and consequences of climate change. This task is, however, hampered by the constraints on governing bodies described previously. When the necessary information is not available, people tend to either delay action until further information emerges, focus on problems that are better understood, reframe the problem to one of a lack of information, or, at best, implement actions that are robust to a range of possible outcomes (Ekstrom *et al.*, 2011).

Information about climate change is often complex and uncertain. Many people remain unaware of how agricultural conditions may change in their region under climate change (Gifford *et al.*, 2011; Kenny, 2011). In some regions, this is due to scientific uncertainties leading to projections that disagree about the direction of change. However uncertainty remains in regions for which models agree about the direction of change. Some farmers have cited this remaining uncertainty as a reason for disregarding climate change projections (Kenny, 2011). Despite this, Dessai *et al.* (2009) point out that uncertainty should not necessarily be seen as a limit to adaptation. Robust decisions can still be informed by uncertain projections if basic information on the nature, direction, and possible magnitude of change is available.

Information about climate change is also often poorly communicated. Scientific information on climate change is not produced in a format that is particularly useful for, or accessible to, the layperson, and translation of this information often leads to misunderstanding, unintended interpretation, or complete disengagement (Moser and Ekstrom, 2010; Dilling and Moser, 2007; Simões *et al*., 2017).

Even when climate change projections are well communicated, seen as relevant by farmers, and provide basic information on which adaptation decisions can be reached, there is often considerable uncertainty about which adaptation options are likely to prove most beneficial (Masud *et al*., 2017). Farmers may lack information about the viability of different crops and livestock species in their area, the technologies available, or the best management practices under new conditions (Acosta-Michlik and Espaldon, 2008; Dasgupta *et al.*, 2014; Ekstrom *et al.*, 2011). Furthermore, the costs of acquiring information are likely to increase in a non-linear fashion under climate change, as adaptation options under modest climate change are likely to be found locally, whereas under more severe climate change, established climate-analogues are likely to be further afield (Nordhagen and Pascual, 2013). Certain attributes, such as education and social connectedness, mean that some farmers have considerably greater access to information on adaptation options than others.

A number of studies have directly identified the constraining effect of insufficient information. For example, Acosta-Michlik and Espaldon (2008) found a lack of information to be equal to financial barriers as the most important constraint on adaptation among rural villagers in the Philippines. In New Zealand, Daigneault *et al.* (2012) found that a lack of information on the costs and benefits of environmental management practices was seen as an important constraint by farmers. Using an ABM of farmer behaviour, they demonstrated that proving the benefits of fertiliser management strategies to farmers was the most effective way to encourage behavioural change.

4.9.3.2 Technical Expertise

Climate change adaptation is often seen to require technical expertise. With perfect information and infinite cognitive ability, Homo Economicus is assumed to be an expert in all fields, meaning that constraints relating to technical expertise are ignored in models of adaptation based on optimisation. In reality, and shortfalls in technical expertise are seen to constrain adaptation for most people (Noble *et al.*, 2014; Klein *et al.*, 2014; Masud *et al*., 2017).

The relationship between technical expertise and adaptation has been identified in a number of places. At a basic level, a number of studies have identified a link between higher levels of education and higher adaptive propensity in the form of greater adoption of technological improvements (see Deressa *et al.* (2009) for a case study in Ethiopia, Masud *et al*. (2017) for a case study in Malaysia, and Brown *et al.* (2016) for a case study in New Zealand); and adoption of environmental practices (see Jay (2005) for a case study in New Zealand and Peerlings *et al.* (2014) for a case study in Europe). The link between specialist extension services and adoption of environmental practices has also been demonstrated in the literature (see Marey-Perez (2003), in Brown *et al.* (2013)).

The relationship between education and adaptation is, however, not straightforward. Burke and Emerick (2016) found no evidence that more educated farmers responded differently to changes in temperature between 1980 and 2000 in the United States. It is clear that the type of education is important. Baumgart-Getz *et al.* (2012) demonstrate that, while targeted education carried out by extension services increased the adoption of best management practices among farmers in the United States, formal education was found to have little effect on adoption rates. A lack of technical expertise may therefore exist as a constraint on adaptation even when farmers are highly educated in a formal sense. Whether education addresses the technical requirements of adaptation is clearly more important than the length of time spent in formal education (Brown *et al.*, 2013).

4.10 Other Considered Constraints

A number of additional constraints were described in the literature but found little empirical support among farmers in the Hikurangi catchment. These are described briefly here so that their consideration and removal is clear to the reader, while in-depth reviews of the literature on each are available from the author on request.

Generic constraints that were investigated in this study but not included in the final modelling exercise included gender, ideological constraints, and constraints relating to past experiences. Gender constraints refer to widely identified deficiency of opportunities available to women relative to men (Agrawal, 2008; Klein *et al.*, 2014; Jones and Boyd, 2011), and may limit the adaptive potential of female farmers. Ideological constraints are strongly held beliefs that relate to people's understandings of the world around them, their religious beliefs and politics, and opinions about how society should operate (Milfont, 2012; Gifford *et al.*, 2011; Moser and Ekstrom, 2010). Adaptation may be constrained when available options clash with people's ideologies. Past experiences of extreme weather events can reduce coping capacity by eroding capital stocks and increasing indebtedness (Wilby and Dessai, 2010; Nelson *et al.*, 2007). Furthermore, past experiences of the failure of adaptation strategies can make farmers less willing to adopt innovations in the future (Brown *et al.*, 2013).

Specific constraints that were investigated but not modelled in this study included tenure and constraints caused by experience. Tenure can constrain adaptation to long term challenges because, when farmers do not own the land that they farm, they may not realise the benefits of adaptation themselves (Mendelsohn and Dinar, 2009; Jay, 2005). Experience practising a certain land use often builds social capital and comparative advantages in that particular industry, which make farmers less likely to change to other land uses (Brown *et al.*, 2013; Fountas *et al.*, 2006).

Transaction costs that were investigated but not modelled in this study included adjustment costs and cognitive constraints. Adjustment costs include the costs incurred to learn about new conditions (Chambwera *et al.*, 2014). These may be particularly important because changes in climate are difficult for farmers to observe directly (Kelly *et al.*, 2005). When changes are perceived and information on appropriate responses is available, cognitive constraints may still preclude adaptation when people are unable to accurately understand and compare all possible risks and adaptation options (Acosta-Michlik and Espaldon, 2008; Dilling and Moser, 2007). People are often found to automate routine activities and avoid cognitive strain, making regular and thorough assessments of options unlikely (Darnhofer, 2014; Jager *et al.*, 2000; Larcom and Rouch, 2015).

4.11 Modelled Economic Impacts of Constraints

There have been a number of attempts to consider the dynamics of adaptation within Integrated Assessment Models of climate change impacts (for a summary, see Fankhauser (2017)). Of these attempts, a small number have sought to assess the economic impacts of adaptation constraints. In an early attempt to quantify the economic impacts, de Burin and Dellink (2011) used a global Integrated Assessment Model (IAM) to test the effects of restricting adaptation to below economically optimal levels. They based their analysis on the following six scenarios for adaptation constraints which were written into their assessment model, and tested individually:

1) ‘Funding’ – the difficulty of financing adaptation effort, simulated by placing limits on adaptation expenditure in each time period.
2) ‘Quantity’ – constraints on the quantity of adaptation that is likely to occur in each time period.
3) ‘Excess’ – adaptive action above the optimal level leading to losses in utility.
4) ‘Delay’ – restrictions on the speed at which optimal adaptation actions are implemented.
5) ‘Rigidity’ – constraints on the extent to which adaptation action can change between two periods.
6) ‘Obsolete’ – a scenario where adaptation options are rendered ineffective due to unexpectedly high rates of climate change.

The authors tested two levels of restriction which they called ‘weak’ and ‘strong’, however no empirical justification was given for these categories, or the magnitude of restrictions assigned under each constraint scenario, making the results theoretical rather than applied. With this approach they found considerable differences in overall costs and benefits of both adaptation and mitigation, concluding that it is “very harmful to ignore existing [constraints] on adaptation when devising efficient climate policies” (p.34). The development of impacts of the six scenarios are shown in Figure 4.3. The ‘Obsolete’ scenario was found to be the most harmful restriction, largely because adaptation costs are incurred yet these fail to reduce damages under rapid climate change. The other five restrictions were also found to reduce utility, with 'Delay' being the second most harmful restriction, and 'Funding' the least harmful. This analysis stops short of combining the possible constraints on adaptation, and is therefore blind to possible interactions between them (Eisenack *et al.*, 2014).

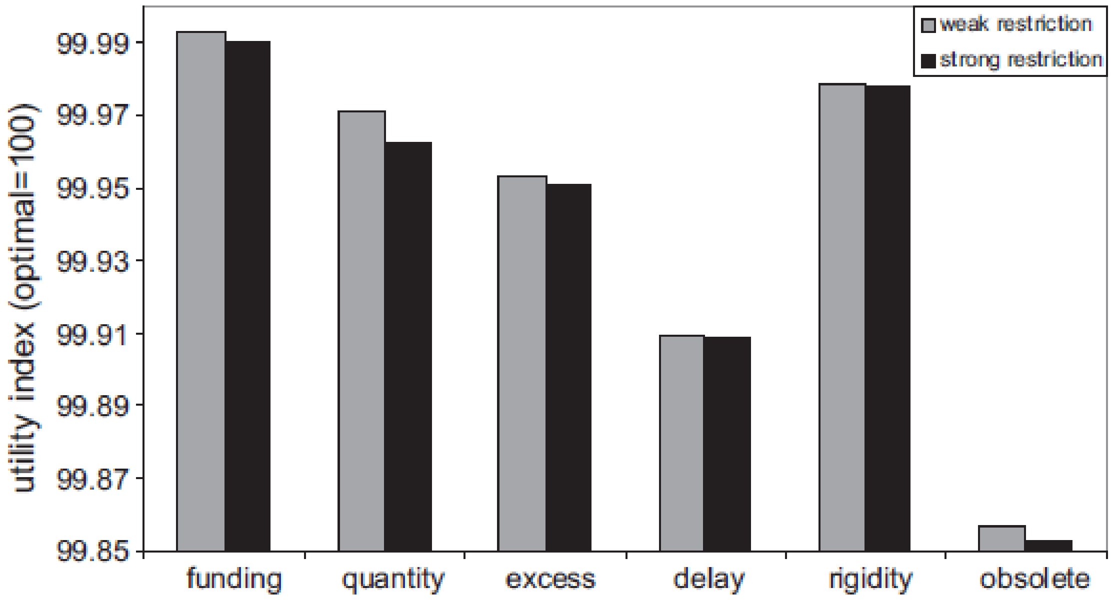

Figure 4.3: Impacts of modelled restrictions on adaptation on the utility index of de Burin and Dellink (2011).

As part of their study, de Burin and Dellink (2011) also investigated the impacts of adaptation constraints on the costs and benefits of mitigation. They found that constraining adaptation below optimal levels leads to a more or less linear positive increase in the benefits of mitigation effort as a consequence of increases in residual damage. Their analysis comprised two scenarios: 'Naïve Mitigation' in which mitigation efforts assume that adaptation will be optimal, and 'Responsive Mitigation' which takes constraints on adaptation efficiency into account. Their results, shown in Figure 4.5, demonstrate that the impacts of adaptation constraints on the costs and benefits of mitigation vary from negligible in the case of 'Delay' in adaptation action, to substantial in the case where high rates of climate change render adaptation 'Obsolete'.

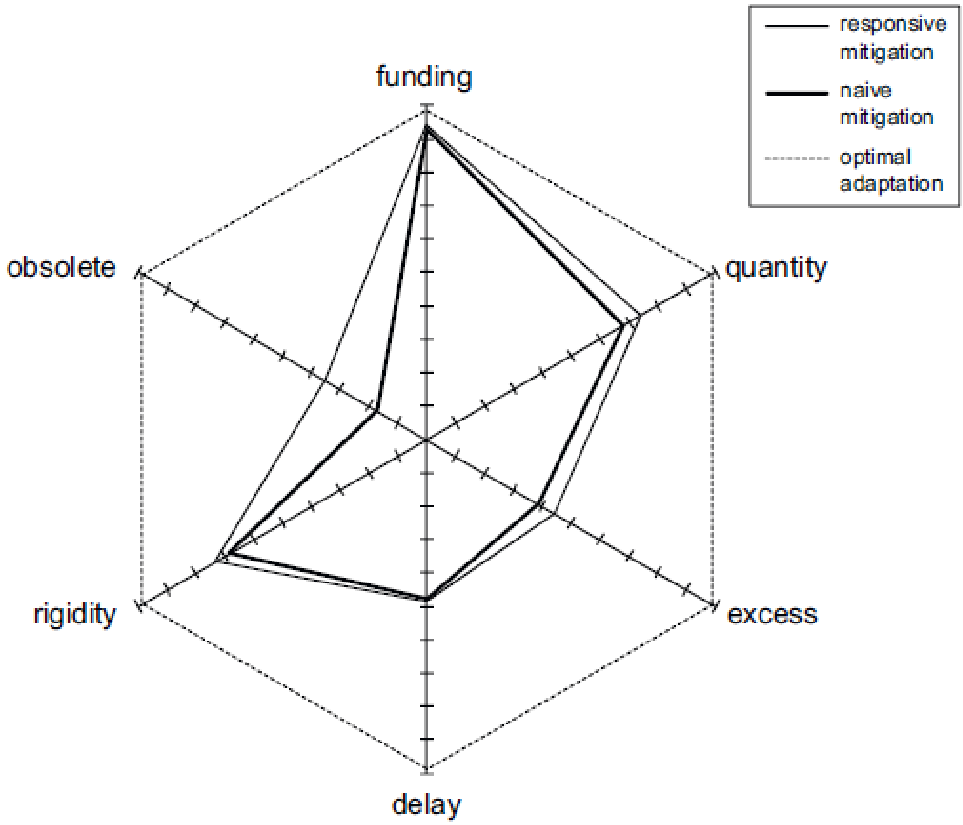

Figure 4.4: Impacts of modelled adaptation restrictions on mitigation action and utility (de Burin and Dellink, 2011).

The few attempts to explicitly model adaptation using IAMs have generally found it to contribute an important source of uncertainty. In an early attempt to include adaptation within the PAGE model, Hope *et al.* (1993) estimated climate change impacts under a scenario with no adaptation to one which they described as 'aggressive adaptation'. They found that employing aggressive adaptation had the potential to reduce the mean value of worldwide economic damages by roughly 98% from 18.1 trillion to 0.3 trillion European Currency Units[4], concluding that "Despite all the uncertainties, the argument for including an aggressive adaptation policy is very strong." (Hope *et al.*, 1993, p.334). These figures also strongly imply that any constraints on the ability to achieve the specified 'aggressive adaptation' would have substantial impacts on worldwide damages from climate change.

The benefits of adaptation estimated by Hope *et al.* (1993) were, however, questioned by de Bruin *et al.* (2009), who pointed out that these were much higher than those found in other literature. de Bruin *et al.* (2009) compared the economic impacts of ignoring adaptation and optimising adaptation using the Dynamic Integrated Climate and Economy (DICE) model. The cumulative costs of climate change under these two scenarios are shown in Table 4.2. These results demonstrate that the

[4] European Currency Units were a unit of account taken as an average of the currencies of the member states of the European Community. It was replaced by the Euro at parity in 1999.

difference between assuming no adaptation and assuming optimal adaptation are substantial for near-term projections, and that this difference increases over time in both absolute and relative terms.

Table 4.2: Accumulated costs of climate change simulated using the DICE model assuming no adaptation and optimal adaptation. Adapted from de Bruin *et al.* (2009).

Annual Costs (Billion USD)	**No Adaptation**	**Optimal Adaptation**	**Damage Reduction Percentage**
Period 2025-2034	204	181	11.3
Period 2045-2054	695	594	14.5
Period 2095-2105	5430	4281	21.2

Together these studies demonstrate that the potential for adaptation to reduce the costs of climate change is extremely uncertain, and could be as low as 21.2% or as high as 98%. While these are valuable estimates of the scope of the uncertainty that poorly specified adaptation may contribute, neither study explored the possible nature of sub-optimal adaptation. Their findings highlight uncertainty about the economic impacts of adaptation that this study seeks to explore.

Chapter 5

Assessment of Adaptation Constraints

In light of the description of adaptation constraints in the previous chapter, this chapter explains how these constraints are assessed in this study. As described in Section 2.2, adaptation constraints are understood to exist within social-ecological systems. These systems are complex, which, as will be described in Section 5.1, necessitates the use of qualitative methods to complement the quantitative modelling exercise. Section 5.2 explores a range of approaches that have been used to empirically inform agent-based models in the past, while Section 5.3 justifies the use of surveys and semi-structured interviews in this case. Section 5.4 then describes the quantitative empirical work, while the qualitative empirical work is described in Section 5.5. Finally, the uncertainties inherent to these empirical methods are discussed in Section 5.6.

5.1 Mixed Qualitative Quantitative Methods

The constraints on adaptation affecting land use change in the Hikurangi catchment were investigated using both qualitative and quantitative methods, in a mixed methodology. Mixed methodologies have become more common in recent years (Bryman, 2006), and have been successfully applied to assess agricultural adaptation to climate change in New Zealand (Kalaugher *et al.*, 2013). The mixing of methods is often justified based on the shortcomings of individual methods. Quantitative data are necessarily narrow and are generally unable to account for the processes that underlie their values (Hay, 2000). These data can provide snapshots of specific conditions; however they poorly capture the intricacies and dynamics of complex systems, and how these may change over time (Darnhofer, 2014; Heckbert and Bishop, 2011; Hay, 2000). Conversely, while qualitative information can explore the processes most relevant to the dynamics of the system, and explore intricacies of context (Kalaugher *et al.*, 2013; Hoffmann *et al.*, 2007; Burton and Peoples, 2008), it is not well suited to estimating the commonness of characteristics within a population (Gifford *et al.*, 2011; Cradock-Henry *et al.*, 2015; Hay, 2000). Combining qualitative and quantitative methods is seen to provide a pragmatic solution to these shortcomings (Gifford *et al.*, 2011; Hay, 2000).

Darnhofer (2014) and Cradock-Henry *et al.* (2015) argue that combining these methods is essential when attempting to understand the dynamics of agricultural resilience. Furthermore, Heckbert *et al.* (2010) advocate mixing methods for the purposes of calibrating behavioural rules for agent-based models, while Eisenack *et al.* (2014) suggest that comparing different research methods can contribute to our understanding of the complex causes and impacts of adaptation constraints.

Mixed methodologies present a large number of potential advantages. In a review of 232 articles that use mixed methodologies, Bryman (2006, p.105) identified 16 distinct justifications for this approach. Ten of these justifications apply to this investigation. These are:

(1) "*Triangulation* or greater validity – refers to the traditional view that quantitative and qualitative research might be combined to triangulate findings in order that they may be mutually corroborated".

(2) "*Offset* – refers to the suggestion that the research methods associated with both quantitative and qualitative research have their own strengths and weaknesses so that combining them allows the researcher to offset their weaknesses to draw on the strengths of both".

(3) "*Completeness* – refers to the notion that the researcher can bring together a more comprehensive account of the area of enquiry in which he or she is interested if both quantitative and qualitative research are employed".

(4) "*Different research questions* – this is the argument that quantitative and qualitative research can each answer different research questions."

(5) "*Explanation* – one is used to help explain findings generated by the other".

(6) "*Unexpected results* – refers to the suggestion that quantitative and qualitative research can be fruitfully combined when one generates surprising results that can be understood by employing the other".

(7) "*Credibility* – refers to suggestions that employing both approaches enhances the integrity of findings".

(8) "*Context* – refers to cases in which the combination is rationalised in terms of qualitative research providing contextual understanding coupled with either generalizable, externally valid findings or broad relationships among variables uncovered through a survey."

(9) "*Illustration* – refers to the use of qualitative data to illustrate quantitative findings, often referred to as putting 'meat on the bones' of 'dry' quantitative findings".

(10) "*Diversity of views* – this includes two slightly different rationales – namely, combining researchers' and participants' perspectives through quantitative and qualitative research respectively, and uncovering relationships between variables through quantitative research while also revealing meanings among research participants through qualitative research".

In aggregate, these justifications demonstrate a strong case for using both qualitative and quantitative methods in this investigation.

Mixed methodologies are, however, criticised in a number of ways. Vague justifications for implementing mixed methodologies can lead to data redundancy in which the researcher's, and more importantly the participants', time is wasted. Furthermore, it can be difficult to aggregate qualitative and quantitative data because they must be understood with reference to the differing purposes for which they were collected (Hay, 2000). The former concern is minimised in this case through a careful research design, as described in Sections 5.3-5.6. The issue of incommensurability is avoided in this case by not attempting to aggregate qualitative and quantitative data, but rather using each to inform the interpretation of the other.

The interdisciplinary approach applied in this study follows the pragmatic constructionist epistemology put forward by Mansilla (2010), as explained in Section 2.6. Insights are not justified based on linear propositional argumentation, but by the bringing together of a range of evidence. This pluralist approach allows different disciplines to contribute in their own way, rather than seeking to explain some disciplines using others, as, for example, the Consilience approach does. As a constructionist epistemology, the objective is to generate new knowledge, and as a pragmatic epistemology, it focuses closely on the purposes for which the data were collected. It therefore allows for the combination of different disciplinary knowledge to be targeted at addressing specific research questions. The new knowledge generated cannot be formally proved, but rather exists in a reflective equilibrium, in which it can be adjusted through new findings and evidence (Mansilla, 2010).

5.2 Empirical Calibration of Agent-Based Models

The empirical assessment of adaptation constraints was designed to match the agent-based modelling method employed in this study. There is a growing literature on best practice in empirical calibration of ABMs (Robinson *et al.*, 2007; Smajgl *et al.*, 2011). Robinson *et al.* (2007) identified five approaches to empirically informing ABMs for land use science, following a major international workshop on the topic. These approaches were: sample surveys; participant observation; field and laboratory experiments; companion modelling; and Geographic Information Systems (GIS) and remotely sensed data. Participant observation, field and laboratory experiments, and companion modelling were considered infeasible given the breadth and objectives of this study. This study used sample surveys, and GIS and remotely sensed data, which are discussed in Sections 5.2.1 and 5.2.2, respectively. In addition, Section 5.2.3 explores the use of information from previous studies and existing databases and Section 5.2.4 explores the use of interviews, both of which were also adopted in this study.

5.2.1 Sample Surveys

Sample surveys are among the most commonly used tools for informing ABMs and they have a number of advantages over other approaches. Surveys are able to be targeted towards answering research questions based on theory, and provide information on the distribution of characteristics and beliefs within broader populations (Brown *et al.*, 2013). Surveys have been used frequently to define behavioural rules within ABMs in the past (see for example Brown and Robinson, 2006; Heckbert and Bishop, 2011; Bharwani *et al.*, 2005; Gurung *et al.*, 2006; Berger and Schreinemachers, 2006).

Surveys are particularly useful for providing information about heterogeneity among agents (Brown and Robinson, 2006; Heckbert and Bishop, 2011; Robinson *et al.*, 2007). Survey data can also be used to develop preference functions to apply to agents. Preference functions can be calculated using a number of techniques including econometric analysis such as regression modelling or random utility modelling (Heckbert and Bishop, 2011). Particularly relevant to the current study, Robinson *et al.* (2007) suggest that surveys can be used to identify constraints on decision making.

Despite their advantages, surveys also have a number of limitations affecting their abilities to inform ABMs. First, the survey respondents must closely match the agents being modelled, a condition that may be difficult to achieve if surveys are administered on a scale different to the modelled population (Brown and Robinson, 2006). Survey questions must also solicit information sufficient to understand the preference or behaviour in question, which is a difficult task in many situations (Brown and Robinson, 2006). Furthermore, questions must be interpreted accurately and consistently by respondents, and responses must be accurate representations of preferences and behaviours (Brown and Robinson, 2006). As Section 5.4.3 will explain, survey responses are often imperfect for a range of reasons. Furthermore, surveys are often one-off and can be criticised for providing a 'snap shot' of behaviours, preferences, and conditions (Darnhofer, 2014). Sample surveys also necessarily focus on specific preferences, behaviours, or conditions, and may be blind to the broader processes determining complex decisions (Robinson *et al.*, 2007). Table 5.1 describes the main strengths and weaknesses of using sample surveys, as they were discussed during the workshop reported by Robinson *et al.* (2007).

Table 5.1: Strengths and weaknesses of using sample surveys to inform agent based models. Source: Robinson *et al.* (2007).

Strengths	Weaknesses
• Can be representative of larger population/geographical area	• Generally a snapshot in time, not very suitable to represent temporal variation due to high implementation costs
• Represents heterogeneity in terms of: household composition, resource endowments, and access to services and markets	• Household is usually represented as unitary unit of decision-making, which is unrealistic for some decisions and neglects the intra-household decision-process
• Suitable for application of statistical methods to isolate the effects of behavioral variables	• Statistical methods are based on many structural and technical assumptions and often lack transparency
• If well documented, the data can be shared among researchers; i.e. an 'outsider' can analyze the data	• If designed by an 'outsider' the questions can be biased (Chambers 1997)
• Can be combined with a community survey or group surveys to capture additional aspects	• Data quality depends on design and implementation (Grosh and Glewwe 2000)

5.2.2 GIS and Remotely Sensed Data

GIS and remotely sensed spatial data are frequently used in ABMs focused on land use change. On a basic level, spatial data can be used to define maps of landscapes, including land use. Spatial data can also help to identify the presence of environmental factors that influence land use (Robinson *et al.*, 2007). For example, spatial data can be used to identify the effects of location on behaviour such as the adoption of technology or the diffusion of innovation (Brown *et al.*, 2013; Robinson *et al.*, 2007; Berger, 2001). Spatial analyses often use panel data to infer the drivers of changes in spatial variables over time (Robinson *et al.*, 2007).

While basic spatial data are generally cheap and easy to attain, they have a number of drawbacks. Investigations are limited to questions that can be answered by existing data (Robinson *et al.*, 2007). Furthermore, inferring relationships using spatial data risks misidentifying relationships due to complex confounding factors not captured in those spatial data. The main strengths and weaknesses of using spatial data to inform AMBs are summarised by Robinson *et al.* (2007) in Table 5.2.

Table 5.2: Strengths and weaknesses of using field and laboratory experiments to inform agent based models. Source: Robinson *et al.* (2007).

Strengths	Weaknesses
• Can be useful in some historical contexts, for generating data about past agent behavior.	• Cannot directly identify agent/household characteristics.
• Inexpensive as long as data are available through public sources.	• Inferences are subject to mis-estimation due to complex interactions and confounding factors in the observed system.
• Can identify suitability and spatial driving factors.	• Requires assumed underlying decision model, which cannot be tested. Analysis cannot refute anything in the conceptual model.
• Good for parameterizing drivers already identified.	• Data-intensive.
• Can cover a large area.	• Model must be simple/have few parameters.
	• Interpreting results can be difficult because of non-stationarity, feedbacks, time lags, heterogeneity in the system.

5.2.3 Use of Previous Studies and Existing Databases

Data from existing databases and findings from previous studies are commonly used to inform ABMs. Some ABM studies rely solely on these sources (see for example Heckbert *et al.* (2010), Happe *et al.* (2006), and Jager *et al.* (2000)). It is also common for studies to use previous findings and existing data to partially inform their ABMs. For example, census data are often used to define socioeconomic characteristics of agent populations (Smajgl *et al.*, 2011). Many behavioural traits such as the tendency for people to lament losses more then they value gains (Tversky and Khaneman, 1986), and to satisfice rather than maximise (Reed *et al.*, 2013) are well established in the literature, therefore it may be best to use established findings rather than investigating them empirically in each new study (Jager *et al.*, 2000; Brown *et al.*, 2013).

As with GIS and remotely sensed data, previous studies and existing data are often easily accessible and cheap, however they also limit what can be investigated. While previous studies can describe the processes behind certain behaviours, it may be difficult to utilise these findings in testing other hypotheses. Furthermore, it may be questionable to use certain empirical findings beyond the context in which they were reached (Kalaugher *et al.*, 2013; Hoffmann *et al.*, 2007).

5.2.4 Interviews

Interviews can be used to generate qualitative information with which to inform ABMs (Heckbert *et al.*, 2010a,b). Interviews are commonly used in social research and, relevant to this study, have been applied by Burton and Peoples (2008) to explore adaptive responses to extreme weather in New

Zealand, by Bharwani *et al.* (2005) to provide information for an ABM of crop choices in light of seasonal forecasts in South Africa, and by Huigen (2004) and Huigen *et al.* (2006) to understand settlement decisions in the Philippines and construct mathematical rules representing these decisions within an ABM.

Interviews can be used as the primary data source for informing ABMs. For example, Huigen *et al.* (2006) based their ABM of settlement decisions in the Philippines on interviews and oral histories. The responses gathered were transformed into an ABM following the seven step 'MameLuke' framework in which secondary data are collected first, hypotheses are then created followed by the formulation of semi-structured questionnaires, primary data are then collected, analysed and the hypotheses adjusted before the ABM is developed, run, and results are analysed. Responses gathered can be translated into heuristic behavioural rules upon which agents can be developed (Huigen *et al.*, 2004; 2006). Interviews can also be used to validate other methods as well as to develop an understanding of the processes underlying decision making (Heckbert *et al.*, 2010).

Interviews do, however, have a number of drawbacks. Interviews are time and resource intensive, and the number of individuals who can be interviewed is often fewer than the number of agents modelled (Smajgl *et al.*, 2011). It may also be difficult to include qualitative information within a quantitative ABM in the absence of complementary quantitative approaches.

5.3 Methods Employed

Smajgl *et al.* (2011) point out that there is no broadly accepted 'standard approach' to empirically parameterising ABMs. The methods described in the previous section demonstrate that, while there is a range of possible ways to empirically inform ABMs, none of them is without drawbacks (Robinson *et al.*, 2007). Because of this, a number of researchers suggest that iteratively combining multiple empirical methods provides the best approach (Robinson *et al.*, 2007; Smajgl *et al.*, 2011). Indeed, the combination of methods has become increasingly popular in ABM research (Heckbert and Bishop, 2011).

Smajgl *et al.* (2011) presented a typology of approaches to combining methods for empirically parameterising ABMs. Their characterisation of the process is shown in Figure 5.1, noting the junctures at which different empirical methods can be employed (Methods 1, M2, M3, M4a, M4b, and M5). For each of these junctures, a range of candidate methods is listed in Table 5.3.

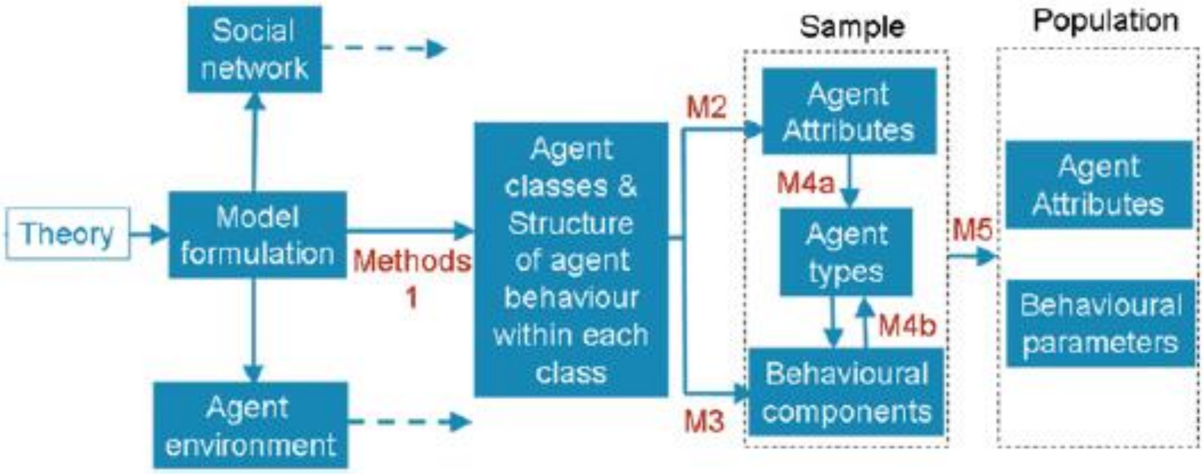

Figure 5.1: Framework for empirically parameterising ABMs presented by Smajgl *et al.* (2011).

Table 5.3: Overview of the potential methods that can be employed at each of the junctures identified in Figure 5.1. Adapted from Smajgl *et al.* (2011).

M1	M2	M3	M4a ATB	M4b BT	M5
Expert knowledge ParticObser Lab experiment Interviews RPG	Survey Census (incl. GIS data)	Survey Interviews Field experiment ParticObser RPG Time-series data Expert knowledge	Clustering and regression Correlation and expert knowledge Expert knowledge Dasymetric mapping	Clustering and regression Correlation + expert knowledge Expert knowledge ParticObser	Proportional Census/GIS based assignment Monte Carlo

Based on these methods, Smajgl *et al.* (2011) characterise 12 possible combinations of methods, which they call ‘cases’. The methods employed in the current investigation most closely follow the second of their possible cases. Specifically, at the first juncture (M1), expert knowledge was employed in the original formulation of the ABM used in this study (Morgan and Daigneault, 2015), and interviews were conducted with stakeholders in order to design the structure of the adaptation constraints that were added in this study, as will be described in Section 5.5. Surveys were used at the second juncture (M2) in order to understand the characteristics and diversity of the farming population in New Zealand, as will be described in Section 5.4. Interview and survey data were combined at the third juncture (M3), in order to parameterise the main adaptive constraints, as will be described in Chapter 7. Juncture M4a is not relevant in this case because, as will be justified in Section 7.3, agents’ attributes were not categorised in this study, but rather varied on a continuous scale proportional to the empirical distributions found in the surveys. Regression analysis was used to link behavioural constraints to agent attributes at juncture M4b, as will be described in Section 7.3. Finally, the attributes of the sample are scaled to the population based on cadastral information about land ownership in the Hikurangi catchment at juncture M5. The second case in the classification of Smajgl *et al.* (2011) was also used by Valbuena *et al.* (2010) who assessed the response of farmers to policy changes in the Netherlands.

5.4 Survey of Rural Decision Makers

Surveys were used in this study to understand the characteristics and variance of important agent attributes, as well as to test the significance and strength of a range of adaptation constraints identified in the literature. In order to maximise the potential reach of survey questions, this study contributed to the design of, and took data from, an existing longitudinal survey programme called the Survey of Rural Decision Makers (SRDM) (Brown *et al.*, 2013; Brown, 2015). The SRDM was first distributed in 2013 with the explicit aim of contributing "to the development of more robust ABMs (specifically, the ARLUNZ model used in this study) that can explore rural decision makers' behaviour and responses to social, economic, and policy changes". (Brown *et al.*, 2013, p. 122). A second round of the SRDM was designed jointly by Landcare Research, AgResearch, and the Ministry for the Environment, and distributed between July and December 2015. The 2015 SRDM collected data on the ownership and structure of farms, land use and land use change, livestock holdings, forestry practices, water and irrigation, land management and technology adoption, networks and farmer support, expectations about climate change, farmer values, norms and preferences, objectives and profitability, labour, demographics, education and community, and opportunities and challenges (Brown, 2015). The full suite of initial questions was considered, and those holding potential relevance to adaptation constraints were noted. A further suite of questions relating to expected changes in climate, challenges in accessing climate change information, expected changes in future land use and management practices, the perceived importance of profit, lifestyle, and environmental performance, past experiences of climate related stress, and the efficacy of institutions were developed and included specifically for the purposes of this study. These questions are listed in Table 5.4, while the full survey (216 pages) is available on request from Brown (2015).

Table 5.4: List of questions included within the 2015 SRDM specifically for the purposes of this thesis.

<table>
<tr><th></th><th>Survey Questions</th></tr>
<tr><td>Transaction Costs</td><td>
1). How easy is it for you to find authoritative information about how temperature and rainfall/snowfall may change in your area in the future? On a scale of 0 to 10, where 0 indicates it is extremely hard/impossible to find this information, and 10 indicates that this information is highly accessible.
2a). Which of the following best describes how you personally expect temperature will change in your region by 2050:
<table><tr><td>Average temperature will decrease</td><td>Little/no change</td><td>Average temperature will increase</td><td>I don’t know</td></tr></table>
2b). Which of the following best describes how you personally expect the amount of rainfall and snowfall in your region to change by 2050:
<table><tr><td>Average amount of rainfall and snowfall will decrease</td><td>Little/no change</td><td>Average amount of rainfall and snowfall will increase</td><td>I don’t know</td></tr></table>
3). Based on these predictions and your broader knowledge, which of the following best describes how you personally expect the prevalence of drought conditions to change in your region by 2050?
<table><tr><td>Substantial decrease in drought prevalence</td><td>Slight decrease in drought prevalence</td><td>Little/no change</td><td>Slight increase in drought prevalence</td><td>Substantial increase in drought prevalence</td><td>I don’t know</td></tr></table>
4c). What impact would the changes in drought prevalence you are expecting have on your farming system? Please select the best description.
<table><tr><td>Provide opportunities for new more profitable land uses</td><td>Increase profitability</td><td>Have little effect on profitability</td><td>Decrease profitability</td><td>Decrease profitability to the extent that other land uses are more profitable.</td></tr></table>
5). How confident do you feel that you or your successor will be able to adjust management practices on your farm in order to maintain the same land-use under the climate you expect to prevail in 2050? On a scale of 0 to 10, where 0 indicates that you are not confident at all and 10 indicates that you are very confident.
6a). Other than your current land-use, which of the following uses do you think your farm is next most suitable for?
<table><tr><td>Dairy</td><td>Sheep and Beef</td><td>Forestry</td><td>Horticulture</td><td>Viticulture</td><td>Dairy support</td><td>Sheep</td><td>Beef</td><td>Other</td></tr></table>
6b). If you changed all your land from (your current land use) to (answer to the previous question), how do you think this would affect your farm’s profitability?
<table><tr><td>Increase profitability by more than 50%</td><td>Increase profitability by less than 50%</td><td>Have little effect on profitability</td><td>Decrease profitability by less than 50%</td><td>Decrease profitability by more than 50%</td></tr></table>
</td></tr>
<tr><td>Motivation and Aspiration</td><td>
1a). To what extent are you motivated by producing high profits on your farm? On a scale of 0 to 10, where 0 indicates that profit is not an important motivator and 10 indicates that profit is an extremely important motivator.
1b). Among farms that are similar to yours, which of the following best describes your profitability?
<table><tr><td>Less profitable than average</td><td>More profitable than average</td><td>Top 30% most profitable</td><td>Top 20% most profitable</td><td>Top 10% most profitable</td><td>Top 5% most profitable</td></tr></table>
2). To what extent are you motivated by maintaining your farming lifestyle? On a scale of 0 to 10, where 0 indicates that maintaining your farming lifestyle is not an important motivator and 10 indicates that maintaining your farming lifestyle is an extremely important motivator.
3a). To what extent are you motivated by caring for the environment on your farm? On a scale of 0 to 10, where 0 indicates that caring for the environment on your farm is not an important motivator and 10 indicates that caring for the environment on your farm is an extremely important motivator.
3b). Among farms that are similar to yours, which of the following best describes environmental quality on your farm?
<table><tr><td>Below average environmental quality</td><td>Above average environmental quality</td><td>Top 30% best environmental quality</td><td>Top 20% best environmental quality</td><td>Top 10% best environmental quality</td><td>Top 5% best environmental quality</td></tr></table>
</td></tr>
<tr><td>Institutional Constraints</td><td>Please rate the following organisations on a scale of 0 to 10 in terms of their effectiveness in managing water resources in your area. 0 indicates that they are totally</td></tr>
</table>

	ineffective, 10 indicates that they are extremely effective. 1a). Central government 1b). Local government 1c). Industry groups such as Federated Farmers/Fonterra 1d). Local community groups 1e). Local farmers
Attitudes	1). To what extent do you think farm management practices in your area will change over the next 30 years? On a scale of 0 to 10, where 0 indicates no change from current farm management practices and 10 indicates an area-wide change away from current farm management practices. 2). To what extent do you think land use in your area will change over the next 30 years? On a scale of 0 to 10, where 0 indicates no change from current land uses and 10 indicates an area-wide change away from current land-uses.

5.4.1 Survey Design

In designing the initial SRDM, Brown *et al.* (2013) acknowledged that using multiple questions to assess single behavioural traits represents best practice in psychometric research. They noted that the Theory of Planned Behaviour provided a suitable model of farmers' decision making (see Pike (2008) for further testimony), and therefore attempted to assess the three central components of this model for each relevant behaviour, namely, attitude towards the behaviour; perceived behavioural control; and subjective norms. Space constraints in the survey meant that it was not possible to follow this approach for all of the behaviours relevant to this investigation. As will be further discussed in Section 7.3.3 however, attempts were made to combine multiple questions to form indices of the relevant behavioural traits.

5.4.2 Survey Distribution

The survey was designed and administered using a web-based platform. This approach took advantage of complex survey logic, in order to avoid asking redundant questions, and to allow a range of different respondents to move efficiently through the survey (Brown *et al.*, 2013). This meant that the survey had to be completed online, via telephone, or in person using a computer, tablet, or smartphone. While online surveys are known to elicit considerably lower response rates than telephone or in-person surveys, this was seen as the only feasible approach given the budget and timeframe of the project (Brown *et al.*, 2013).

The survey was sent to 65,000 email addresses of farmers listed in the National Animal Identification and Tracing database (1,831 responses = 2.8% response rate), 1,897 individuals who responded to the 2013 SRDM (636 responses = 33.5% response rate), and was advertised by a number of industry groups including Beef + Lamb New Zealand, the Farm Forestry Association, Federated Farmers, Horticulture New Zealand, the QEII Charitable Trust, and Rural Women (Brown *et al.*, 2016). For the first 2,850 completed surveys, the respondent could nominate a charity to receive a $10 donation in recognition of their time. The survey garnered 3,311 responses in total, 2,832 of which were from commercial farm owners and farm managers, the remainder being from lifestyle block owners or hobby farmers. Due to space constraints in the survey, a randomly selected 25% (708) of the 2,832 respondents were asked questions about climate change relevant to this study. Given the mixture of distribution techniques, it was not possible to determine an overall response rate. The sample of responses collected did, however, closely match the land use and geographical characteristics of the broader population captured in the 2012 agricultural census (Brown *et al.*, 2016). Another round of the SRDM is being distributed in 2017.

5.4.3 Biases

The strategy used to distribute the SRDM biases the overall dataset in a number of ways. Firstly, the dataset is biased towards farmers who use computers and email. While this is not ubiquitous, approximately 80% of the rural population had broadband internet access at the time of sampling (Brown and Roper, 2017). It is also likely that the survey was more frequently answered by household members who are more inclined to check emails. This may not align perfectly with those who dominate rural decision making. The dataset is further biased towards farmers who are registered on the National Animal Identification and Tracing database, and those who had answered the survey in 2013. Again, while this database captures a large proportion of farmers in New Zealand, it is possible that there are systematic differences between those registered on the database and those not. An obvious risk is that, given the major source of responses was a livestock database, non-pastoral agriculture could be under-represented. However, while drystock farmers are slightly over-represented in the data, the overall dataset closely matches population data from the 2012 census in terms of farmer age and industry (Brown and Roper, 2017). For a full description of the sample population, see Brown *et al.* (2016) and Brown and Roper (2017).

It is also possible that survey responses were affected by economic and weather conditions at the time (Cradock-Henry *et al.* 2015; Lee *et al.*, 2016). The six month period within which the SRDM was distributed is seen as sufficiently long to avoid major bias caused by short-term weather events in New Zealand. It should be noted, however, that northern parts of Canterbury in the country's South Island were experiencing a major drought in the second half of 2015. It should also be noted that the pay-out per kilo of dairy solids fell to its lowest point in ten years during the second half of 2015. The impacts of these climatic and economic conditions on the survey dataset are unknown, but they can be expected to have changed some responses relative to what could be expected under more 'normal' conditions. It therefore constitutes a potentially important form of uncertainty. Other uncertainties associated with the survey method are described in Section 5.6.

5.5 Semi-Structured Interviews

Semi-structured interviews were undertaken in order to understand the relevant processes constraining adaptation in the Hikurangi catchment. Specifically, these were used to understand the salience, origins, and processes of adaptation constraints as well as their interplay within the wider adaptation context. The results of these interviews were then combined to explore common themes and viewpoints held by members of the study population. These interviews were designed to explore issues and questions that arose from the socioeconomic surveys, and were flexible to allow for the identification and exploration of new questions that arose during the fieldwork itself. This flexible approach is commonly used as a way to capitalise on information that presents itself during research (Hay, 2000).

The findings of this initial period of fieldwork were also scrutinised by three experts in the agricultural economy of the Hikurangi catchment during a follow-up fieldwork period, which is described further in Section 7.4.3. This provided further triangulation of the initial findings and was a useful way to assess the trustworthiness and dependability of these findings (Bradshaw and Stratford, 2010).

5.5.1 Sample of Interviewees

Interviewees were selected using a snowball-sampling strategy, similar to that of Bradshaw and Stratford (2010). In this approach, farmers were asked to identify others in their community who may be either particularly adaptive or particularly constrained, and who may be happy to partake in the fieldwork. Those identified were then contacted by telephone. In line with the recommendations of Neef and Neubert (2011), the objectives and requirements of the study were kept in mind when involving participants, and care was taken not to interview farmers or stakeholders unnecessarily. Four farmers declined the invitation to partake in an interview, which biased the resulting data towards farmers who were more willing to discuss the issues described. This bias may, however, be small given that the response rate was higher than 88% when accounting for the 32 interviews conducted.

This snowball approach was initiated using networks established by Dr. Nicholas Cradock-Henry during previous research into climate change vulnerability and resilience in Northland. This initial sample was made up largely of farmers engaged in community groups, which, as Burges and Smith (2008) point out, is a valuable starting point for understanding the objectives and priorities of the wider community. This approach yielded a disproportionately high number of interviews with dairy farmers; therefore the initial sample was broadened by writing to 20 land owners, identified in the cadastral land ownership database, whose land was put to uses other than dairy. This yielded five responses, which, while lower than the response-rate achieved via telephone, was still considered high given the strategy.

In addition to interacting with a broad range of farmers, and following Nelson *et al.* (2014), farmers were asked to identify individuals, be they extension workers, land managers, financial service agents, local politicians or similar, whom they considered to be integral to the adaptation process. Those identified (referred to henceforth as 'adaptation agents' for simplicity) were then also approached to partake in the qualitative research. This sequence of interaction is similar to the progressive contextualisation approach used by Huigen *et al.* (2006), in which reasoning progresses from the central actors, in this case farmers, outward to other actors who influence their behaviour. Important findings of the initial farmer interviews were identified and cross-checked with adaptation agents to assess their robustness. This triangulation of results was an important way of establishing the rigour of the qualitative data gathered (Bradshaw and Stratford, 2010).

Unlike the socioeconomic surveys, the sample of farmers included in the qualitative research was not intended to be representative of the wider population. It was considered more important to interact with a broad range of farmer types than to ensure these types are represented proportionally (Bradshaw and Stratford, 2010; Zabala, 2014). Hay (2000) likens social reality to an orchestra, pointing out that valuable insights can be gathered by focusing on each individual instrument and assessing its contribution for a period of time. Focusing on individuals or groups who are otherwise dominated by the wider population enables an understanding of the multiple realities which make up society. The size of the sample was considered carefully; however Bradshaw and Stratford (2010) suggest that this should be secondary to the quality of the sample. As they point out (p.76): "there are few if any rules in qualitative inquiry related to sample size, and it depends on what is needed in the way of knowledge, on the purpose of the research, on its significance and for whom, and on logistics and resources".

A total of 38 individuals were interviewed across 32 separate interviews during the initial period of fieldwork. This number was considered sufficient for the purposes of this investigation, and compares favourably to the 17 interviews undertaken by Cradock-Henry *et al.* (2015) - a total which they note is comparable to, or more than, that achieved in similar studies examining stakeholder perspectives in agriculture. Of the interviewed sample, 32 interviewees were farmers and six were adaptation agents. All of the farmers interviewed were owner-operators, because this group was seen to have the most agency in adaptive decisions. This does, however, ignore the potentially important role of other family members, farm workers, and sharemilkers in these decisions. The interviewees spanned a broad range of ages and farm sizes. Some owned highly profitable portfolios of properties, while others were in the process of downscaling or exiting the industry because of a lack of economic turnover. One of the adaptation agents and seven of the farmers interviewed were female, while the rest of the interviewees were male. In order to safeguard the anonymity of the respondents, all of the survey responses are discussed in the masculine in this thesis.

5.5.2 Interview Structure

Topics including the existence, severity, origins, and processes of adaptation constraints were discussed with farmers and other relevant individuals during the semi-structured interviews.

Interviews range from sequential lists of questions to conversations with little formal structure (Smajgl *et al.*, 2011; Jupp, 2006; Dunn, 2010). Structure is provided to various extents by interview schedules which can be flexible and are ordered in a variety of different ways depending on the topics of interest. For example, in order to explore the development of settlement patterns in the Philippines, Hiugen *et al.* (2006) ordered their interview schedules chronologically, and explored the history of settlement and expansion over the respondents' lifetimes. By contrast, Bharwani *et al.* (2005) focused on identifying the most important factors influencing crop choices, which allowed respondents to identify these at the outset.

Before each interview was conducted, informal transect walks around the interviewees' farms, similar to those advocated by Kalaugher *et al.* (2013), were undertaken. During these walks notes were taken about the farmers and their farms in order to collect basic information about context and to establish rapport with the farmer before the formality of the recorded interview. The question schedule for these transect walks is available on request from the author.

Following Bharwani *et al.* (2005), the interview schedule used in this study sought at the outset to identify which factors farmers considered most important in the process of adaptation. This was achieved by first discussing whether the farmers had made changes to their land uses or management practices over their time on the farm, and whether they intended to make changes in the future. The farmers were then asked whether there were (are) any specific challenges they faced (would face) when changing land use on their farms. Once farmers identified what they considered to be their most important challenges, henceforth understood to be adaptation constraints, the origins of, and processes driving these constraints were discussed. The final section of the interview schedule focused on the processes underlying a number of adaptation constraints which, by their nature, were unlikely to be identified by the farmers themselves. These included constraints relating to information, cognition, and perception of climate risk, as well as ideological and attitudinal inhibitions. This ordering loosely reflects a hybridised 'funnel' and 'pyramid' structure (Dunn, 2010), which begins with straightforward and tangible questions about the farm, moving in to more abstract and general questions before addressing sensitive issues at the end of the interview. The question schedules for the initial semi-structured interviews and the three follow-up interviews are available on request from the author.

Because of its strong political associations and politicised interpretations in New Zealand (Milfont, 2012), care was taken not to explicitly discuss climate change until the final sections of the interviews. Further to this, in acknowledgement of the findings of Niles *et al.* (2013), and following the recommendations of Resinger *et al.* (2011), care was taken to distance the discussion of adaptation and local impacts from issues of mitigation. This approach also aligns with the recommendations of Dunn (2010), who suggested that it is most important to order interviews in a way that preserves rapport with the subjects. Following the approach of Burton and Peoples (2008), the interview schedule used in this study was implemented flexibly, and questions could be re-ordered or omitted entirely as more was learnt about the interviewees' situations. The interview schedules were piloted with one farmer from outside the study site, in order to test their appropriateness for assessing adaptation among farmers in New Zealand, in line with best practice (Dunn, 2010). The interview schedules were also discussed informally with a number of experts in agricultural economic research. Both of these processes resulted in multiple changes to the survey schedules.

All interviews were audio-recorded and transcribed verbatim. The dialogue was then analysed for broad themes by coding responses using the qualitative analysis software NVivo (as applied by Nelson *et al.* (2014) and Cradock-Henry (2011)), following the best practice recommendations of Cope (2016). The coding process was both deductive and inductive. An initial codebook was written reflecting adaptation constraints and important themes identified in the literature. As the interviews were coded, these 'analytic codes' (Cope, 2016) were then ordered, adjusted, added to as new information emerged , or removed when the theme did not appear in the empirical data. Once each of the interviews was coded, all of the coded content was revisited in sequence, reorganised, and sections of text with multiple themes were cross-coded to reflect this. Notes were taken throughout this process to record thoughts, possible relationships, and directions of enquiry to return to later. Coding also gave an opportunity to reflect on the research process and the positionality of the researcher during the interviews.

The coded data were then analysed both quantitatively and qualitatively. Content analysis was used to compare the frequency with which specific themes and subjects appeared during the research (Cope, 2016). The statements stored under each of the relevant analytic codes were then considered in depth, in order to understand the meaning and nuance of references to each topic. The results of this analysis are presented in Chapter 6.

5.5.3 Fieldwork Practicalities

The fieldwork was guided by a number of practical considerations. Semi-structured interviews and transect walks are time consuming for both the researcher and the participants. As Pike (2008, p.24) points out; "It is no myth that farmers are perhaps the most highly surveyed section of the population. The burden of information gathering is quite extensive". With this time burden in mind, and in line with the recommendations of Hoffmann *et al.* (2007), fieldwork for this study was undertaken between January and May to take advantage of a relatively quiet season for pastoral farmers in the North Island.

Farmers must weigh the benefits of participating in research against the opportunity cost their time entails (Neef and Neubert, 2011). Hoffmann *et al.* (2007) argue that if the results of research are distributed to people beyond those who participated in the research, then there is a case for remunerating participants for their contributions to this research. However, they go on to acknowledge that if participation is voluntary and free from further obligations, as it was in this study, then payment is usually unnecessary. No payment was, therefore, offered to participants in this study.

The decision not to remunerate participants for their time is likely to have influenced the sample of farmers who participated to some extent (Hoffmann *et al.*, 2007). As Neef and Neubert (2011) point out, poorer or struggling farmers are likely to be particularly concerned with meeting the needs of the farm and may be less likely to partake in research as a consequence. Furthermore, farmers decide whether to partake in research based on the expected benefits and opportunity costs which are affected by their livelihood situations and well as their political leanings, social environment, and public spiritedness (Neef and Neubert, 2011).

5.5.4 Research Ethics

Given the sensitive nature of topics such as farm financial performance and personal ideologies, an ethics assessment was undertaken prior to the fieldwork. Involvement in the research was entirely voluntary, and care was taken to ensure that participants understood the objectives of the research. It was also made clear to each participant that the immediate outcomes of the research were purely academic and were not linked to any particular development intervention or policy formulation. An information leaflet was delivered to every farmer at the point of initial contact so that they could make an informed decision about whether or not to participate. Prior to each interview, the interviewees were asked to sign the consent form, and give verbal consent to being audio-recorded. The project gained ethical approval from the University of Cambridge, and care was taken to uphold standards of ethical practice throughout the field investigation.

During the interviews, care was taken to be thoughtful towards a number of sensitive issues. Farm financial performance was approached cautiously, and efforts were made to ask whether respondents were comfortable discussing financial performance before it was questioned directly. Particular care was taken when interviewing challenged enterprises, and respondents were reminded that they were under no obligation to answer questions they felt uncomfortable with. The utmost care was also taken to ensure that the data collected were held securely and analysed so as to preserve anonymity.

5.6 Data Uncertainties

The data produced using surveys and semi-structured interviews in this investigation contain a number of uncertainties stemming from the resolution of the analysis, subjectivity, and reactivity. Assessing the constraints on adaptation at the owner-operator level introduces uncertainty in terms of data resolution. While the single owner-operator is the most appropriate level for analysis in this instance, as explained in Section 2.5.1, this level does not account well for influences on farmer decision making from family and farm workers, regulatory, or commercial interests, nor does it account for different ownership or management structures. These are known to influence farm decision making (Brown *et al.*, 2013; Pike, 2008). While many of these influences were discussed during the interviews, they were not the foci of inquiry.

The research techniques applied in this study are also likely to encounter problems of subjectivity and reactivity. Subjectivity is an inherent property of social research stemming from differing interpretations of the questions being asked, and different understandings of the systems being discussed (Gill, 1993; Sarantakos, 2005). Subjectivity is impossible to eliminate entirely (Sarantakos, 2005). It exists on the part of research participants because of deficiencies, error, and prejudices in their understandings of the topics discussed (Heckbert *et al.*, 2010). Subjectivity also exists on the part of the researcher, in this instance because he was raised and has studied and worked in an urban setting far removed from the realities and complexities of agriculture. As a result, the researcher's understanding of the issues important to agricultural adaptation are likely to differ from the understandings of farmers. The researcher may have interpreted the interviewees' responses differently from how they were intended, as meanings dependent on social and cultural understanding were lost.

It is particularly difficult to identify contextual factors that influence one's own subjectivity because these often form the basis of one's own understanding (Redman and Kinzig, 2003). Because of this, there are thought to be considerable advantages to studying communities other than one's own (Redman and Kinzig, 2003). Therefore, while the researcher could not appreciate the full richness or complexities of the system and meanings dependent on this understanding were lost, coming from a non-agricultural background allowed for a less predetermined perspective of certain aspects of the system.

Reactivity also contributes uncertainty, as respondents often present the version of reality that they think will advance their interests, or that they think the researcher wants to hear (Robinson *et al.*, 2007). Furthermore, respondents are likely to adjust the information they present depending on how they view the researcher (Neef and Neubert, 2011). For example, researchers can be seen as ignorant or naïve outsiders or potentially useful experts depending on the interpretation and attitudes of both the researcher and the participant (Neef and Neubert, 2011). Burges and Smith (2008) found that farmers' perceptions of the attitudes researchers held towards them were the most important factors in the success or failure of participatory research programmes. They also found that these perceptions could change over time and through interaction, as understanding is generated and trust built. According to Martin *et al.* (2011), the development of understanding and trust may be particularly difficult when the research makes use of models. Because of the timescale of interactions involved, models tend to lack transparency and may be seen as illegitimate or irrelevant as a consequence. While this is likely to have caused problems in this research, Dunn (2010) suggests that interviewing as a research method provides a valuable opportunity to show respect for participants by allowing them to define what they see as important and to find out more about the nature of the project.

The problems of subjectivity and reactivity can be minimised through careful research design and implementation (Hay, 2000). Burges and Smith (2008) suggest that being flexible, open-minded, and honest in dealings with participants is critical in minimising reactivity. It is also essential that this subjectivity is continually scrutinised and openly acknowledged throughout the research process, an approach called 'critical reflexivity' (Hay, 2000). According to Dowling (2010, p.31), being critically reflexive means "analysing your own situation as if it were something you were studying." In line with the recommendations of Dowling (2010), and using the questions she proposed as a starting point, a research diary was maintained during fieldwork.

Chapter 6

Constraints to Adaptation in Northland

This Chapter describes the findings of the qualitative research as they relate to the adaptation constraints identified in the literature. The first section describes the addition of new constraints which were not identified in the literature review. Section 6.2 reconsiders the salience of a number of constraints identified in the literature that found little support in the empirical data and compares the balance of evidence between the three overall categories of constraints described in Section 4.8.1. Section 6.3 examines each of the salient adaptation constraints, describes what the qualitative data reveal about their origins and processes, and describes how these data were used to design the constraints modelled in this study.

The model will be described in full in Section 7.2. The qualitative results are presented before this full description because the structures of the constraints that the model examines depended on these results. For the purposes of this chapter it is important to know that the model is called the Agent-based Rural Land Use New Zealand model, or ARLUNZ. As an ABM, it simulates the interactions of autonomous agents, which in this study represent farmers. These agents make decisions based on behavioural routines that can be adjusted by the modeller. In this study, constraints are modelled as behavioural rules that adjust the probability that farmers will change to a more profitable land use when one is available. These were designed using the qualitative information about the processes of each of the constraints explored in this chapter. Some constraints were also quantified based on this information, while others were quantified quasi-objectively through econometric analysis of the survey data, as Section 7.3 will explain.

6.1 New Categories

The adaptation constraints identified in the literature and presented in Chapter 4 provided the initial thematic framework, known as a 'node structure' used to code the interview data in NVivo. This structure was expanded and adjusted during the coding process. Most of the additions were to add detail or create more specific categories within the original adaptation constraints. The only new category added was a node for 'Labour', which, while not being a prevalent theme in the literature on adaptation constrains, was mentioned 66 times across 17 of the 32 interviews. The absence of labour issues from the literature on adaptation constraints may reflect the focus on institutional constraints and governance in the literature described in Section 4.8.

6.2 Relative Salience of Constraints

The proportional split of references between the categories of generic constraints, specific constraints, and transaction costs, as identified in the interviews, is shown in Figure 6.1. Generic constraints account for more than half of all references to adaptation constraints, while specific constraints account for slightly more than a quarter and transaction costs accounted for slightly less than one fifth. This proportional split is likely to be biased by the interview structures to some extent. As explained in the previous chapter, the first half of the interview schedule was designed to allow interviewees to identify constraints or challenges themselves without being prompted by the interviewer, while the second half of the interview schedule prompted farmers to discuss constraints which, by their nature, were unlikely to be identified by the interviewees themselves. Therefore some adaptation constraints were consistently discussed with each respondent while others relied on being identified independently. In this case, two constraints under the 'generic constraints' category were questioned directly in each interview, whereas only one constraint in each of the other two categories was consistently prompted. It is likely, therefore, that specific constraints and transaction costs are underrepresented among interview responses.

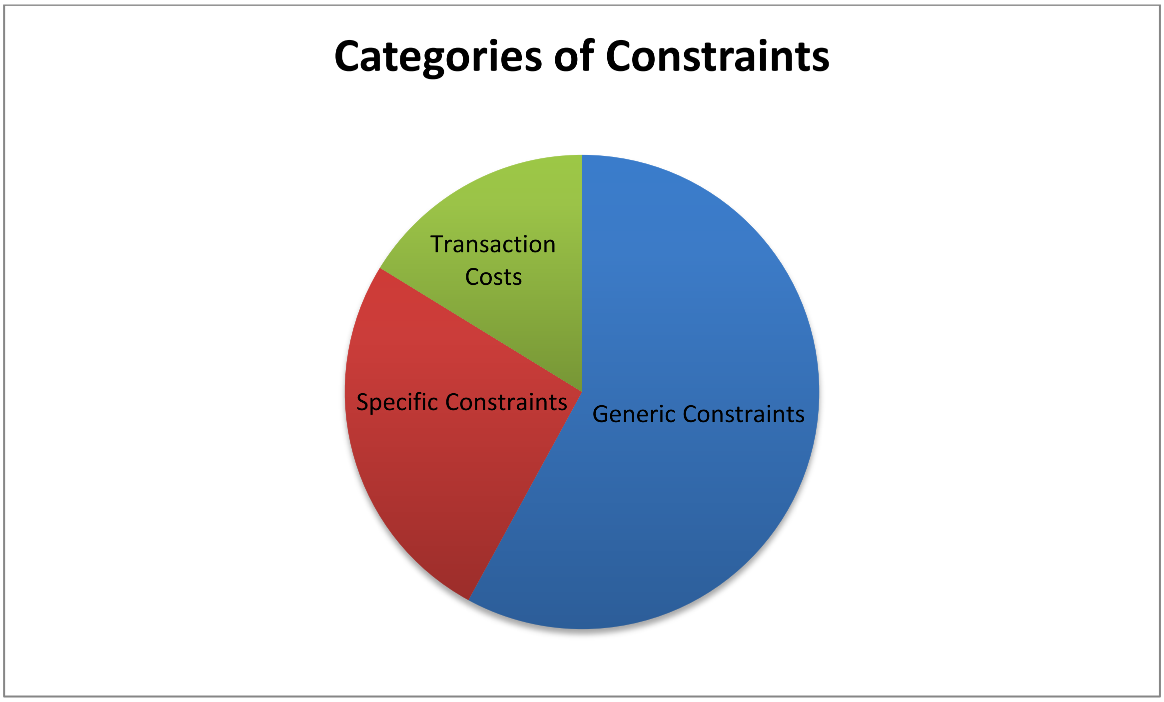

Figure 6.1: Proportion of references to adaptation constraints that fall under each category of constraints.

The number of interviews in which each adaptation constraint was mentioned, and the total number of times each constraint was mentioned across all the interviews, are shown in Table 6.1. The constraints are ordered by the total number of references across all interviews, and are shaded by the categories of generic constraints (blue), specific constraints (red), and transaction costs (green).

As explained in Section 4.13, a number of constraints identified in the literature found scant or contradictory empirical evidence in the Hikurangi catchment and they were not, therefore, included in the modelling exercise. These constraints are included in Table 6.1 for clarity. Three constraints, namely gender, tenure, and ideological constraints, were omitted because little evidence emerged of their relevance during the interviews. Two other constraints, namely experience constraints and cognitive constraints, found some empirical support during the interviews; however they were found to have no significant influence on adaptive propensity when tested quantitatively, as described in Section 7.3. While references to these omitted constraints are not discussed further in this chapter, full descriptions of the empirical evidence relating to each, and rationale for not including them further are available from the author on request.

Constraints included in the modelling exercise are highlighted in yellow in Table 6.1. Constraints marked with an asterisk were questioned explicitly during the interviews, while those not marked were independently identified by the interviewees. This convention is held throughout this chapter. It is likely that the constraints that are not marked with an asterisk were underrepresented because they were not necessarily considered by each of the interviewees. While the number of references is not a strictly valid measure of the salience of adaptation constraints, it does signal that some constraints are likely to be less important than others. These results are interpreted in the following sections, which describe the proportional split of references within each constraint category, and draw qualitative insights about the origins and processes of each of the modelled constraints.

Table 6.1: Adaptation constraints ordered by the total number of references across all interviews (henceforth referred to as 'references'. The constraints are shaded by category with blue shading representing generic constraints, red shading representing specific constraints, and green shading representing transaction costs. Constraints highlighted in yellow were included in the modelling exercise, while those marked with an asterisk were questioned explicitly during each interview.

Adaptation Constraint	Number of Interviewees	Number of References
Farmer Motivation and Aspiration*	30	282
Financial Constraints	29	163
Information Constraints*	31	150
Institutional Constraints and Governance	17	106
Perception of Climate Change Risk*	30	94
Labour	17	66
Scale Constraints	20	59
Perceived Self-Efficacy*	18	51
Behavioural Constraints	18	40
Response Lags	16	32
Experience as a Constraint	18	26
Cognitive Constraints	16	24
Cultural Constraints	12	21
Social Information	11	20
Technical Expertise	15	19
Disaster Experience	12	16
Past Experiences as Constraints	11	13
Adjustment Costs	8	8
Path Dependence	7	8
Ideological Constraints	2	2
Tenure	1	2
Gender	0	0

6.3 Origins and Processes of Constraints

6.3.1 Generic Constraints

Table 6.2 shows the number of references to each category of generic constraints, while Figure 6.2 shows this split graphically. Farmer motivation and aspiration was the single most referenced adaptation constraint. During the coding process, this constraint gained a number of sub-categories reflecting a wide range of individual motivations. One of these motivations was lifestyle, which was questioned directly when interviewees were asked how the main land uses in the region compare in terms of lifestyle. The constraint 'perception of climate change risk' was also directly prompted in each interview. Interestingly, however, it received fewer references than 'institutional constraints and governance', despite the fact that this constraint was not prompted in the interview schedule.

Table 6.2: Total number of references to each adaptation constraint under the category of Generic Constraints. The 'Sources' field refers to the number of individual farmers who referenced each theme.

Generic Constraints	**Sources**	**References**
Farmer Motivation and Aspiration*	30	282
Institutional Constraints and Governance	17	106
Perception of Climate Change Risk*	30	95
Labour	17	66
Behavioural Constraints	18	40
Response Lags	16	32
Cultural Constraints	12	21
Social Information	11	20
Disaster Experience	12	16

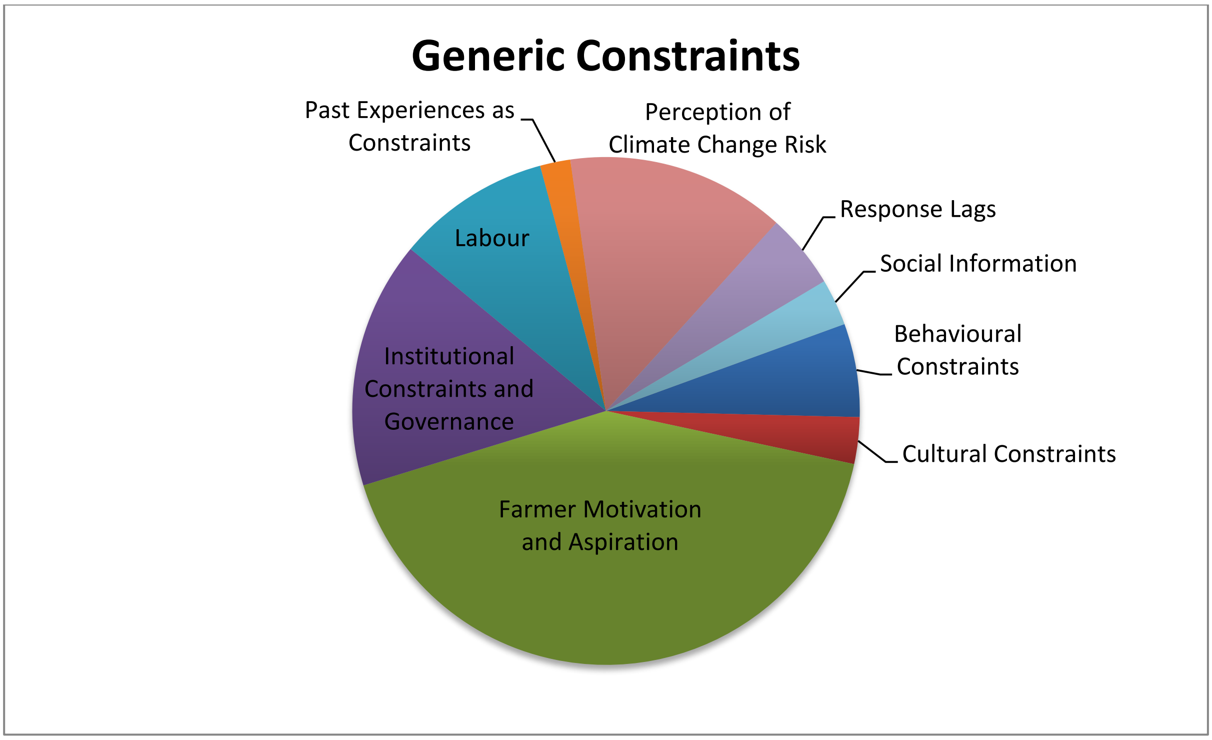

Figure 6.2: Proportion of references to each individual constraint under the category of Generic Constraints.

6.3.1.1 Farmer Motivation and Aspiration

Farmer motivation and aspiration was the single most cited adaptation constraint across the interviews conducted. References to motivation formed nine separate sub-categories during the coding process which are listed in Table 6.3. The dominance of 'lifestyle' as a motivation likely reflects its prompting during the interviews. However, even if lifestyle was mentioned in relation to each of the four main land uses in each of the 25 interviews with farmers, there would still have been 54 unsolicited references to lifestyle as a motivating factor in land use decisions. The importance of lifestyle echoes the findings of Bartolini *et al.* (2007) and Greiner and Gregg (2011) who found lifestyle to be the most important motivator among farmers in Italy and Australia, respectively. The next most cited motivation was profit. Smaller numbers of farmers cited environmental protection, pride in the land, diversification, income smoothing, production, and regulation as being important motivations.

Table 6.3: Important motivating factors in farm decision making listed by the total number of times each was mentioned during the interviews.

Motivation	Sources	References
Lifestyle*	25	154
Profit	23	52
Environmental Protection	11	21
Pride in the Land	8	15
Diversification	7	12
Income Smoothing	8	10
Production	5	8

Lifestyle

Responses relating to lifestyle generally described the dairy industry negatively, citing the long working hours and lack of time off as motivations to consider other land uses. One farmer commented "You're tied to a dairy farm, you've gotta' be there every day". An industry representative elaborated "… it's not only the early morning and the time, it's the tie, it's the commitment, that you cannot decide now I'm (going to) the beach. It can't be done tomorrow. You can't *not* milk your cows." There was compelling evidence that some farmers were willing to forfeit profit in order to avoid the difficult dairying lifestyle. One dairy farmer admitted: "well, inevitably you would forfeit profit to switch to beef and it's about what you can afford". One couple reflected on a dairy farm that they sold which was converted to less profitable maize. Asked about the motivation for this change, one of the farmers inferred laziness as a motivation by saying "he didn't want to be bothered milking because it's a bit of work." One farmer who switched from dairy to beef explained that "after four years we just got sick of running everything, just running around". Asked whether he would consider changing back to dairy if it were returning $5,000 per year more in profit he responded "If it was returning $50,000 or $60,000 less, I'd still go beef". Asked if he would think twice if the difference were $100,000, he reflected on the potential his farm would have for higher profits in dairy, but concluded: "we wouldn't change this farm".

The aversion to dairy was, however, not universal. A small proportion of farmers suggested that dairying provided the best lifestyle out of the four main land uses. One large dairy farmer explained "I enjoy the work, the mixture of the management challenge, the physical workout, the creativity of doing your landscape…" Another dairy farmer who had shifted to once a day milking explained that this change relieved some of the burden of continuous milking, saying "My main aim was for profit, and it coincided that the lifestyle was good…"

The lifestyle of dairy farming was most commonly compared to that of drystock farming. Drystock was generally seen as the ‘easiest’ of the main land uses and one that provides a good lifestyle. One dairy farmer admitted “I think most dairy farmers want to be beef farmers”. Asked which land use he would practise if they all returned the same profit, another dairy farmer responded “Well, beef… wouldn’t everybody do beef?.. Beef’s an easy lifestyle.” An industry representative linked changes from dairy to beef farming to farmer age, explaining that “you’ve got an aging farmer base in Northland. I suppose for some it became an opportunity to scale back big farming operations so they’re no longer in the shed”. The preference for beef farming existed among horticulturalists and silviculturalists too. One avocado orchardist explained his preference for beef farming over growing avocados, saying “it’s probably going to be less work”. When asked what he would do if all land uses produced the same return, one silviculturalist replied “… cattle, I’d just go cattle. Straight cattle”.

Farmers reported mixed opinions about forestry, with some identifying it as the least work of any of the main land uses, but many pointing to the lack of cash flow as a major drawback. One dairy farmer with experience in forestry explained “… if it was going to be the same forever then forestry would be easy… (but) the return is not ‘til the end so you’ve got to have some income for all those years…” For some, the lack of cash flow meant that they would be willing to forfeit profit in order to avoid going into forestry. One dairy farmer admitted that he would prefer to remain in dairy even if forestry were guaranteed to provide 10% more profit over the forest lifecycle. A number of farmers pointed out that because of the lack of cash flow, a secondary form of income would be necessary in order for forestry to become a viable land use option. Conversion to forestry was, therefore, restricted to the proportion of farmer agents that can be expected to earn at least 10% of their income from sources other than agriculture, based on the SRDM. This constraint is henceforth referred to as ‘Minimum Cash Flow’.

Some farmers, particularly those with experience in forestry, also expressed an aversion to forestry purely in terms of lifestyle. One dairy farmer reflected on his experiences working in forestry as a young man, saying “It’s a hard game played by hard men with hard things to play with. Cattle are a lot easier, a lot easier on men and a lot easier on family.” Another farmer for whom forestry was a secondary land use said “There’s no lifestyle in forestry, just plant the bloody trees and that’s it.”

Opinions about the lifestyle afforded by horticulture varied by crop. An avocado orchardist who was interviewed said that kiwifruit were “actually a lot more work-intensive than avocados”, explaining that his elderly neighbour had changed his kiwifruit orchard into a beef block to reduce his workload. He further admitted that kiwifruit would be substantially more profitable on his land than avocados were, but explained that “I don’t want the extra work, I’d rather be playing golf”. Farmers also expressed reservations relating to cash flow and risk associated with horticulture. One dairy farmer said that “when we were little we owned a kiwifruit orchard, and that was probably enough to put me off horticulture… one single thing can erode your returns miserably”. Horticulture was, however, seen to have lifestyle advantages. As one industry representative pointed out, you can “get a decent irrigation system going and go to the beach”.

On balance, drystock farming was seen most favourably by farmers in terms of lifestyle across all four main land uses. Agents were, therefore, programmed to be 10% more likely to accept advice to convert to drystock farming from another land use, and 10% less likely to convert from drystock farming to another land use. This constraint is henceforth referred to as ‘Lifestyle Preference’. It was difficult to separate farmers’ preferences for dairy and horticulture. Forestry was the least preferred lifestyle of the four main land uses, however the aversion to forestry was often related to cash-flow, which is accounted for by the Minimum Cash Flow constraint.

Environmental Protection

In line with the literature in section 4.9.1.1, environmental protection was seen as an important motivator by a number of farmers. However it was less frequently mentioned than either profit or lifestyle. Concern about the environmental impacts of farming differed greatly between farmers. Some linked environmental considerations to regulatory pressures. Other farmers held strong concern for the environment, over and above regulatory pressure. One dairy farmer explained “we are only guardians of the land; we are only stewards of it, so my footprint, while I am liking to make it look cool and be efficient, I don’t want to turn it into an environmental bloody disaster”. A number of farmers talked about incurring costs over and above regulatory compliance, or forfeiting potential profits in order to improve the environmental credentials of their farm.

Notably, concern for the environment was strongly held by Maori. As one farmer explained “Environmental compliance is fundamental to Maori and to me, too, I believe”. Another farmer, who was given the title “Kaitiakitanga” (guardian) by the local iwi (tribe) said that regardless of how much extra profit it could return, he would not consider switching to intensive monoculture dairying because of the importance he placed on his environmental reputation, particularly in the eyes of local Maori. He further explained “It’s probably like a religion...” The strength of environmental concern among Maori suggests that Maori farmers are less likely to consider changes to land use that negatively affect the local environment. A constraint was therefore added making Maori farmers less likely to accept changes to more intensive land uses. It was not possible to quantify this effect using the data collected, so a 10% reduction in the likelihood of accepting advice to change to more intensive land uses was used as a conservative estimate. This constraint is henceforth referred to as

'Kaitiakitanga' and its magnitude is further scrutinised in qualitative validation work described in Section 7.4.3.

Other Motivations

A number of other motivations were identified by the interviewees. However these are not described in depth here because they were not modelled in this study. Many farmers cited profit as a necessary objective, and related it specifically to age. Profit and age were, therefore, included in an index for aspiration which was tested econometrically as described in Section 7.3.4. Eight farmers described working to improve the farm because of the pride these improvements afforded, however there no way was found to quantify its influence using the data collected. Seven farmers mentioned diversification as an important motivation, however in its current configuration, ARLUNZ is unable to simulate multiple land uses on the same farm. Eight farmers mentioned income smoothing as a motivation for land use change. The hierarchy of lifestyle preference described previously included consideration of income regularity, therefore income smoothing is ignored as a separate category. Five farmers mentioned increasing production as an important motivator in farming, but again, this constraint was not widespread and there was no way to estimate the magnitude of the influence using the data collected.

6.3.1.2 Institutional Constraints and Governance

Institutional constraints were the second most frequently cited generic constraint. References to institutional constraints and governance were broken into three common themes: institutional assistance, regulatory hurdles, and institutional failings, as shown in Table 6.4. The theme 'regulatory hurdles' describes rules, laws, or regulations that require farmers to take actions that may reduce the return they could get from their land. Institutional assistance describes support provided to farmers by institutions or regulatory bodies. The theme 'institutional failings' describes the failure of institutions to effectively support farmers in maximising their economic returns. Regulatory hurdles were by far the most frequently referenced theme, followed by institutional failings. Institutional assistance was the least frequently referenced theme, suggesting that institutional involvement may be a net constraint on adaptation.

Table 6.4: Prominent themes in the references to institutional constraints and governance listed by the total number of times each was mentioned during the interviews.

Theme	**Sources**	**References**
Regulatory Hurdles	12	28
Institutional Failings	7	16
Institutional Assistance	4	9

The seven farmers who mentioned institutional failings largely referred to ineffective management within their own industry. These criticisms suggest that revenue made from the land is suboptimal because of failings in the institutions farmers interact with. There is reason to expect that these failings would be accounted for under the Ricardian framework, because they exist across a range of land uses in the baseline period. These failures are, therefore, ignored in the analysis.

A number of interviewees made it clear that there are likely to be regulatory limits reached if land uses change in the future. For example, there are regulatory limits placed on clearing new land in Northland. One forester explained that under the Resource Management Act (1991) “The Northland Regional Council… had the whole of Northland classed as… high value natural heritage... Basically it was protected”. In light of this, areas of the catchment classed as native forest in the baseline land use map were prohibited from changing to other land uses. This constraint was further scrutinised in qualitative validation exercise described in Section 7.4.3.

The nine references to institutional assistance came from three industry representatives and one farmer. They generally acknowledged that institutional support can be fickle and selective. To test the potential impact of institutional support and failings, an index of farmers’ opinions about the effectiveness of regional councils and local farmers in managing water resources was constructed. The significance of this index on adaptive propensity was then tested econometrically as described in Section 7.3.4.

6.3.1.3 Perception of Climate Risk

Interviewees were asked a number of questions about their perception of climate change risk. Specifically, they were asked whether they thought their farm was vulnerable to floods and droughts relative to other farms in the region. The responses were grouped into those who perceived themselves as being at more risk than average, less risk than average, or at about average risk. As shown in Table 6.5, the respondents overwhelmingly saw themselves as less vulnerable than average to climate related risks. This suggests that farmers in the region may underestimate the risk climate change poses. This finding conforms closely with the literature described in Section 4.9.1.4.

Interviewees who saw themselves as less vulnerable than average generally cited a specific aspect of their farm or management strategy to justify this perception. Some related resilience to experience. For example, one older farmer explained "when I first started farming we were still learning, we were young, but now I've had enough experience that… the flood comes in tomorrow we just keep rockin'…" Others related resilience to the production and storage of feed. For example, one large dairy farmer said "we have oats in the winter, so we've pretty much covered our bases for drought in the summer or if it's really wet in the winter". Some farmers cited local conditions as reason for complacency, one going as far as saying "the rest of New Zealand could be Sahara desert and we would still have water here".

Of the smaller number of farmers who saw themselves as more vulnerable than average, many cited the physical characteristics of the farm to justify this perception. Some predominantly hill country farmers acknowledged their vulnerability to drought. One dairy farmer explained that he only had "about 15 hectares of flat land. The rest of it's not steep but rolling so it tends to dry out quicker than a flat paddock…" Another farmer explained "We're vulnerable to floods because of our situation because of where we are… If the stop bank fails or the pumps fail then we're bloody vulnerable".

Another farmer who had recently sold his land in the Hikurangi Swamp reflected on the flooding he experienced in his time running the farm, saying "It's massive... It's pretty bloody hard... Climate change has done that to us". This exists as an interesting example of a farmer perceiving extremely high risk of climate change – possibly higher than the objective risk. However none of the other interviewees shared this perception.

Table 6.5: Number of sources and references to perceptions of climate change risk grouped relative to the average perceived by the interviewees.

Perception of Climate Related Risk	**Sources**	**References**
Less at Risk	23	45
More at Risk	6	8
About Average Risk	4	5

The interviewees were also asked whether they thought climate change posed a risk to productivity on their farm, and if so, how serious this risk was. The responses were grouped into those who perceived serious risk, those who did not think the risk was serious, and those who thought climate change may bring opportunities, as shown in Table 6.6. The split between these three categories in terms of the total number of references was remarkably even.

Table 6.6: Number of sources and references grouped by perception of climate change risk.

Perceived Seriousness of Climate Risk	**Sources**	**References**
Serious	6	7
Not Serious	6	6
Potential Opportunities	5	7

Of those who thought that that climate change poses serious risks to productivity on their farms, most cited increasing climatic variability, increased flooding, and higher risk of drought. One industry representative also mentioned failure to adapt as a potential risk, saying “Key risks are going to be drought… The risk goes that farmers don’t necessarily change their practices to accommodate for that. That will leave them very exposed for failure effectively.” Two of the farmers saw the risk of climate change as serious enough to affect their decisions about whether to farm in the region. One farmer who had recently sold land explained that “Climate change is exactly the reason we sold the low lying land”, elaborating that the increased risk of tropical cyclones flooding the area was the key risk he perceived. Another dairy farmer on the edge of the eastern hill country explained:

> “We are limited by our high winter rainfalls and poorly drained soil types and to a lesser extent by the summer dry, but if those extremes are accentuated further it will make it harder and harder to farm economically here… does our business need to look at somewhere else where we can manage those risks better, say, in Canterbury they manage rainfall by irrigating…?”

The view that climate change posed enough risk to affect the decision to farm in the area was not widespread, but these examples show that there is considerable diversity in the perception of climate change risk among farmers in the region.

Diversity was also clear between farmers who thought that climate change did not pose a serious risk to them. Some thought that the risk simply did not exist because they believed that climate change was a fiction. Others believed that climate change was occurring but thought that Northland’s geography, in particular the highly maritime climate, would dampen the effects of climate change relative to other areas. One of the farmers saw the risk as small because of his ability to adapt, saying “I expect to have to change the way I farm as climate change has an impact”.

Three of the five interviewees who talked about climate change leading to potential opportunities in the region described expectations that conflict with the current scientific projections. Specifically, they all thought that climate change was likely to bring increased summer rainfall. These expectations are, however, likely to be misplaced as the most recent and comprehensive climate projections for the region, described in Section 3.3, suggest that rainfall is likely to decrease in Northland. One avocado orchardist did correctly identify opportunities afforded by increasing temperatures, while a representative from a seed supply company identified the potential to change crop and pasture species to take advantage of any changes that materialise. One dairy farmer saw proactive adaptation as a particularly large opportunity, saying "Climate change, to me, is the best business plan you can have. While people are spinning their wheels about, (saying) "we're doing nothing", you can do something." These responses present further evidence of considerable diversity among farmers in terms of the perception of climate change risk. This diversity was simulated in the model by introducing a variable delay on land use change, with those holding expectations in line with projections enacting their decisions immediately, and those whose expectations differ from projections delaying their action in proportion with this difference.

6.3.1.4 Labour

Labour was commonly and independently identified as a major challenge in land use and management change. A number of farmers suggested that skills and training were lacking among many in the labour force. One dairy farmer explained "… we're not teaching at a level that enables them to come out with enough skills to add value to our product". Another farmer pointed out "It's actually not that easy to get skilled people. It's not a job for dummies." Four of the farmers interviewed admitted having trouble finding workers who were able to complete the necessary work. With this finding in mind, and with the exception of conversions from dairy to drystock which requires little labour, the rate of expansion of the area of each land use was restricted to 20% per five year time step.

A number of interviewees suggested that there were critical points of scale at which labour becomes problematic. Along with scale, labour requirements were also linked to age. A number of farmers also linked labour constraints to financial constraints. Data about farmer age, farm scale, and farm financial performance were therefore added to an index of labour constraints, which was then assessed econometrically as described in Section 7.3.4.

6.3.1.5 Response Lags

Response lags were referenced by a large proportion of farmers. Many farmers highlighted the necessity of response lags by pointing out that the speed at which changes are made affects the quality of the finished system. Asked why he incrementally improved the drainage infrastructure on his farm over a five year period, one farmer explained “It’s quite tricky to find the springs and get the layout of it right and if you try to do it all, you might not do as good a job.” The link between speed and quality was echoed by a drystock farmer who said “It all takes time just even the designing part of it. I’d just rather do it piece by piece and do it properly rather than wailing like an idiot and making a whole heap of mistakes and have to go and fix it up later.”

There was a clear link between response lags and financial constraints in the interviewees’ responses. Asked why completing a conversion from beef to dairy had taken almost a decade, one farmer responded “We had to chip away at it slowly just as we’ve had the money…” Asked whether he thought the conversion could have been completed more quickly if they had borrowed money he responded “Yeah, definitely”. This was echoed by another dairy farmer who said “More money, the quicker it is. The simple solution to it.” Based on this connection, financial index scores are used to add heterogeneity to the response lags affecting each agent.

Response lags differed by specific land use changes. A number of dairy farmers reported it taking a substantial length of time for their farms to reach their productive potentials after converting the land from drystock farming. The lags largely occurred because of the time it took to raise the pasture productivity. As one farmer said “You cannot get pasture that’s been running beef into dairy pasture immediately… you can pour a ton of fertiliser to the acre and it won’t achieve it… Building fertility in the ground and improving it, it’s just time really.” Reports of how long this took varied by farmer. One farmer explained that it took between five and six years to improve drainage on his land, saying “We did that on that 100 hectare block, so we’re doing 20 hectares every year.” Another couple who converted a mixed dairy and beef farm into solely dairy reported that this took them ten years to complete. Discussing the time it takes to re-grass a farm, a seed supplier who specialised in pasture improvement and frequently worked on dairy conversions explained “We aim for 15% in a lot of cases. We get around the farm in about eight years. If we can do that, we are right up with probably the most or as much new grass growing as we can handle.” Based on these estimates, the benefits of converting to dairy from drystock were reduced by between 25% and 50% in the first five year time step[5], and between 0 and 25% in the second time step. These reductions in payoff were annualised over a 25 year planning horizon, equating to a 5% to 15% reduction in payoff per time step. The strength of the constraint within these limits was determined by each farmer’s financial index, so that farmers who are less financially constrained reach full profitability more rapidly than those who are more financially constrained.

[5] Time steps in the ARLUNZ model are five years long, as is further justified and explained in Section 7.2.

One farmer who was considering converting part of his dairy farm to horticulture reported being deterred by the considerable time lags involved with establishing an orchard. As he explained "You've got to plant the shelter and put the drainage in and the irrigation and then plant the trees. Then sit and wait for three years or four years or whatever…" The benefits of establishing an orchard were therefore reduced by between 80% and 100% in the first time step depending on the farmers' financial index score. This is based on the logic that the orchard will take between four and five years to set up and so will at best provide returns in the fifth year of the time step. These reductions in payoff were annualised over a 25 year planning horizon, equating to a 16 to 20% reduction in payoff per time step.

One seed supplier who had experience converting a felled forestry block to pasture explained "it's probably taken five to eight years to actually get productive pastures…" The same seed supplier had been involved with the conversion of a tamarillo orchard to pasture, noting that this was a much quicker job and the pasture was productive within three years. Based on these reports, the benefits of converting from forestry to either drystock or dairy are non-existent in the first time step after the decision is made, while in the second time step they are between 40% and 100% depending on the farmers' financial index (assuming that pastures become productive after five years at best and eight years at worst). The benefits of changing from horticulture to drystock or dairy was reduced by between 40% and 80% depending on the farmers' financial index (assuming between two and four years' lost production), after which they are full. These reductions in payoff were annualised over a 25 year planning horizon, equating to a 20% to 32% reduction in payoff per time step for a forestry conversion and an 8% to 16% reduction in payoff per time step for a horticulture conversion.

6.3.1.6 Cultural Constraints

A number of interviewees reported being culturally constrained in their land use decisions. Cultural identities were linked to occupation. When asked about why he chose to run dairy cows on his land, one farmer responded "first and foremost I'm a dairy farmer…" This justification was echoed by another farmer who bought a beef farm and converted it to dairy. Asked why he changed land use he explained "We were dairy farmers, not beef farmers". There was some evidence that the cultural identity of being a farmer precluded other land use options within individual tenure cycles. In response to a question about whether he would consider planting forestry, one drystock farmer explained "I mean I'm not a forester. I like trees but I'm not a forester." Some respondents pointed out that cultural identities interact with specific aspects of different land uses. For example, dairy farmers who see themselves as hard working may not want to change to beef farming because it is seen as an 'easier' option. As one industry representative explained "you know, that whole cow versus [drystock] 'lazy farmer'…"

Based on this evidence, the likelihood of an agent changing land use within their farming lifecycle was reduced within ARLUNZ, making it more likely that land use change occurs either at the point of succession or sale. It was not possible to quantify this effect using the data collected, so a 10% reduction in the likelihood of accepting advice to change during a single tenure cycle was taken as a conservative estimate. This constraint is henceforth referred to as 'Cultural Identity' and its magnitude was further scrutinised in the sensitivity analysis described in Section 7.4.3.

6.3.1.7 Social Information

The references to social constraints in the interviews highlighted considerable diversity in the levels of social connectedness between farmers. A small number of the farmers interviewed also worked in agricultural services or contracting, giving them a broader and more detailed view across different farming practices in the region. One farmer explained "… we do top dressing, we have a digger that (covers farm roads) and all that sort of thing. We see what works and what doesn't… (it provides a) huge advantage, just massive." At the other end of the scale, a number of farmers admitted that they were quite isolated from others in their industry. One dairy farmer explained that there were no dairy farms with similar management objectives to his in the region, saying "We don't really mix a lot with farmers really". With this diversity in mind, information about the profits of other farmers visible to each agent varied based on the empirical data on social and geographical connections.

There was also evidence to suggest that information provided by social networks is often inaccurate. One farmer with contracting experience explained that farmers he spoke to were particularly inclined to report inaccurate costs if "they got ripped off and they don't want to tell anyone it cost them $100,000 when it should have been $50,000". Another dairy farmer gave more strategic reasons for withholding information, saying "I glean information from all sorts of people, but I don't willingly give those system changes that I am tinkering with to my neighbours or to anyone else because they are my competitors..." Withholding strategic information also occurred in the forestry industry, as one forester explained referring to timber pay outs "Everybody's very cagey about what they got." Based on this evidence, uncertainty was built into the information gathered through social interaction. The information on profit gathered through social networks varied by a random factor with a mean of 100% and a standard deviation of 10%. The magnitude of this constraint is further scrutinised in the sensitivity analysis described in Section 7.4.3.

6.3.1.8 Disaster Experience

All of the farmers interviewed had experienced multiple climate-related stressors between 2010 and 2015. The positive impact of floods and droughts on preparedness for future events identified in the literature in Section 4.9.1.5 was evident in the interviews. Unsurprisingly, past experiences were frequently linked to age and the length of time farming in the area. For example, one farmer who had farmed on the edge of the Hikurangi swamp for more than fifty years explained "Now I've had enough experience that we just, the flood comes in tomorrow, we just change our management and just keep rockin' and, um, still keep producing. So yeah look, we've just learnt how to manage them and that's probably the key…" Asked whether he thought they were more or less vulnerable to drought than other similar farms in the area, one drystock farmer replied "Probably less (vulnerable) now because we've learned the lessons over the last three droughts..." Talking about a severe wind event that damaged most of the avocado orchards in the region in 2008, one orchardist explained "We didn't know anything in 2000. Unfortunately if I don't have another [windstorm] for another ten years then all us that were around will probably be gone and they won't have a bloody clue what to do."

It is clear that the economic costs of climate related events are likely to reduce when farmers have experienced them in the past. Based on this evidence, data on the age of farmers and the length of their experience in farming were used to calculate a disaster experience index that was regressed against adaptive propensity, as described in Section 7.4.3.

6.3.1.9 Behavioural Constraints

Seven interviewees demonstrated potential behavioural constraints during their interviews. These instances were, however, narrowly focused on an aversion to management risks. The themes in the references to behavioural constraints overlapped considerably with the themes of uncertainty and risk, which were mentioned by a large proportion of the farmers interviewed. The majority of farmers showed some aversion to risk and many reported risk reduction as an important aspect of their strategic decision making.

Some farmers noted that there were differences in the risk profiles of different land uses and that this affected their land use decisions. Asked whether there was a profit difference at which he would consider changing his land from dairy to forestry, one hill country farmer replied "No, probably because I'd be too scared about forestry collapsing". In response to a similar question about converting land to horticulture, another dairy farmer replied "(it's) one of those things where you grow something for a year to harvest once and one single thing can erode your returns miserably. With these cows, a flood or a drought might knock us, but it doesn't wipe us out." Asked what motivated him to convert his farm from drystock to dairy, one farmer responded "A lot steadier income… beef's always been all over the place, same as sheep".

These findings reflect the literature reviewed in Section 4.9.1.2 suggesting that people tend to be more risk averse than would be financially optimal. With this in mind, behavioural constraints were assessed using data on risk tolerance collected in the Survey of Rural Decision Makers. These data were combined in an index which was regressed against adaptive propensity as described in Section 7.4.3.

6.3.2 Specific Constraints

The number of references to each adaptation constraint under the category of specific constraints is shown in Table 6.7, while Figure 6.3 shows this split graphically. Again, there was substantial disparity between the total numbers of references relating to each adaptation constraint within this category. Financial constraints were the most cited specific constraints. Interestingly, even though it was questioned directly in each interview, perceived self-efficacy was referenced fewer times than both financial constraints and scale constraints. This may be because the question about perceived self-efficacy was asked directly after, and in relation to, a question about the perception of climate change risk. The responses to these two questions were often conflated, and many respondents, particularly those who were sceptical about the science of climate change, found them difficult to answer.

Table 6.7: Total number of references to each adaptation constraint under the category of Specific Constraints.

Specific Constraints	Sources	References
Financial Constraints	29	163
Scale Constraints	20	59
Perceived Self-Efficacy*	18	51
Experience as a Constraint	18	26
Path Dependence	7	8

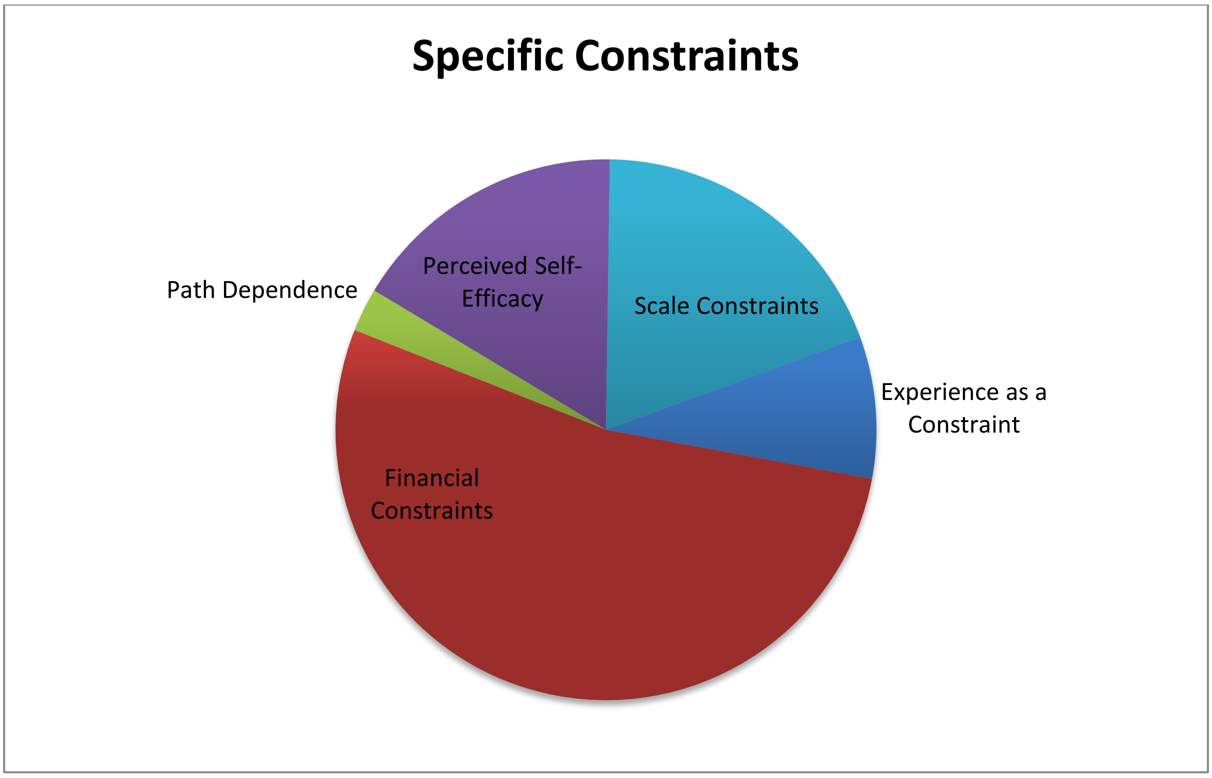

Figure 6.3: Proportion of references to each constraint under the category of Specific Constraints.

6.3.2.1 Financial Constraints

The literature reviewed in Section 4.9.2.1 suggested that financial constraints would be among the most commonly reported constraints. This was indeed the case, as they were referenced 163 times during the interviews. References to financial constraints were separated into those describing the costs of changing between specific land uses, and those describing the strategies farmers used to secure finance. These two themes are discussed in turn.

Specific Conversion Costs

The costs of changing land use from drystock to dairy were the most frequently described conversion costs, mentioned in 14 interviews. In general, these costs were seen to be substantial because of the large amount of new infrastructure needed to develop a dairy farm, and the work required to improve pasture productivity. As one industry representative explained "… there's the infrastructure challenge, you know, obviously races, fencing your streams, building the shed…" On top of the infrastructure costs, most drystock farms would require pasture improvement or re-grassing in order to become productive dairy farms. According to a seed supplier who was commonly involved in this type of development, the average cost of this improvement is "… probably in the vicinity of $1,000 a hectare… grass to grass is at least $1,000 a hectare… That's about as cheap as you can get it."

When combined, the costs of converting a drystock farm to a dairy farm can be extremely high. One dairy farmer explained that when he converted a beef farm to a dairy farm "we totally re-grassed it, fenced it… put a better water system in... We spent $150,000 on the effluent system… there's been fencing all the streams off. It's been a huge cost to our business. If I add them all up, this probably would be about $300,000 or $400,000 worth of costs…" Another farmer who ran beef on land that he admitted would be highly suitable for dairy explained "we can look at the costs of doing it, and it basically costs us roughly over two million dollars to convert it, by the time you build the cow shed and buy the shares. You'd have to put another house on it. You'd have to race every paddock, effluent and dealing with Fonterra..." Based on this estimate of $2,000,000 for a 347ha property, the costs of changing land use from drystock to dairy would be $5,763.70 per hectare. This cost was annualised over a 25 year planning horizon, giving a value of $229.23 per hectare, which was then factored into agents' land use decisions within ARLUNZ.

By contrast, the costs of changing land use from dairy to drystock were small to the point of being insignificant. A farmer summed up the process simply, saying "You put bulls instead of heifers and basically carry on". Based on this evidence, the costs of changing land use from dairy to drystock are disregarded in the analysis.

Four interviewees provided insights on the costs of planting forestry. A representative for a seed supply company explained that "… establishing a forest is quite costly because you have ongoing costs… It's basically blanket sprayed and then the plants are released. They quite often have a fungicide put over the top of the trees and a fertiliser in the first sort of 12 to 18 months." A different industry representative highlighted different costs, pointing out that "… you've got to make sure that at some stage you're going to be able to harvest those trees… You have to build a road to get logging trucks in there." Based on this evidence, the costs of conversion to forestry were seen as significant and were factored into this analysis. The costs of planting were based on estimates of 1,000 seedlings per hectare (Menzies *et al.*, 2001) at an estimated cost of $285 per thousand, plus 44 cents per tree planting costs, plus $400 per hectare fertiliser in the first year and $450 per hectare thin to waste (Askin and Askin, 2014). In total, therefore, the costs of converting from another land use into forestry were estimated at $1,575 per hectare. This cost was then annualised over a 25 year planning horizon, giving a value of $63 per hectare. This cost was factored into agents' land use decisions within ARLUNZ.

Four industry representatives commented on the possible costs of converting forested land to pasture. One representative for the dairy industry said "I'd say it's quite difficult… you've got to get rid of the stumps… Also you'd have to do your fencing, your water reticulation, fertiliser. You'll have a very low fertility base. Coming out of forestry you would argue it wouldn't have had fertiliser or lime for 25 plus years. There's a big capital cost… getting seed in as well." These costs were counted based on estimates provided in the Farm Financial Budget Manual (Askin and Askin, 2014). Fencing costs were estimated with an average paddock size of 6.25ha, each requiring 500m of new fencing at a contracted price of $6,380, which contributed on average $1020.8 per hectare. Water reticulation costs were based on surface (direct) pumping systems at $800 per hectare, and one 750L concrete trough per paddock (single cost $442.50, divided by the number of hectares per paddock comes to $70.8 per hectare). Fertiliser was assumed to be applied at 1,000kg per hectare at a cost of $342 per hectare and ground spreading cost of $35.55 per hectare. Lime was assumed to be applied at 1,000kg per hectare, costing $18.50 per hectare and $68.77 per hectare for fixed wing spreading. Based on estimates from the seed supplier in Northland, purchasing and sowing seed added a further $1,000 per hectare, which made the total per hectare cost of converting forested land to pasture $3,356.42. This cost was then annualised over a 25 year planning horizon, giving a value of $134.26 per hectare, and was factored into agents' land use decisions within ARLUNZ.

The costs of converting horticulture to pasture are also likely to be significant. One industry representative who had been involved in a conversion of this type reflected that it had been "… a big job, removing all the pergola-type structures and taking all the posts out… you've also got the different use of chemicals because you have residual strips under your crops… It does affect pasture for a while because they are designed not to let grasses and things invade." In total, he estimated that the conversion from horticulture into pasture cost around $3,000 per hectare. This estimate was annualised over a 25 year planning horizon, and applied within ARLUNZ.

While none of the horticulturalists interviewed had developed their orchards from pasture, the avocado orchardist interviewed had a good idea of the costs of doing this because he got a quote for the costs of developing kiwifruit on his land. The quoted cost for his 4.04 hectares was $350,000, of which the licence to sell kiwifruit commercially accounted for $150,000 and the remainder would go to infrastructure and labour. Based on this estimate, the cost of developing horticulture from pasture is taken to be $86,633.66 per hectare. This cost was annualised over a 25 year planning horizon, giving a value of $3,465.35 per hectare, and was factored into agents' land use decisions within ARLUNZ.

Financing Options

Evidence relating to financing options demonstrated that some farmers are not financially constrained, while others will either choose or be forced to undertake conversions out of cash flow. Using the SRDM data, the inability to undertake various farm developments because of financial constraints was combined into an index and taken as a proxy for being limited to cash flow (based on the logic that these developments would be possible if the farmers were willing or able to borrow from the bank, or use alternative finance arrangements). The impact of this index on adaptive propensity was then investigated econometrically, as reported in Section 7.3.4.

6.3.2.2 Scale Constraints

Scale was mentioned as a constraint in 20 out of the 32 interviews, and was associated with both advantages and disadvantages. The advantages referred to in the interviews reflected those mentioned in the literature summarised in Section 4.9.2.2. Specifically, having a larger farm allowed fixed costs to be split over greater production. A farmer who had built up a large area of land explained: "… it was about acquiring scale of production… I've always said that anybody who's below average of the industry in terms of scale becomes at risk." Another dairy farmer made a similar assertion, saying "You need to be doing, like, 100,000kgs milk solids out of a farm to make them economic".

There was also evidence to suggest that smaller farms needed to focus on intensive land uses such as dairy in order to support livelihoods. When one small hill country dairy farmer was asked whether he would ever consider moving into drystock or forestry, he replied "scale is too small and would never make a return". Based on this evidence, owners of farms of less than average size were programmed to be less likely to accept suggestions to change to a less intensive land use. The order of intensity from highest to lowest was dairy; horticulture; drystock; forestry. This reduction in likelihood occurred in proportion with the scale percentile the farm was in.

6.3.2.3 Perceived Self-Efficacy

Perceived self-efficacy was questioned explicitly in each interview. Following a question about climate change, respondents were asked whether they thought they were able to manage the impacts of severe weather in the current climate. The interviewees sometimes found this question difficult to answer and frequently reverted to talking about climate change, meaning that the direct response rate to this question was not high. Despite this, those who did directly answer the question provided strong evidence that perceived self-efficacy may constrain adaptation in this context.

References were split into those that demonstrated high perceived self-efficacy and those that demonstrated low perceived self-efficacy, both of which can constrain adaptation when they depart from a person's actual ability to adapt. As shown in Table 6.8, approximately twice the number of references demonstrated high perceived self-efficacy than low perceived self-efficacy.

Table 6.8: Comparison of the number of references to, and sources citing, high perceived self-efficacy and low perceived self-efficacy.

Perceived Self Efficacy	Sources	References
High	14	17
Low	7	8

Among the references to high perceived self-efficacy, the respondents were generally cautious in the assessment of their own abilities. None of the references gave clear reasons to suspect that the farmers held unrealistic perceptions of their abilities to adapt. Responses often cited specific flexibility in management systems or widely-used adaptation strategies that could be employed.

Constraints on adaptation were more evident in the references to low perceived self-efficacy. These references generally reflected a fatalistic attitude in relation to climate extremes and climate change. While it is the case that individual farmers have little influence over the course of climate change, they are in a position to mediate how changes affect their production. Despite this, a number of farmers cited the lack of influence over climate to justify the attitude that there was nothing they could do to change the impacts. In some cases, they even contradicted this view in other parts of the interview. For example, reflecting on a windstorm that damaged much of his crop, one orchardist explained "I had this lady come around from Radio New Zealand after the storm. She couldn't understand my flippant attitude towards it. I just said 'Look, there's absolutely nothing I could have done about it." Despite this attitude, the same orchardist also implied that he had learnt from the experience and was in a better place to manage future events, saying "You also need gaps in your shelter belt, one thing we found from that storm, the wind was getting into the block, you could see it was going like a vortex, it had nowhere to get out. You need little gaps…"

One farmer said that he did not look at climate projections "only because I have no control over (them)". Another farmer cited uncertainty in the projections as a reason to carry on as usual, saying "… no one actually knows what's really going to happen until it does happen. I tend to worry about it when it does happen." Based on this evidence, an index for perceived self-efficacy was constructed based on SRDM data. The impact of this characteristic on adaptive propensity was then assessed econometrically, as described in Section 7.3.4.

6.3.2.4 Path Dependence

As explained in Section 4.9.2.2, while path dependence was not mentioned as frequently as other specific constraints, there is reason to believe that it is a particularly important constraint among dairy farmers. The large capital and infrastructure investments needed to develop a dairy farm described in Section 6.3.2.1 were commonly cited as reasons to continue dairying, despite the fact that they are sunk costs. One dairy farmer who thought that horticulture could be more profitable on part of his land justified remaining a full dairy operation by saying "I guess all the capital infrastructure and things have been put there to milk cows". Another dairy farmer explained that "Basically I look at them that if you've got a cow shed that's the factory. You might as well have the cows. You can run beef anywhere, but if you've got a cow shed then you put many cows through it, so you make the best use of the land you've got." Another dairy farmer referred to the advantages of incremental improvement and investment in herd genetics, explaining "Our herd's built up with 50 years of breeding, and you can't get rid of them, you can't just go and buy another herd… there's a lot of momentum…" From these responses it is clear that land use decisions are path dependent, particularly among dairy farmers given the large investments in infrastructure and herd genetics. This inference was tested econometrically using SRDM data to find out whether there was a significant difference between dairy and other land uses in terms of land use change propensity.

6.3.3 Transaction Costs

Only two constraints from the category of transaction costs, namely information constraints and technical expertise, were modelled in this study. The number of references to each is shown in Table 6.9 and split graphically in Figure 6.4. More than 85% of these references relate to information constraints. This split may understate the salience of technical expertise, as information constraints were questioned directly in each interview, while technical expertise was not.

Table 6.9: Total number of references to each adaptation constraint under the category of Transaction Costs.

Transaction Costs	**Sources**	**References**
Information Constraints*	31	150
Technical Expertise	15	19

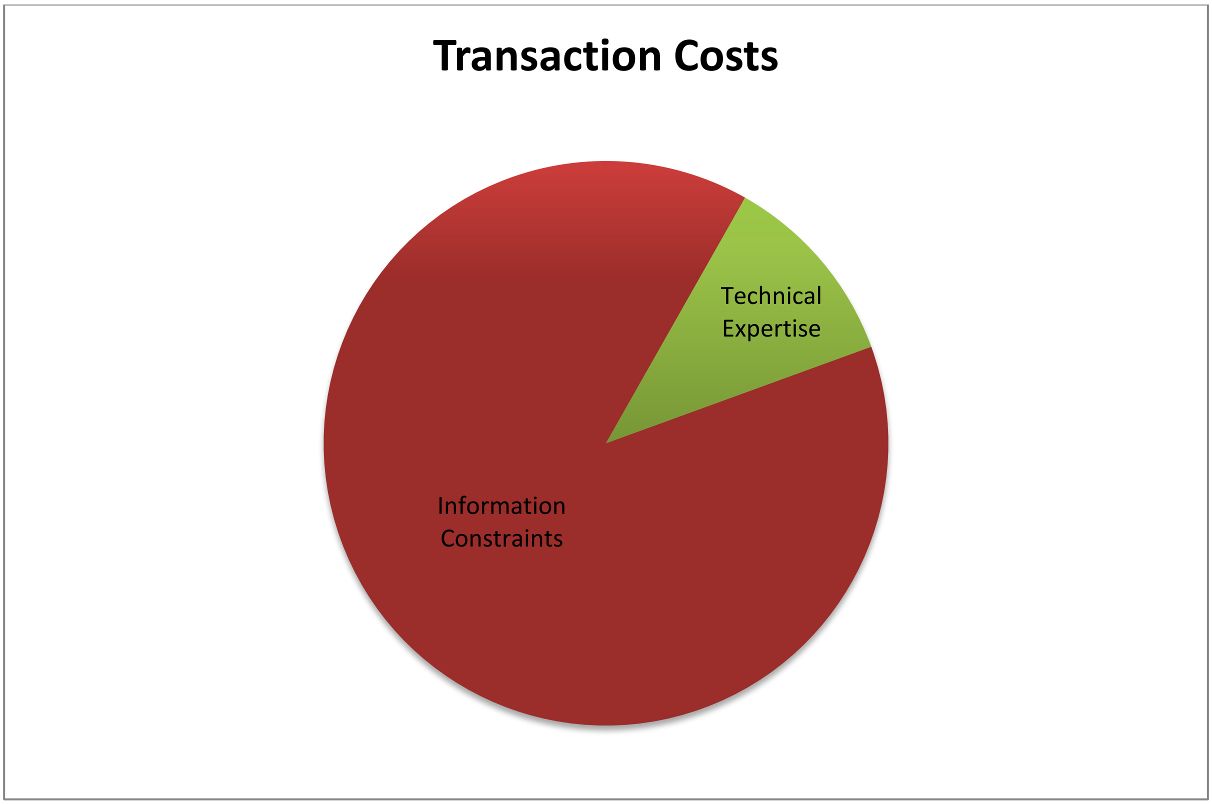

Figure 6.4: Proportion of references to each constraint under the category of Transaction costs.

6.3.3.1 Information Constraints

Each of the interviewees was asked explicitly about whether the availability or accessibility of information constrains their adaptive decision making. The farmers interviewed were asked whether they gather information about how climate change may affect agricultural conditions in the region, and if so, where they got this information from. Industry representatives were asked whether their organisation provides information about possible changes in climate in the region. These questions were commonly followed by questions about whether they thought this information was credible, easily interpretable, and/or salient. The results are broken into those statements relating to information about climate change and those relating to information about the process and benefits of land use change.

Climate Change Information

Responses from farmers to the question about whether they gather information about how climate change may affect agricultural conditions in their region were broken into those who do look at projections, those who do not look at projections, and those who do not believe the projections are credible, as shown in Table 6.10. Only three farmers said that they gathered information on how climate change might affect agricultural conditions in their region. Of those three, two said that this information had little impact on their decisions. Referring to climate change projections, one said "You look at them, you think about them, but whether you take any action on them or not…

generally no, I just keep doing what I do". Only one farmer used projections in long term strategic decision making, saying that he was re-considering the location of his business with the intention of moving somewhere where increasing variability under climate change could be managed more easily.

Table 6.10: Comparison of the number of farmers who look at climate change projections with those who do not look at climate change projections and those who do not believe climate change projections are credible.

	Sources	**References**
Does Look at Projections	3	7
Does not Look at Projections	19	23
Does not Believe Projections	10	12

During the 25 interviews with farmers, 19 farmers said that they did not gather information about how climate change might affect agricultural conditions. Among these responses, one farmer explained "Don't get me wrong, I'm definitely not interested in four or five years out. Anything can happen in that time. The world could blow up for that matter." A number of farmers justified not looking at projections using a fatalistic outlook. For example, one farmer said "it's gonna' change regardless" while another said "We farm more what we've got control over more than what we don't have control over".

Among those who did not look at climate change projections, many were sceptical about whether the projections were credible. A small number of farmers held strongly sceptical views. For example, one farmer said "… to be honest, my opinion is that global warming is a lot of bullshit…" Some farmers thought that the information had been politically manipulated. One said "I don't trust the information, I'm afraid… There's a lot of good information coming saying how bad it's going to be, and there's some equally solid information that seems to be hidden". Other farmers were more circumspect, questioning aspects of the science but remaining undecided about the credibility of projections. For example, one self-described denier said "I shouldn't deny it totally… I suspect it will get warmer, but not by as much as they say. I'm dubious as to whether it's man-caused or whether it's just nature going through a natural process."

The responses described above show that there is massive diversity in farmers' opinions of climate change projections. Very few farmers both gather and use information about how agricultural conditions may change under climate change. A much larger proportion are sceptical about whether the projections are credible, and a small number seem convinced that they are not. This suggests that the vast majority of farmers are likely to respond only to *observed* climate. Given that climate is defined as an average of conditions over 30 years, changes in response to observed climate are likely to substantially lag changes in conditions. Using the simplifying assumption that changes will be linear, the moving 30-year average of *observed* climate is likely to trail the current conditions by 15 years, or three time steps in the ARLUNZ model. This inference is tested quantitatively using questions in the SRDM about the ease of finding credible information and expectations of changes in temperature, rainfall and drought conditions. The impact of these climate change information constraints on land use change propensity were then assessed, as described in Section 7.3.4. Based on the results of this assessment, those who misidentified the direction of projected change were prohibited from changing land use until alternative uses were shown to be more profitable for three consecutive time steps in the ARLUNZ model, while no additional constraints were placed on those farmers whose expectations aligned with scientific projections.

Information about Land Use Change

Information about the process and benefits of land use change appears to be far more abundant and more frequently utilised than information about climate change. Asked how easy information about different land uses was to access and interpret, one farmer reflected on recent advances, saying "… years ago we had to pick up and do a lot of reading and ringing on the bloody phone and talking to people, but now with the internet you can find out anything and everything… for instance the fodder beet was one of them you can go on YouTube and look up and see how they grow it and harvest it…" Another farmer pointed out advances in computer model assisted farming, saying "… we model everything through the Farmax [model]… It will tell you if you want to grow an animal at a kilo a day you will need this much grass at this time of year."

Despite these recent advances in information sharing, the farmer who used Farmax also pointed out "it's not as [commonly used] as it should be. There's a lot of guys there that's still a bit scared of it… Farmers generally are very hands-on sort of people. Some of them just don't like computers. There's still a lot of them out there that don't handle them." Furthermore, while information relevant to agriculture is abundant, a number of respondents pointed out that it is not necessarily cheap or easy to interpret. One farmer explained "It takes a hell of a lot of energy. What I've started to do is engage into private/public partnerships with organisations like Landcare Research, like NIWA, places like that… It's hugely expensive, massively expensive on personal capital, non-earning capacity."

A number of organisations provided information about the process and benefits of land use change. A representative from DairyNZ said:

> "… we have a whole website full of information… DairyNZ employs three consulting officers [in Northland] and their job is to get out there in front of farmers… we give them booklets up to the kazoo about reproduction and pasture management, pasture renewal, and kaikuyu management… everything we put out is freely available for farm consultants as well."

Despite its abundance, many farmers questioned the quality, and some questioned the independence of the information provided by the institutions they interacted with. One farmer suggested that DairyNZ were under the influence of agrochemical companies, while another said:

> "What [DairyNZ] have done is bugger up [agricultural] research… they used to be the science where we got all the information from. We are now based with advertorial science running New Zealand's dairy industry… it's sponsored by people who are putting the product in there, that only comes out with a preconceived result."

When asked who farmers would go to for information about changing land use, a representative from an environmental organisation replied, "Possibly DairyNZ, regional council, Federated Farmers possibly." When questioned about whether this was because he thought they provided good advice, he made the pointed correction "That's I believe who they'll go to."

These findings demonstrate that there is a considerable amount of information available to assist farmers who are looking to change land use, but many farmers are suspicious of its independence. This suggests that a proportion of farmers are unlikely to trust, and therefore heed, the information provided by agricultural institutions, which may increase the information costs of land use change. The effect that this has on land use change propensity was tested using SRDM questions about whether farmers had avoided changes in the past because of a lack of advice or demonstration of the benefits of alternative management strategies.

6.3.3.2 Technical Expertise

A consistent theme throughout the responses was that there were costs associated with learning a new land use that could only diminish through experience. One farmer who decided to shift away from an expanding horticultural region to continue dairy farming said "… I guess I was observing people who saw the gold at the end of the rainbow but had no skills and were failing at horticulture, and I thought, I don't want to be one of those". Another dairy farming couple who had recently diversified into kiwifruit said they still had "a lot to learn. We still haven't learned half enough." Another dairy farmer who had diversified into beef farming said "It's not rocket science, but it still takes a bit of learning. You'll make a few cock-ups and that will cost you a few thousand bucks." Reflecting on the management changes required to convert land from dairy to drystock, a representative of the dairy industry said "… given my experience, it has been challenging for them. I'm gauging that from trying different crops and the result of the crop… there's not a lot in that initial uptake that has true success." This evidence suggests that farmers who have low technical expertise are likely to see reduced profit in the short-term if they change land use. The impact of technical expertise on adaptive propensity was tested using SRDM data, as described in Section 7.3.4.

Chapter 7

Modelling Approach

While this study highlights problems with standard approaches to modelling adaptation, it is acknowledged that modelling is essential for understanding social-ecological systems. The physical, biological, ecological, social, and economic systems that comprise SES are too complex to investigate analytically (Johnson, 2000; Bharwani *et al.*, 2005; Morgan and Daigneault, 2015). Models are able to provide simplified representations of these systems through which specific processes and phenomena can be analysed (Anastasiadis *et al.*, 2013; Bharwani *et al.*, 2005). As Gurung *et al.* (2006, p.2) point out however, each model is simply “a given kind of representation among other possible ones”. It is important, therefore, to describe models fully so that those who use the information they produce are able to understand how this was derived, and in turn, judge whether the models are valid for their applications.

This chapter provides a description of the modelling approach used in this study, framed by a discussion of alternative methods. It begins by describing agent-based modelling in broad terms before identifying the advantages of this approach over a range of alternative modelling approaches. The model used in this study is then described, followed by an explanation of the use of empirical survey data to form indices on which quasi-objective mathematical constraints were developed. The verification and validation procedures are then explained, followed by an explanation of uncertainties, and a description of the computational experiments designed to explore the model’s functions and understand the strength of its findings.

7.1 Justification of Modelling Approach

7.1.1 Advantages of Agent-Based Modelling

For the purposes of this study, ABM has a number of advantages over traditional economic modelling approaches. As explained in Section 2.4, model studies assessing the economic impacts of climate change generally estimate adaptation exogenously using either econometric or Ricardian approaches that assume rational choice. Because of the problems of this assumption outlined Chapter 4, neither of these approaches is considered appropriate for the current investigation. ABMs allow for departure from the rational choice assumption underlying econometric and Ricardian approaches (Reed *et al.*, 2013; Heckbert *et al.*, 2010a; Brown *et al.*, 2013).

ABMs are based on multi-agent systems which were a focus of research in the field of artificial intelligence as early as the 1970s (Acosta-Michlik & Espaldon, 2008). The approach simulates social phenomena and has become popular in the social sciences (Acosta-Michlik & Espaldon, 2008). According to Janssen (2004, p.156), ABM can be defined as:

> "the study of systems that are populated with heterogeneous populations of agents, and with their environment, on the basis of internalised social norms and mental models, internal behavioural rules and cognitive abilities, and formal and informal institutional rules that affect how agents interact."

Agents are the units of analysis within ABM (Railsback and Grimm, 2012). They can represent human actors, non-human actors such as livestock or forests, or passive entities such as mineral resources (Janssen, 2004). According to Parker *et al.* (2003), human agents have three common characteristics within ABMs: they are autonomous in their decision making; their decisions affect and are affected by their environments; and they interact and communicate with one another. Agents' behaviours are based on models of cognition that range in complexity from basic stimulus-response decision making to proactive adaptation (Parker *et al.*, 2003). These models of cognition comprise behavioural rules which can be probabilistic (Green, 2013). Agent decision making can also be adaptive, as ABMs may allow these choices to evolve over time in response to new information (Bharwani *et al.*, 2005; Heckbert *et al.*, 2010a).

In addition to probabilistic behaviours, inter-agent variability can be programmed when agents have different decision criteria based on their defined characteristics. In many cases, this heterogeneity between actors is a critical driver of macro-level outcomes (Filatova at al., 2009; Tran *et al.*, 2013; Parker *et al.*, 2003). By contrast, traditional economic models are poorly suited to simulating heterogeneity between actors (Berger and Schreinemachers, 2006; Heckbert *et al.*, 2010). This shortcoming has been labelled as one of the key deficiencies of existing land use and land cover change models (Morgan and Daigneault, 2015).

Another specific strength of ABMs is their ability to simulate social interaction between agents and across landscapes (Berger *et al.*, 2007; Parker *et al.*, 2003; Robinson *et al.*, 2007; Brown *et al.*, 2013). Agents may be programmed to interact within a market, partaking in transactions when these are perceived to provide benefits (Nolan *et al.*, 2009). Social interaction is particularly relevant for a number of aspects of adaptation, including the diffusion of technologies, social learning, and collective action (Darnhofer *et al.*, 2010; Rogers, 1983; Schreinemachers *et al.*, 2009).

ABM provides a promising approach to modelling agricultural change because it allows researchers to assess the macroscale implications of microscale behaviours (Parker *et al.*, 2003; Brown and

Robinson, 2006; Heckbert *et al.*, 2010a; Heckbert and Bishop, 2011). ABMs have been seen as promising tools in the field of ecological economics. Heckbert *et al.* (2010a, p.43) state that ABMs have the potential to "understand how social-ecological systems function and can quantitatively explain many of the deviations that ecological economics takes from mainstream disciplines". They have also been seen as valuable in the assessment of climate change adaptation (Bharwani *et al.*, 2005; Acosta-Michlik and Espaldon, 2008). Reed *et al.* (2013, p.74) state that "By coupling models such as agent-based models with biophysical and climate models, it is possible to model which adaptation options are likely to be adopted where, and consequently how they may mitigate the effects of climate change". Furthermore, relevant to the focus of the current study, Berger and Troost (2014, p. 324) state that ABMs "provide a simulation approach for providing… local level assessments, [that consider] important micro-level constraints such as environmental externalities, limited adaptive capacity, and behavioural barriers".

A further advantage of ABMs, particularly those coupled with spatial visualisation software, is that they are often easier for stakeholders and policymakers to engage with and understand than standard economic models (Parker *et al.*, 2003). Green (2013) suggests that the flexibility and potential for policymakers to engage with the modelling process mean that ABM is likely to become more common in applied policy research. According to Nolan *et al.* (2009, p.426), these advantages and the accelerating development of ABM techniques mean that "It is an opportune time to get involved in this new form of computational modelling, a time not unlike the explosion of econometric work begun in the 1960s…"

7.1.2 Alternative Modelling Approaches

A number of alternatives to econometric or Ricardian models exist, however none provide the advantages that ABM is capable of in this instance. Equation-based models differ from econometric or Ricardian techniques, however they struggle to include complex behavioural rules because they rely on reaching equilibrium solutions (Parker *et al.*, 2003). These models quickly become intractable when feedbacks between heterogeneous agents are included (Railsback and Grimm, 2012; Parker *et al.*, 2003; Nolan *et al.*, 2009). The assumption that equilibrium solutions exist is also problematic because, as Parker *et al.* (2003) point out, complex agricultural systems are unlikely to ever reach equilibrium. ABMs, by contrast, are highly flexible because agent behaviour is defined by sets of rules that can be adjusted without needing to reach equilibrium solutions (Janssen, 2004; Heckbert *et al.*, 2010b; Parker *et al.*, 2003). This flexibility allows ABMs to explore a much broader range of questions than equation-based models (Nolan *et al.*, 2009).

A number of researchers have sought to specify adaptations within process models using mathematical programming. For example, Kelly *et al.* (2005) modelled adjustment costs under climate change using a Bayesian learning simulation to approximate how farmers learn from changes in weather conditions over time. In more recent work, Fitzgerald *et al.* (2009) modelled the adaptation potential of dairy farming in Ireland, allowing farmers to adjust management practices including stocking rates, feed production, and fertiliser regimes. While process models contribute valuable understanding, it is widely acknowledged that they are incapable of including some adaptations (Kelly *et al.*, 2005). Unspecified adaptations are generally assumed to be optimised, meaning that process models are likely to overestimate farmers' responses to climate change, albeit to a lesser extent than Ricardian approaches (Kelly *et al.*, 2005). Furthermore, process models generally assume straightforward cause-and-effect relationships between stimuli and adaptation responses which are unlikely to occur in practice (Adger *et al.*, 2013).

Models using goal-driven functions based on mathematical programming provide an alternative to the proscriptive and limited treatment of adaptation in process models (Schrinemachers and Berger, 2006). When applied to agriculture, the objective function of mathematical programming is often the maximisation of catchment profits, benefits, or utility (Berger *et al.*, 2010; Daigneault *et al.*, 2012). This objective function can be constrained in a range of different ways. For example, Daigneault *et al.* 2012; 2013; 2014a,b) model agricultural adaptation by maximising revenue at the catchment scale subject to empirically informed Constant Elasticity of Transformation (CET) functions. These CET functions constrain the rate at which specific adaptations can occur and they are seen as particularly useful in modelling policy responses, as they simulate smooth transitions within land use and management patterns and avoid model overspecialisation and unrealistic discontinuities that can occur when model parameters are changed (Daigneault *et al.*, 2012; 2014a,b). While this approach to simulating adaptation provides what appear to be realistic results, it remains a 'black box' approach to simulating adaptation dynamics, and has little appreciation for the processes of adaptation and adaptation constraints.

Alternative modelling approaches capable of simulating adaptation endogenously include Bayesian networks, systems dynamics models, evolutionary models, and agent-based models. While Bayesian networks can include probabilistic information about behaviour, feedbacks are not easily represented (Heckbert *et al.*, 2010a). System dynamics models are able to account for feedbacks, however they are built on static functions and are not generally adaptive (Parker *et al.*, 2003; Heckbert *et al.*, 2010a). Evolutionary models are able to adapt solutions to changing circumstances; however they do not explicitly account for the decision making processes, and are therefore best suited to simulating evolutionary biology rather than human adaptive behaviour (Parker *et al.*, 2003).

By contrast, decision making is explicitly modelled within ABMs, making them appropriate tools for the assessment of complex adaptive behaviour.

Heckbert *et al.* (2010a) propose a problem-focused decision tree depicted in Figure 7.1 which demonstrates the rationale for using ABM in this investigation. A number of weakness of AMB are discussed in the following section, while Section 7.2.3 notes the broad range of topics AMBs have been applied to. Section 7.2.4 then highlights the applications most relevant to the current study, while Section 7.2.5 describes the frontiers of the discipline, and Section 7.2.6 describes the coupling of ABMs with other models, forming the specific class of model used in this study.

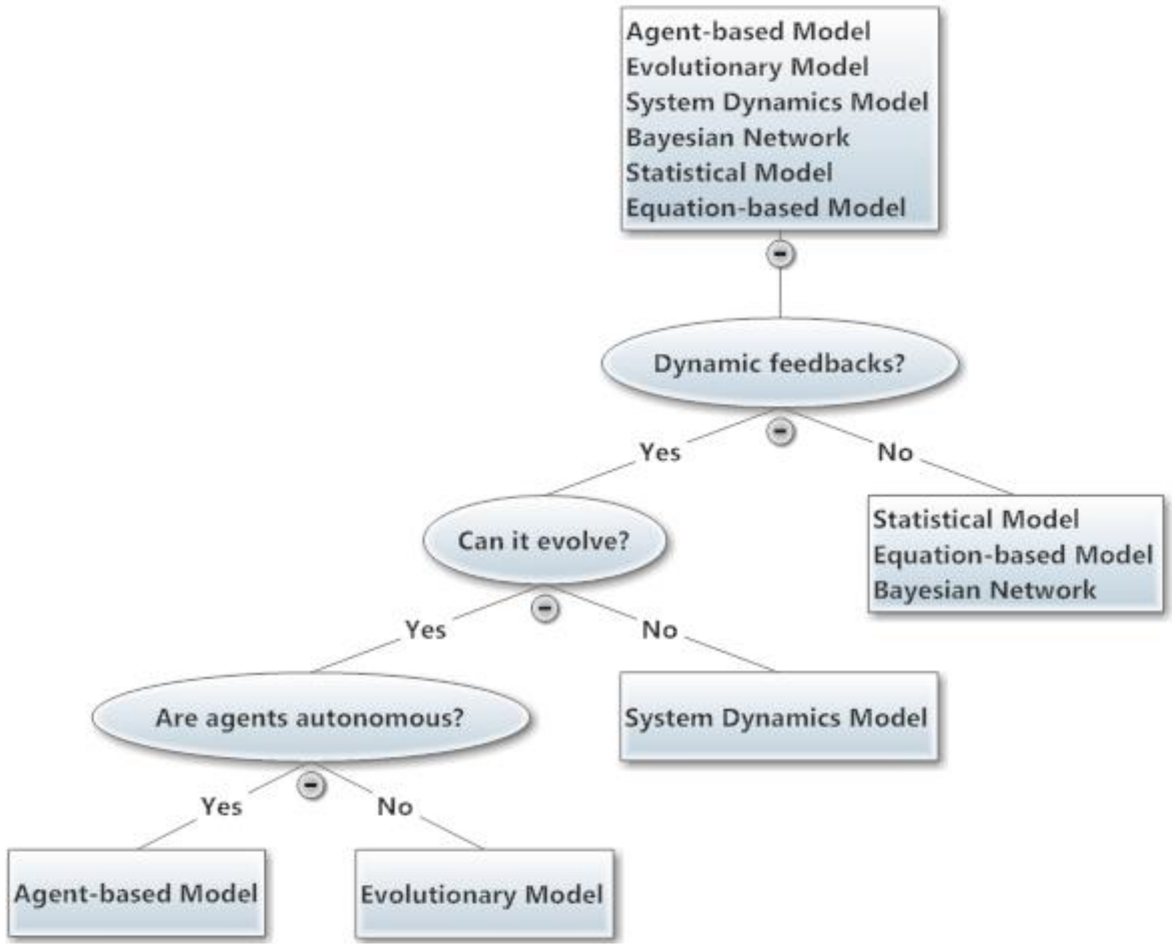

Figure 7.1: Decision tree for using complex systems models adapted from Heckbert *et al.* (2010a).

7.1.3 Drawbacks of ABM

While ABM has numerous advantages over traditional economic modelling approaches, there remain a number of drawbacks. The ability to add a wide range of constraints and behaviours to ABMs is seen by many as a strength, however the complexity that this adds is a substantial drawback (Heckbert *et al.*, 2010a). Couclelis (2001) suggests that it remains unclear whether the benefits of this flexibility outweigh the drawbacks of this added complexity.

The results of ABMs are generally seen to be emergent. Emergent phenomena are described as macro scale system properties that cannot be feasibly predicted or explained by the properties or behaviours of the system's microscale elements (Reed *et al.*, 2013; Green, 2013; Nolan *et al.*, 2009; Parker *et al.*, 2003). The emergent nature of ABMs mimics phenomena that are seen as emergent in the real world (Reed *et al.*, 2013; Nolan *et al.*, 2009). Many such phenomena have been identified, including market-clearing prices, resource allocations, and, relevant to the current study, patterns of agricultural land use (Nolan *et al.*, 2009; Parker *et al.*, 2003).

In ABM, the outcomes of interactions are path-dependent and exceedingly difficult to predict simply by extrapolating the actions of individual agents (Reed *et al.*, 2013; Parker *et al.*, 2003; Green, 2013). Therefore, while ABMs can suggest plausible macro level outcomes based on theories of behaviour, they do not explain the processes that led to those outcomes, meaning they are sometimes seen as 'black box' models (Parker *et al.*, 2003; Schreinemachers *et al.*, 2009). The qualitative assessment of the origins and process of adaptation constraints undertaken in this study is, therefore, a valuable way to form candidate explanations for the model processes.

Verification and validation of ABMs is also challenging if not impossible because emergent outcomes develop from abstract concepts of behaviour (Heckbert and Bishop, 2011; Heckbert *et al.*, 2010a; Nolan *et al.*, 2009). Parker *et al.* (2003, p.326) suggest that the emergent nature of model outcomes, coupled with weak empirical verification and validation, mean that it can be "difficult to establish what [agent-based] models tell us about reality". The drawbacks of ABM considered in light of its advantages imply a number of important considerations about the application and interpretation of these models.

7.1.4 Application and Interpretation of ABMs

Planners and policy makers frequently make decisions that would benefit from knowledge about how land use may change in the future (Berger and Troost, 2014). Central to this knowledge is information about how people respond to environmental and regulatory conditions (Berger and Troost, 2014). As explained in Section 7.1.2, ABM provides the best computational tool for exploring these questions; however, as described in the previous section, there remain important questions about the validity of the models, and substantial limitations to what we can interpret from them. In light of these uncertainties, Couclelis (2002, in Green, 2013), suggests that ABMs should be seen as 'research models' more than 'policy models'. Green (2013, p.5) supports this argument to an extent, warning that "If we see ABMs as forecasting tools, and create policy on that basis, we will suffer the inevitable disappointment of one caught out by their own unreasonable expectations". He goes on to explain that ABMs can, however, provide important insights about the complexities of social-ecological systems as long as the modeller's expectations are modest.

Determining an appropriate level of abstraction is crucial for the successful application and interpretation of ABMs. Parker *et al.* (2003) cite an analogy by Casti (1997) who likened models that aim to minimise abstraction to photographic portraits which mimic reality. By contrast, models with high levels of abstraction were likened to Picasso portraits, which capture broad aspects of reality, but emphasise specific features in order to explore certain questions. This study explicitly questions the impacts of adaptive constraints, and therefore fits better in the second category of greater abstraction.

The level of abstraction also affects the potential for generalisation. A highly calibrated model with low levels of abstraction may only apply to the context in which it was constructed, while a highly abstract model may be successfully applied to different contexts (Green, 2013; Janssen and Ostrom, 2006). The appropriate level of abstraction for any modelling exercise, therefore, depends on the aims of that exercise. If the aim is to provide detailed information about a certain context for use in developing local policies, then a low level of abstraction is preferable. If, as is the case in this study, the aim is to explore the general impacts of stylized behaviours and conditions, then a high level of abstraction is appropriate (Parker *et al.*, 2003).

Many practitioners see ABMs as computational laboratories within which to run experiments to test social and environmental theories (Janssen, 2004; Janssen and Ostrom, 2006; Heckbert *et al.*, 2010a). ABM is used in this study as a tool to examine the theoretical consequences of optimisation within climate change adaptation research. The application of ABM in this study follows a simple structure described by Parker *et al.* (2003, p.325) in which "there is a target empirical macroscale phenomenon" – in this case, agricultural adaptation to climate change – "The modeller develops a series of rules, interactions, and specifications for the agents and their environment" – in this case, the main constraints on adaptation – "and then allows agents to interact within a simulation environment. If the macro-phenomenon that results resembles the empirical phenomenon of interest, then the modeller has uncovered, at the very least, a candidate explanation for the empirical phenomenon." ABM is therefore used in this study with an understanding of the limitations of the method and its findings.

7.1.5 Relevant Applications of ABM

ABM has been used frequently across a broad range of disciplines (see Parker *et al.* (2003) for an overview), and there have been a number of applications relevant to the current study. A small number of studies have attempted to strengthen the empirical foundations of ABMs by using observations of human behaviour to formulate agent preference functions. For example, Brown and Robinson (2006) tested the effects of assigning empirically derived lifestyle preferences to different categories of actors in an ABM of urban sprawl in Michigan, USA. They found that introducing heterogeneity of agent preferences significantly increased urban sprawl. Heckbert *et al.* (2010b) assessed the effects of preference functions derived from stated and revealed preference studies on an ABM of the interactions between foresters and hunters in Alberta, Canada. They found that weighting hunters' preferences resulted in dramatically different spatial distributions for hunting. Huigen (2004) and Huigen *et al.* (2006) used interviews, surveys, and auxiliary social data to calibrate an agent based model of land use and settlement decisions in the Philippines. They found that the use of these data resulted in modest improvements in model performance.

In New Zealand, some work has been done in the past, and much work is being done at present to include empirical information about farmer behaviour within the ARLUNZ model (Brown *et al.*, 2013). For example, Daigneault *et al.* (2012) used qualitative interview data to provide empirical grounding to the ARLUNZ model as part of the Sustainable Land Management and Climate Change project. More recently, Brown *et al.* (2013, 2015) undertook two extensive surveys of rural decision making aimed explicitly at producing data with which to inform the ARLUNZ model. Based on these data, Morgan *et al.* (2015) tested the impacts of defining agents' behaviour based on empirical data against the impacts of simulating change based on network and imitation dynamics. They found little difference in overall catchment revenue between the two approaches; however there were substantial differences in the timing of land use change. The work of Morgan, Daigneault, and Brown has, however, focused on farmers' responses to policy rather than adaptation to climate change or the constraints on this process.

Two previous applications of ABMs are particularly relevant to the current study because they implicitly assess adaptation constraints. Bharwani *et al.* (2005) constructed an ABM of cropping decisions using empirical data to investigate adaptation to climate variability in South Africa through the use of seasonal forecasts. They found that when the accuracy of seasonal forecasts was 65%, wealthy farmers were able to take advantage of these forecasts and determine their cropping strategies using them. At this level of accuracy, however, forecast information remained too risky for poorer farmers, who chose to maintain high diversity in their cropping strategies in order to ensure resilience. Only when certainty grew to 85% did forecasts assist poorer farmers. This demonstrates that household wealth and information uncertainty interact to reduce adaptation to below what would be considered optimal under rational choice.

A second example of adaptation being constrained within an ABM comes from Acosta-Michlik and Espaldon (2008), who assessed the vulnerability of farmers in the Philippines to climate change and globalisation. They simulated adaptation using a variant of the 'consumat' approach of Jager *et al.* (2000), in which behaviour was constrained to represent cognitive elements of decision making. The analysis identified financial constraints and lack of information as the most important contributors to vulnerability in the Philippines, and by implication, the most important constraints on adaptation included in the consumat approach.

7.1.6 Frontiers of ABM

In applied research, empirical insight is necessary in order to realise many of the benefits of ABM (Smajgl *et al.*, 2011; Brown *et al.*, 2013). As described in the previous section, a small number of studies have used empirical insights to parameterise or calibrate ABMs; however Heckbert *et al.* (2010, p.39) still refer to empirical calibration as a "frontier for ABM research in ecological economics". Berger and Schreinemachers (2006) reflect that, while the experimental and hypothetical use of ABMs is widespread, there are few examples of empirical parameterisation or calibration. In light of this research gap, Nolan *et al.* (2009) suggest that agricultural economists may be well-placed to advance the empirical parameterisation and calibration of ABMs because of the strong tradition of empiricism. Furthermore, Berger and Troost (2014) suggest that empirically parameterised and calibrated ABMs provide a promising approach to the investigation of behavioural responses to climate change. Beyond the primary objective of estimating the economic impacts of adaptation constraints, this study seeks to provide a further example of the use of empirical insight within ABM.

7.1.7 MAS/LUCC

The complexity of agricultural land use change means that single models generally cannot simulate all of the relevant processes (Anastasiadis *et al.*, 2013). Combining two or more models that account for different processes can provide a more complete understanding of the system in question (Anastasiadis *et al.*, 2013; Parker *et al.*, 2003; Heckbert *et al.*, 2010). There is mounting evidence that a class of models known as Multi-Agent Systems for the simulation of Land Use and land Cover Change (or MAS/LUCC) improve upon previous attempts to model agricultural land use change (Berger and Troost, 2014; Morgan and Daigneault, 2015).

MAS/LUCC models comprise two key components: an ABM of the decision making processes of the relevant actors; and a cellular model of ecological and biogeophysical dynamics, (Parker *et al.*, 2003; Janssen, 2004). Cellular models are made up of a lattice of individual cells where each exists in one of a defined set of states which change over time based on predefined rules (Parker *et al.*, 2003;

Janssen, 2004). Cellular models and ABMs are coupled through the specification of feedbacks between the agents and their physical environments (Parker *et al.*, 2003).

The ability to explicitly model behaviour and space, as well as the interactions between these dimensions, make MAS/LUCC a promising approach to researching land use change under climate change (Berger and Troost, 2014; Parker *et al.*, 2003; Bithell and Brasington, 2009). Specifically, MAS/LUCC models can account for spatial interdependencies that are known to affect behaviour (Parker *et al.*, 2003; Morgan and Daigneault, 2015). For example the diffusion of information and innovation is, to some extent, geographical (Parker *et al.*, 2003). The importance of accounting for spatial effects has been demonstrated by Rincón-Ruiz *et al.* (2013, p.32), who showed that using a distance decay function significantly improved their model's explanatory power, concluding that "failing to do so can lead to serious mistakes".

7.2 Modelling of Constraints

The modelling of behavioural traits using ABM often involves consideration of the agents' decision making processes, the specification of agent attributes and heterogeneity, and the calculation of constraints based on empirical data. Robinson *et al.* (2007, p.17) identify the following seven key questions that should be considered when formulating ABMs relating to questions of land use and management.

1) What decision models and cognitive processes do actors use to make decisions?

2) What differences exist between actors with regard to these processes?

3) What are the primary classes of actor and how many are there of each?

4) Who interacts with whom?

5) Do actors adjust their decision making or learn – if so, when and how?

6) What is the sequence and duration of agent actions and interactions, event occurrences, and information updates for agents?

7) What environmental or social factors influence actor decisions and what are their relative strengths of influence?

These questions are addressed in the following seven sections.

7.2.1 ARLUNZ

This study made use of, but heavily modified, a pre-existing ABM of agricultural land use decisions in New Zealand, called the Agent-based Rural Land Use New Zealand model, or ARLUNZ (Morgan and Daigneault, 2015; Morgan *et al.*, 2015). ARLUNZ was designed to "examine and resolve complex environmental issues within the rural environment, provide information about how farmers will adapt (both economically and socially) to global change, and reduce vulnerability to resource scarcity" (Morgan and Daigneault, 2015, p.3). The original ARLUNZ model was written in Version 5.0.5 of the ABM software NetLogo (Wilensky, 1999) using the String, Shell, and GIS extensions (Morgan and Daigneault, 2015). Adjustments were made to the model in this study using Version 5.3.1 of NetLogo[6]. Within NetLogo, ARLUNZ comprises three layers: the landscape; the agents; and the economic information mediating their interaction (Morgan and Daigneault, 2015). ARLUNZ is coupled with a sub-model called the New Zealand Forest and Agriculture Regional Model (NZFARM) which calculates the optimum land use for each farm in each time step. The three layers of ALUNZ are now discussed in turn, followed by an explanation of the coupling with NZFARM.

7.2.1.1 Model Landscape and Climate

ARLUNZ was originally set up to model the Hurunui catchment in North Canterbury (Morgan and Daigneault, 2015; Morgan *et al.*, 2015). It was extended to the Hikurangi catchment in Northland for the purposes of this study by Dr. Fraser Morgan. The landscape was defined using a geographically explicit outline of the catchment within which cadastral boundaries were embedded using data from Land Information New Zealand (2015) and land quality was defined spatially using the Land Use Capability (LUC) dataset (Lynn *et al.*, 2009). Current land use was also defined based on Land Use New Zealand data from 2011 (Landcare Research, 2011). While this database originally included 17 different land uses[7], the model was restricted to only consider farms of greater than 100ha[8] practising one of the four main land uses of dairy, drystock, forestry, and horticulture which together accounted for 82.3% of the area available for production.

Climate forcing was added to the model as part of this study, using the NetLogo GIS extension. Climate forcing was defined by the most recent downscaled yield change data for pasture, forestry,

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[6] While alternative ABM software packages exist (see for example Nolan *et al.* (2009) for a comparison of NetLogo and an alternative package called RePast), the use of a pre-existing model was seen as a major advantage in this case. Furthermore, the use of NetLogo is common to a number of other projects cited in this study, including Heckbert *et al.* (2010b), Filatova *et al.* (2009), and Acosta-Michlik and Espaldon, (2008).

[7] The 11 land uses that were excluded from this analysis are pig farming, deer farming, viticulture, carbon offset forestry, Manuka, sheep dairy, goat dairy, indigenous production forestry, agro-forestry, native forest, and irrigated dairy.

[8] This restriction was included to avoid modelling 'hobby' farms or lifestyle blocks used for non-commercial purposes.

and horticulture, produced by Rutledge *et al*. (2017) and described in Section 4.3. The forcing added was spatially explicit at the 0.05 degree grid square resolution, as shown in Figure 3.4.

7.2.1.2 Model Agents

ARLUNZ includes two types of agent: farms and farmers. Farm agents are used to store information about individual farms. They are immobile and have no decision-making ability. They are created at the centroid of each cadastral land parcel in the setup phase of the model. Farm agents have areas defined by the extent of their cadastral boundaries overlaid on a 25ha raster landscape. The farm agent also calculates a predominant land use based on the vector landscape information.

Farmer agents are created at the same location as farm agents. Farmer agents store behavioural, social, and economic attributes, and implement the decision making routines defined within the model. While each farmer agent follows the same decision-making routine, and uses the same market values, their behavioural and social attributes are heterogeneous. These attributes are defined for each farmer agent using random draws from normal distributions based on data from the SRDM (2015), using routines developed as part of this study. The social and behavioural attributes calculated then inform behavioural constraints that alter the farmer agents' likelihood of changing land use.

7.2.1.3 Market Information

The final layer of ARLUNZ is a set of overarching values, known as 'globals', which store information about economic and market conditions that mediate the decisions of farmer agents. Values such as commodity prices are based on real-world data in the first time step. Farm commodity prices are updated in each subsequent time step to reflect a 2% annual increase, which is in line with forecasts from the Ministry for Primary Industries (Ministry for Primary Industries, 2013).

These three levels define a behaviourally heterogeneous population which interacts on a heterogeneous and spatially explicit landscape within an evolving market. Each of these levels is empirically defined to some extent. Each layer also affects land use decisions, as farmer agents decide whether or not to change land use based on a combination of their behavioural characteristics, the specifics of their farms, and the market prices they can expect.

7.2.1.4 Coupling with NZFARM

Advice on the most profitable land use for each farm is provided by the NZFARM sub-model. NZFARM is a comparative-static, non-linear, partial equilibrium econometric model of land use in

New Zealand[9] (Daigneault *et al.*, 2012, 2014). The original version of NZFARM uses environmental and economic data to optimise land use and maximise revenue at the catchment scale, and has been used extensively for agri-environmental policy analysis in New Zealand (Daigneault *et al.*, 2012; 2013; 2014a, 2014b; Samarasingh *et al.*, 2011; Greenhalgh *et al.*, 2012). For use within ARLUNZ, the NZFARM model was modified to maximise revenue at the individual farm level (Morgan and Daigneault, 2015). NZFARM is written in General Algebraic Modelling Systems (GAMS) version 23.7, and it is linked to ARLUNZ by what Morgan and Daigneault (2015, p. 3) describe as "loose coupling" using the Python 2.7 programming language. This allows the NZFARM model to calculate the optimal land use for each farmer agent based on input costs, output prices, potential yields, and environmental constraints (Morgan and Daigneault, 2015). If the optimum land use differs from the current land use, then the farmer agent is instructed to consider changing to the optimum land use (Morgan and Daigneault, 2015).

NZFARM is essentially a Ricardian model, and it optimises land use based on data from New Zealand as a whole. Because data from the whole country are unable to capture local environmental anomalies, NZFARM is not particularly well calibrated to the Hikurangi catchment, meaning that it suggests substantial changes in land use away from the initial land use pattern in the first time step. Ricardian models would make similar suggestions if applied to higher resolutions affected by conditions not captured by larger scale data. Re-calibration of the NZFARM model to better reflect the specifics of the Hikurangi catchment, while possible, goes beyond the scope of this study. Adjustments in response to low-resolution calibration of NZFARM are problematic in that they affect the forcing to which adaptation occurs; however the differences between constrained and optimised specifications are still good measures of the constraints on this adaptation.

7.2.1.5 Decision Making within ARLUNZ

As explained in Section 7.1.1, ABMs allow agents' decisions to depart from the assumptions of economic rationality (Heckbert *et al.*, 2010; Nolan *et al.*, 2009). At one extreme, agent behaviour can be modelled based on heuristics, in which decisions are made based on pre-defined decision trees. At the other extreme, agents can retain an optimising function, often conceptualised as a utility function.

Under an heuristic approach, agents' decisions are boundedly rational, reflecting the complexity of the environments and choices available to the agents (Parker *et al.*, 2003). While actual human behaviour is highly complex, adding complexity to the structure of an ABM is not necessarily beneficial. Gurung *et al.* (2006) point out that the objective of ABMs is not to comprehensively

[9] Daigneault *et al.* (2012) describe the data used to inform NZFARM, while Daigneault et al (2014) describe the design, parameterisation, and validation of NZFARM.

simulate decision making, but rather to test how simple behavioural patterns affect broader outcomes. Through their empirical analysis of water management in Bhutan, they concluded that "very simple models with a low degree of realism can be very efficient" (Gurung *et al.*, p.29).

Optimisation provides a more straightforward decision making framework under which agents work to maximise their utility, albeit in a constrained behaviour space (Morgan *et al.*, 2015). Optimisation can be used to maximise a utility function, as employed by Heckbert *et al.* (2010b), or to maximise agent revenue, as employed by Morgan *et al.* (2015). Decision making frameworks based on optimisation lend themselves to the use of microeconomic data. As highlighted by Evans *et al.* (2006), these data may overlook social and spatial dynamics relevant to the processes of land use change (Morgan *et al.*, 2015). However, Happe *et al.*, 2006 suggest that the assumption that people work to maximise profit is reasonable for most agricultural areas in the developed world where subsistence farming is negligible.

Schrienemaches and Berger (2006) point out that heuristic and optimisation based approaches can also be complementary, and using elements of both can be beneficial. This study uses a hybridised approach in which a revenue maximising function is specified as the central focus of the agents, however the agents' decisions are constrained in a range of different ways based on the empirical findings of the study. The decision making framework used in for each time step in this model is described in the following section and summarised as decision trees in Figures 7.2 and 7.3.

Decision Process

Land use decisions rest solely with the farmer agent within ARLUNZ. In the absence of adaptation constraints, the underlying objective of each farmer agent is to maximise profit on its farm. If the optimum land use calculated by NZFARM is the current land use practised by the farmer, the farmer does not consider changing land use. If the optimum land use differs from the current land use, the farmer agent considers changing land use by comparing a pseudo-randomly generated number of between 0 and 1 with a number representing their likelihood of land use change. Each agent's likelihood of land use change is initially set to 1. In the baseline Ricardian run, this likelihood is unaltered, meaning that agents always accept advice to change land use, and always practise the land use that provides the highest profit across their farm as a consequence. The decision process of the Ricardian run is shown in Figure 7.2.

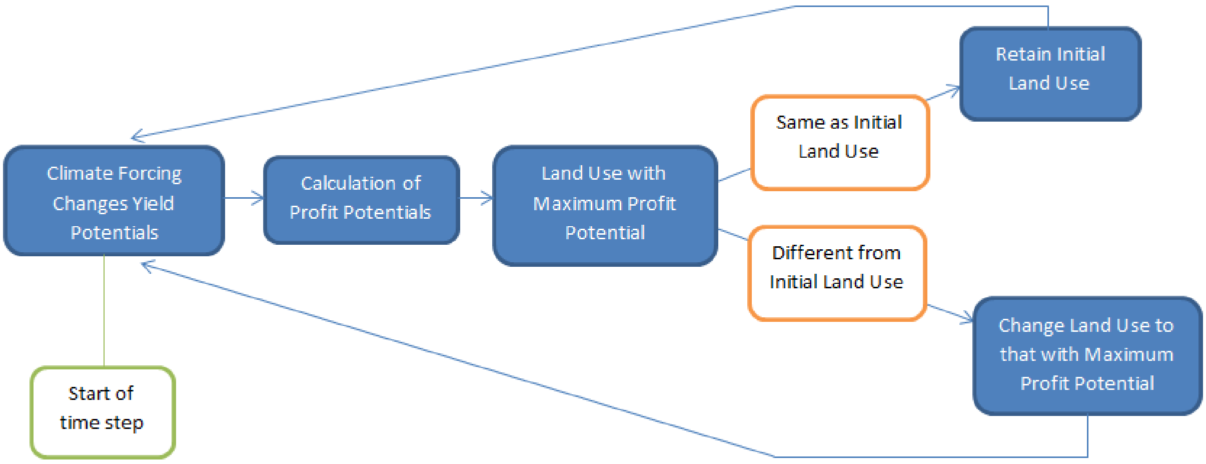


Figure 7.2: Diagram of the recursive decision making process of farmer agents in the baseline 'Ricardian' version of ARLUNZ.

In the constrained model specification, each agent's likelihood of land use change is adjusted in proportion with the empirical adaptation constraints. The decision process of the constrained specification is shown in Figure 7.3. The adjustment costs, described in Section 6.3.2.1 affect the profit maximisation calculation itself by including the costs of adjustment within the calculation of optimal land use. Social and geographic networks distort economic information, so that some see the potential benefits of land use change as being higher than the actual benefits, while others see these as lower than the actual benefits. Behavioural constraints, institutional constraints, and those relating to motivation and aspiration affect the likelihood that famer agents decide to change land use when a new land use is shown to be more profitable. These constraints differ between farmer agents in proportion with their behavioural, social, and economic attributes, defined and specified empirically in this study. Each farmer agent, therefore, has a different likelihood of land use change based on empirical distributions of behavioural, social and economic attributes.

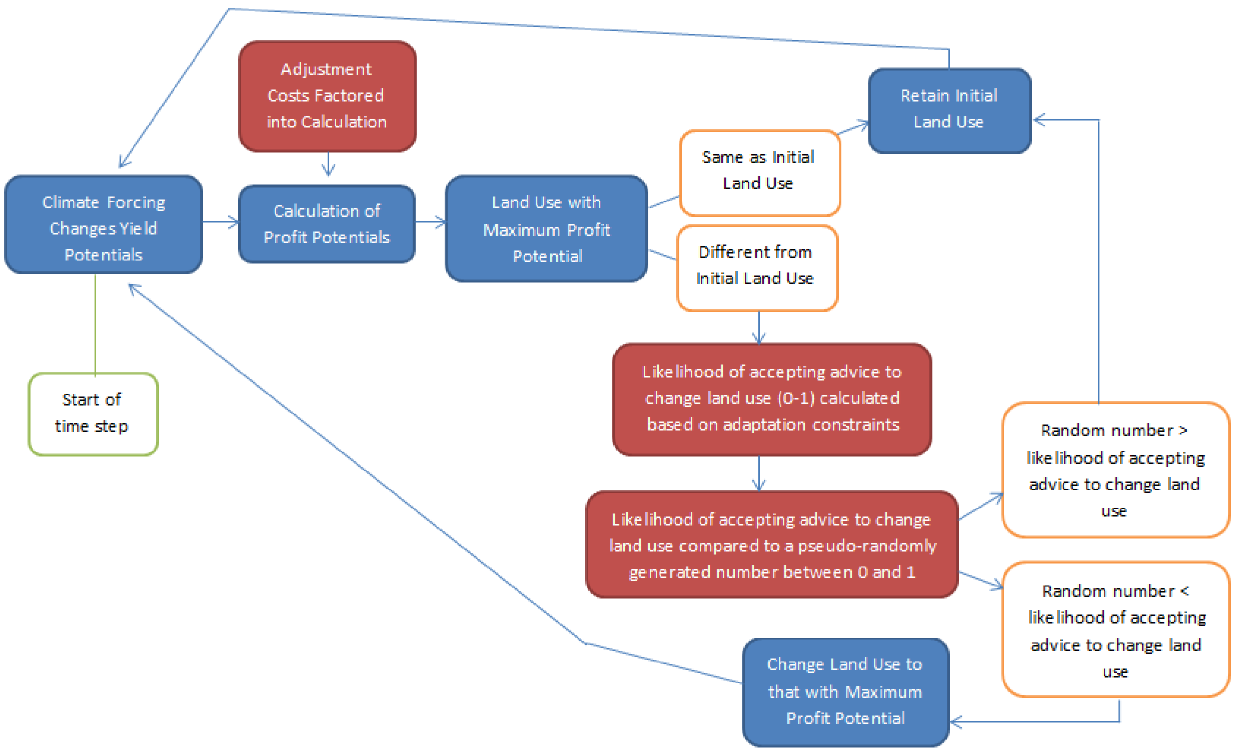


Figure 7.3: Diagram of the recursive decision making process of farmer agents in the scenario in which adaptation constraints are included.

Most of the constraints written into the ARLUNZ model work by adjusting a single value representing the likelihood of accepting NZFARM's recommendation to change land use. Because of this, the sequence in which these constraints are applied within the behavioural routine is important. Constraints applied first adjust this number from its starting point of 1. In specifications with multiple constraints, those applied later in the sequence adjust a value that is generally lower than 1 because other constraints have already reduced the likelihood of accepting advice below 1. Constraints applied later in the sequence, therefore, have less influence when multiple constraints are applied. To account for this, the placement of each constraint was considered carefully.

A large body of research in psychology has sought to develop models of decision making. Of a range of competing models, Pike (2008) and Brown *et al.* (2013) suggest that the Theory of Planned Behaviour (Azjen, 2002) provides the most appropriate model for farmers' decision making. While this model was considered when structuring the decision making routines of agents, it was not able to provide a clear notion of the appropriate sequence of constraints. For example, it is not clear whether environmental concern is considered before or after risk perception in the Theory of Planned Behaviour. The constraints were instead sequenced in an *ad hoc* manner.

Six of the 16 constraints modelled either did not directly apply to the adaptive propensity value, or applied absolute limits rather than adjustments, therefore the sequence of these constraints was not important. Two constraints, ‘Climate Change Information’ and ‘Cultural Identity’, were considered to be pre-conditions for the land-use-change decision, and were therefore applied at the start of the decision making sequence. Two other constraints, ‘regulation’ and ‘labour constraints’, were considered likely to appear later in most farmers’ decision making processes, and were therefore shifted to the end of the decision making sequence. It was not considered possible to reliably sequence the remaining six constraints within a decision making routine, as farmers would likely differ in the sequence with which they make each consideration. These six were, therefore, ordered in accordance with the frequency with which each was referenced during the qualitative fieldwork, with constraints that found greater empirical evidence appearing higher in the sequence, and having more relative influence as a consequence. While this sequence may not represent a ‘real’ chronological decision-making process, it is a pragmatic way to account for uncertainty in the application of adaptation constraints.

7.2.1.6 Model Assumptions

ARLUNZ makes a number of important assumptions that warrant mention. Each time step in the model represents five years, and each model run comprises 15 time steps representing 75 years from 2010 to 2085. The length of each time step conforms with Morgan and Daigneault (2015) who justify it as aligning with the lengths of different life stages as defined by Burton (1999, in Morgan and Daigneault, 2015). The technology available to farmers is held constant, and there are assumed to be no technology-related changes in farm productivity.

The assumptions and specifications of the version of ARLUNZ used in this study were described in detail following the Overview, Design concepts, and Details (ODD) protocol (Grimm *et al.*, 2010). This ODD description is available on request from the author.

7.3 Use of Empirical Insight

The ways by which the Survey of Rural Decision Makers described in Chapter 5 was used to inform the ARLUNZ model are described over the following five sections. Section 7.3.1 describes how the population of agents within ARLUNZ were generated based on empirical data. Section 7.3.2 then describes two different ways by which adaptation constraints were calculated in this study. The specification of indices representing the major constraints on adaptation were described in Chapter 4, and quantification of quasi objective constraints are described in sections 7.3.3 and 7.3.4, respectively. Section 7.3.5 presents the results of this quantification before Section 7.3.6 describes how these constraints were implemented within ARLUNZ.

7.3.1 Specification of Agent Attributes

While the farmer agents all follow the same decision making procedure, the attributes and conditions affecting their decisions differ. There are two commonly used approaches to specifying heterogeneity in ABMs: the separation of agents into categories, and the specification of agents based on empirical distributions. These approaches are commonly used by geographers and economists, respectively, and each has advantages and disadvantages (Morgan *et al.*, 2015).

The separation of agents into categories has the advantage of reducing the complexity of the model (Morgan *et al.*, 2015; Brown *et al.*, 2013). It also allows for inferences to be made about different behavioural groups within a population. While aiding the conceptual design and interpretation, the categorisation of agents can be criticised as artificial. Brown *et al.* (2013) point out that categorisations are gross simplifications of diversity, and regardless of the methods used to identify different categories, they remain subjective.

An alternative approach advocated by a number of economists is to specify agent attributes based on empirical distributions (Heckbert *et al.*, 2010a; Janssen and Ostrom, 2006). When detailed microeconomic data exist, Morgan *et al.* (2015) suggest that this more detailed approach to agent specification is preferable. The attributes of the agents within ARLUNZ were, therefore, specified based on the data relating to each attribute surveyed in the SRDM. Similar to Berger and Schreinmachers (2006), data on relevant attributes were used to estimate probability density functions based on dataset means and standard deviations. Random draws were then taken based on these probability density functions in order to define attributes for each agent.

7.3.2 Design of Constraints

Behavioural constraints can be identified and calculated in a number of different ways. Behavioural traits or preferences can be identified and quantified quasi-objectively using factor analysis (see for example Brown and Robinson (2006)). However, while objectivity in the identification and quantification of salient factors is desirable, the latent factors identified using factor analysis are still interpreted subjectively.

An alternative approach is to identify important behavioural traits or preferences based purely on theory or direct observation. In this study, the relevant behavioural traits or preferences were identified in a review of the literature described in Chapter 4, and through a suite of semi-structured interviews with farmers described in Chapter 5. This approach has the advantages of clarity in the interpretation of behavioural traits and preferences and control over the focus of the investigation, while subjectivity is minimised by cross-referencing theory with empirical findings.

Once identified, the adaptation constraints need to be specified and quantified. These tasks can also be carried out quasi-objectively, using formal statistical methods, or in an *ad hoc* manner based on theory and observations. This study used both approaches. A number of constraints were quantified in an *ad hoc* manner, as described in Chapter 6, while others were quantified quasi-objectively using regression analysis as Section 7.3.4 will describe. Finally, the functional design of constraints and the ways in which they were represented within the ARLUNZ model was largely based on judgement, as explained in Section 7.2.3.3.

7.3.3 Specification of Constraints

The dependent variable in this study was the adaptive propensity of farmers. In the context of the ARLUNZ model, adaptive propensity is equivalent to the likelihood that agents will accept the advice of NZFARM to change land use if a more profitable alternative exists. The influence of the identified constraints on the dependent variable of adaptive propensity was investigated in the SRDM, described in Section 5.4. It was not possible to measure directly the dependent variable, or many of the identified constraints used in this study. Multiple measures were therefore aggregated as indices in efforts to reduce error variance, based on the assumption that this variance is not systematic and is therefore likely to cancel out as more measures are added (Peters, 2014; Booysen, 2002). When multiple indicators measure the same construct, combining these indicators provides theoretical advantages over the use of a single indicator, while focusing the interpretation on a single metric (Sullivan and Meigh, 2005; Booysen, 2002). Indexing is common in social scientific research (Booysen, 2002; Babbie, 2010; Atkinson, 2003). It provides a way to integrate quantitative and qualitative data (Sullivan and Meigh, 2005) and it has been used to characterise behavioural traits for the purposes of ABM in the past (Brown *et al.*, 2013; 2016). Indexing requires the consideration of four processes: the selection of indicators, scaling, weighting, and aggregation (Booysen, 2002). These processes are discussed in turn.

7.3.3.1 Selection of Indicators

The first step in constructing indices to represent the salient adaptation constraints identified in this study was the selection of component variables. This process is generally based on theory, data availability, and intuitive appeal, while practical considerations of simplicity, reliability, and comparability are also important (Booysen, 2002).

The selection of component variables can be performed quasi-objectively using bivariate or multivariate statistical analysis. Bivariate analysis tests the strength of correlation between candidate variables, and those most strongly correlated with each other are selected as indicator variables (Babbie, 2010). This relies on the assumption that indicators of a single latent construct (represented as an index) are likely to be highly interdependent and therefore strongly correlated (Babbie, 2010). Multivariate techniques use a proxy for the index in question to test the explanatory power of combinations of candidate variables. When such a proxy is available, however, it could be argued that this could replace the index itself, because even the best grouping of component variables would remain an imperfect attempt to approximate the proxy. A further problem with bivariate and multivariate techniques for indicator selection is that they require the collection of data on a wide range of variables, many of which are rendered obsolete. With the constraints on data gathering described in Section 5.5.3 in mind, these techniques were seen as inappropriate for this investigation.

In this study, indicator variables were selected based on a combination of theory described in Chapter 4, and the findings of the qualitative field work described in Chapter 6. As described in Section 5.4, a number of questions relating to adaptation constraints identified in the literature were included in the SRDM, and many other SRDM questions held relevance to specific adaptation constraints. The full suite of SRDM questions was carefully considered, and questions holding relevance to adaptation constraints were selected as indicator variables. The indicator variables comprising each of the indices used in this study are listed in Table 7.1.

The *ad hoc* selection of indicators is often criticised for containing the researcher's political and social judgements (Todaro, 1989). Variable selection is also commonly biased by data quality and availability (Booysen, 2002). It is acknowledged that, in this case, the selection of indicator variables was influenced by space constraints in the SRDM, by what could be reasonably asked of each respondent, and by the reliability of the respondents' answers. It is also acknowledged that many indicator variables used are imperfect, and that indicator selection was influenced by judgements about which concepts the dependent variable and the adaptation constraints entail.

7.3.3.2 Scaling of Indicators

Scaling of indicators provides a way to integrate cardinal and ordinal data, or those with different scales or units. Scaling can be achieved either by calculating standard scores or using Linear Scaling Transformation (LST) methods. Standard scores are the statistical deviation of an indicator value from the mean of all values of that indicator (Booysen, 2002). Linear Scaling Transformation methods seek to scale values relative to logical minimum and maximum values for the variable in question. For example, based on the range of average national life expectancies worldwide, the Human Development index uses a minimum of 25 years and a maximum of 85 years in its LST calculations (UNDP, 1996). In many of the indices used in this study, minimum and maximum values were either pre-defined (for example, as Likert scales), or simply taken as the minimum and maximum values recorded in the datasets. When this was not the case, judgements informed by assessment of the data were used to define maximum values. The LST calculation and the minimum and maximum values for each variable are shown in Table 7.1.

7.3.3.3 Weighting of Indicators

In some cases, weightings are applied to indicator variables in efforts to reflect their relative importance in an index. Weightings are often applied based on expert judgement (see for example, Brooks *et al.* (2005)), or tailored by researchers to emphasise components of interest; however this approach can be criticised as being subjective (Booysen, 2002). Weightings can be calculated objectively using principal component analysis, however as Booysen (2002) points out, this surrenders a degree of structural control and may make it more difficult to target indices toward answering specific research questions. Booysen (2002) goes on to argue that any attempt to weight indicators can be criticised, while Atkinson (2003) and Babbie (2010) suggest that not weighting indicators should be the standard approach. Experts were not asked about the relative importance of the indicator variables used to form indices in this study because it was not clear that this was knowable to any reasonable degree of confidence. In light of this, weightings were not applied to the indicator variables used in this study.

7.3.3.4 Aggregation of Indicators

Aggregation is the final step in the calculation of indices, and can be achieved using either simple addition or functional combination. The latter approach requires the functional relationship between indicator variables to be estimated (Booysen, 2002). While functional relationships between variables are often identifiable in general terms, estimating their influence can be difficult. As a consequence, the vast majority of indices are calculated using simple addition as an average of their indicator values (Booysen, 2002). In line with the standard approach described by Brown *et al.* (2013), indices were calculated as the unweighted average of the relevant items. The results were multiplied by 100 to produce indices that range from 0 to 100 in which 0 represents the greatest constraint on adaptation in that dimension while 100 represents the total absence of that constraint. The aggregation equations for each of the indices used in this study are shown in Table 7.1.

Table 7.1: Description of the indicator variables, scaling and aggregation processes for each of the indices used. The constraints are shaded by category with blue shading representing Generic Constraints, red shading representing Specific Constraints, and green shading representing Transaction Costs.

Index	Indicator Variable	Variable Name	Data Type	LST Min	LST Max	LST Equation	Index Equation
Dependent variable	Likelihood of converting land use within 2 years	plan_convert	Likert	1	3	$LST = \frac{value - 1}{2}$	Dependent Variable Index = ((LST plan_convert + LST cc_land_use_exp)/2)*100
	Expectation of land use change under climate change*	cc_land_use_exp	Likert	0	10	$LST = \frac{value}{10}$	
Farmer Motivation and Aspiration	Ranking of the importance of financial performance*	objective_fin	Likert	1	3	$LST = 1 - \left(\frac{value - a}{2}\right)$	Aspiration index = ((LSTobjevtive_fin + LST age)/2)*100
	Age	age	Cardinal	21	85	$LST = 1 - \left(\frac{value - 21}{64}\right)$	
Behavioural Constraints	Risk tolerance	risk	Likert	0	10	$LST = \frac{value}{10}$	Behavioural Index = ((LSTrisk + LSTexperiment + LSTamong_first)/3)*100
	Preference to wait for others to experiment	experiment	Likert	0	10	$LST = 1 - \left(\frac{value}{10}\right)$	
	Likelihood of being among first to try new practices	among_first	Likert	0	10	$LST = \frac{value}{10}$	
Perception of Climate Risk	Expectations for change in average temperature by 2050*	cc_temp_exp	Binary	0	1	$LST = value$	Risk Perception index = ((LSTcc_temp_exp + LSTcc_rain_exp + LSTcc_drought_exp)/3)*100
	Expectations for change in average rainfall by 2050*	cc_rain_exp	Binary	0	1	$LST = value$	
	Expectations for change in the prevalence of drought by 2050*	cc_drought_exp	Binary	0	1	$LST = value$	
Disaster Experience	Impact of previous land use change on financial performance	luc_affect_fin	Likert	1	3	$LST = \frac{value - 1}{2}$	Experience – Index = ((LSTluc_affect_fin + LSTluc_affect_env + LSTluc_affecr_life)/3)*100
	Impact of previous land use change on environmental performance	luc_affect_env	Likert	1	3	$LST = \frac{value - 1}{2}$	
	Impact of previous land use change on lifestyle	luc_affect_life	Likert	1	3	$LST = \frac{value - 1}{2}$	
Social Information	Number of farmers met with in the previous 12 months – same industry	num_farmers_same_industry	Cardinal	0	100	$LST = \frac{value}{100}$	Social Index = ((LSTnum_farmers_same_industry + LSTnum_farmers_different_industry)/2)*100
	Number of farmers met with in the previous 12 months – different industry	num_farmers_different_industry	Cardinal	0	100	$LST = \frac{value}{100}$	
Institutional Constraints and Governance	Effectiveness of regional councils in managing water*	water_mgmt_councils	Likert	0	10	$LST = \frac{value}{10}$	Institutions Index = ((LST water_mgmt_councils + LST water_mgmt_farmers)/2)*100
	Effectiveness of local farmers in managing water*	water_mgmt_farmers	Likert	0	10	$LST = \frac{value}{10}$	

Index	Indicator Variable	Variable Name	Data Type	LST Min	LST Max	LST Equation	Index Equation
Labour	Age	age	Cardinal	21	85	$LST = 1 - \left(\frac{value - 21}{64}\right)$	Labour Index = ((LST age + LST labour_ease + Scale Index + Financial Index)/4)*100
	Ease of finding qualified employees	labour_ease	Likert	0	10	$LST = \frac{value}{10}$	
Financial Constraints	Frequency with which a lack of finance was cited in decisions not to change	sum_financial_constraints	Sum of Binary	0	2	$LST = 1 - \left(\frac{value}{2}\right)$	Financial Index = (LST sum_financial_constraints) *100
Scale Constraints	Total farm area	area	Cardinal	1	5000	$LST = \frac{value - 1}{4999}$	Scale Index = ((LST area + LST total_stockUunits)/2)*100
	Total number of stock units	total_stock_units	Cardinal	1	15000	$LST = \frac{value - 1}{14999}$	
Perceived Self-efficacy	Frequency with which a lack of skills were cited in decisions not to change	sum_skills_constraints	Sum of Binary	0	2	$LST = 1 - \left(\frac{value}{2}\right)$	Self-efficacy Index = ((LST aggregate skills constraint + LST cc_mgmt_exp + LST cc_mgmt_exp)/3)*100
	Expectation of management change under climate change*	cc_mgmt_prac_exp	Likert	0	10	$LST = \frac{value}{10}$	
	Expectation of land use change under climate change*	cc_land_use_exp	Likert	0	10	$LST = \frac{value}{10}$	
Technical Expertise	Frequency with which a lack of skills were cited in decisions not to change	sum_skills_constraints	Sum of Binary	0	2	$LST = 1 - \left(\frac{value}{2}\right)$	Expertise Index = ((LST sum_skills_constraints + LST sum_ag_training)/2)*100
	Agricultural training completed in the past	sum_ag_training	Sum of Binary	0	3	$LST = 1 - \left(\frac{value}{3}\right)$	
Agricultural Information Constraints	Lack of advice cited in decisions not to change	advice	Sum of Binary	0	2	$LST = 1 - \left(\frac{value}{2}\right)$	Information Index Ag. = ((LST demonstrate + LST advice)/2)*100
	Lack of demonstration cited in decisions not to change	demonstration	Sum of Binary	0	2	$LST = 1 - \left(\frac{value}{2}\right)$	
Climate Change Information Constraints	Ease of finding authoritative information on the impacts of climate change*	cc_info_ease	Likert	0	10	$LST = \frac{value}{10}$	Information Index CC = ((LST cc_info_ease + LST temp_exp_consistency + LST precip_exp_consistency + LST drought_exp_consistency)/4)*100
	Consistency of farmer's temperature expectations with science*	temp_exp_consistency	Binary	0	1	$LST = 1 - value$	
	Consistency of farmer's precipitation expectations with science*	precip_exp_consistency	Binary	0	1	$LST = 1 - value$	
	Consistency of farmer's drought expectations with science*	drought_exp_consistency	Binary	0	1	$LST = 1 - value$	

* Question included in the 2015 SRDM specifically for the purposes of this thesis.

This approach yielded 13 independent variable indices for adaptation constraints and an index for the dependent variable of land use change propensity. This is smaller than the number of constraints identified in the literature review because space limitations and difficulty investigating certain constraints using surveys meant that a number of constraints were unable to be assessed in the SRDM. Of the 708 farmers who were asked the specific questions about climate change relevant to this study, 403 provided information sufficient to calculate the dependent variable index. These 403 cases had a number of missing data for many of the independent variables. Two of the independent variables were missing more than half of the 404 observations common to the dependent variable. Social Information and Labour Constraints provided only 86 and 155 responses common to the dependent variable, respectively. This was considered too few observations to impute the missing data, and these two variables were removed from the analysis as a consequence. The remaining 11 indices had far greater crossover with the dependent variable, as shown in Table 7.2. Missing data for these variables were imputed using the dataset means.

Table 7.2: Number of observations each index holds in common with the dependent variable index.

Index	Number of Observations Common to the Dependent Variable
Farmer Motivation and Aspiration	371
Behavioural Constraints	374
Institutional Constraints and Governance	403
Perception of Climate Risk	354
Scale Constraints	333
Financial Constraints	268
Disaster Experience	397
Perceived Self-Efficacy	266
Technical Expertise	263
Agricultural Information Constraints	266
Climate Change Information Constraints	403

7.3.3.5 Index Validation

Formal validation of indices can occur in two main ways: item analysis and external validation. External validation involves assessment of the correlation between index scores and external validators or proxies (Booysen, 2002). Similar to multivariate indicator selection however, the use of a proxy to validate an index is tenuous theoretically, because if the proxy represents the construct in question well then the index could be seen as obsolete, and if it represents the construct poorly then it is a poor measure of index validity. The alternative approach, item analysis, tests the correlation between indicator variables based on the assumption that when these are poorly correlated, indicator variables may be inappropriate (Booysen, 2002). Item analysis may be useful when the indicator variables are intended as repeated measurements of the same overall construct, however it is inappropriate if the construct of interest is multidimensional and the indicators measure different dimensions (Peters, 2014).

Most of the indices used in this study were multidimensional. For example, when calculating an index for the impact of past experiences, there was no reason to expect that the financial, environmental, and lifestyle impacts of previous land use change would be closely correlated; however negative experiences in any of these dimensions were likely to reduce the likelihood farmers will change land use in the future. While there is no way to formally test the validity or reliability of multidimensional indicator variables, aggregating these measures can be warranted based on theory (Peters, 2014).

Based on the theory and rationale for each index calculated in this study, two show a degree of uni-dimensionality in their formulation: behavioural constraints, and climate change information constraints. The validity of these indices was tested formally using item analysis. Peters (2014) recommends using the Greatest Lower Bound (GLB), or the Omega statistic[10] to assess index validity. The former can be interpreted as "the lowest possible value that [an index's] reliability can have" while it is argued that the latter "provides a more accurate approximation of [an index's] reliability" (Peters, 2014 p. 60). Peters (2014) goes on to argue against the use of predefined cutoff values for reliability, suggesting that disclosing the GLB and the Omega statistic with its confidence interval is preferable. In light of this, the GLB and Omega statistic were calculated for behavioural constraints and climate change information constraints using the programming package R. The results of these calculations are reported in Table 7.3.

Table 7.3: Greatest Lower Bound and Omega statistic with its confidence interval for the two quasi unidimensional indices used in this study.

Index	Greatest Lower Bound	Omega	Omega Confidence interval
Behavioural Constraints	0.68	0.66	0.64-0.68
Climate Change Information Constraints	0.71	0.71	0.68-0.75

7.3.3.6 Index Uncertainty

It is important to acknowledge that while indices provide a useful method to characterise adaptation constraints in this study empirically, they can be criticised in a number of ways. Uncertainty is

[10] Cronbach's alpha statistic is a commonly used form of item analysis that is widely interpreted as a measure of the reliability or internal consistency of an index (Peters, 2014). As Peters (2014, p.56) points out, however, "Although most authors and reviewers seem content with this, Cronbach's Alpha is both unrelated to [an index's] internal consistency and a fatally flawed estimate of its reliability."

contributed throughout the indexing process. Indicator variables remain subjective because our understanding of complex social phenomena is imperfect and so is any attempt to collect data on them (Booysen, 2002). Furthermore, even less is understood about how indicator variables interrelate, meaning that even the most comprehensive attempts to weight these variables and aggregate them into an index are gross simplifications of reality (Booysen, 2002; Alkire and Foster, 2011). With these limitations in mind, the indices used in this study are presented as a practical response to data limitations. They should be judged by whether they improve upon the representation of the relevant adaptation constraints relative to any of the single questions asked in the SRDM. They remain imperfect approximations of complex phenomena, and should be interpreted as such.

7.3.4 Quantification of Constraints

Once identified and specified, the influence of behavioural traits and preferences on a variable of interest can be quantified using regression. In this instance, the dependent variable was the propensity of farmers to change land use, and the independent variables were the salient constraints on adaptation identified in Chapters 4 and 6. When adaptation constraints were found to significantly correlate with the propensity of farmers to change land use, the identified relationship was applied to the agents within ARLUNZ, constraining their land use change propensity in proportion with this empirical relationship.

Ordinary Least Squares (OLS) regression is the most commonly used form of regression and it has been described as a "common language for regression analysis throughout economics, finance, and the social sciences more generally" (Stock and Watson, 2015 p. 165). In this study, however, the dependent variable and many of the independent variables were either measured using truncated data or comprise indices that are truncated by definition, making OLS regression inconsistent (Stock and Watson, 2015). For such datasets, this inconsistency manifests when the OLS estimators suggest that for a certain value of the independent variable, the dependent variable would take on a value that is impossible as the variable is defined. This is clearly inconsistent by the definitions used in the data collection, meaning that a different approach is required.

Tobit regression models provide a method for assessing correlations in continuous[11] variables that are truncated at certain values (Stock and Watson, 2015; Brown *et al.*, 2016). In Tobit regression, the dependent variable is estimated by:

$$y_i^* = \boldsymbol{x}_i'\boldsymbol{\beta} + u_i, u \sim N(0, \sigma^2)$$

[11] The continuous nature of the data used makes count models such as negative binomial or Poisson models inappropriate.

Where y_i^* is a latent variable equal to the observed variable, y_i when the latent variable falls between the two cutoff points, which in this case are 0 and 100, such that:

$$y_i = \begin{cases} 100 \text{ if } y_i^* \geq 100 \\ y_i^* \text{ if } 0 < y_i^* < 100 \\ 0 \text{ if } y_i^* \leq 0 \end{cases}$$

$\boldsymbol{x}$ is a vector of independent variables which in this case include the indices listed in Table 7.2. u is the error term, which is assumed to be normally distributed. While this produces similar results to OLS regression, the Tobit estimator is consistent (Brown *et al.*, 2016), therefore its results are adopted in this study.

7.3.5 Regression Results

The results of the Tobit regression analysis are reported in Table 7.4. The Tobit coefficients reported are interpreted as the expected change in the uncensored dependent variable (adaptive propensity) associated with a one unit change in the independent variable in question. Seven adaptation constraints, namely aspiration constraints, constraints caused by risk perception, institutional constraints, scale constraints, financial constraints, information constraints relating to climate change, and cognitive constraints, were found to have no statistically significant effect on adaptive propensity. Despite their insignificant effects on adaptive propensity, these variables are retained in the model because they have been identified as salient in both the literature and the qualitative data. This gives reason to expect that removing them from the model would contribute to omitted variable bias.

Five constraints were found to significantly affect adaptive propensity. Four of these constraints show the expected positive correlation. Specifically, each point on the behavioural constraints index was associated with a 0.24 point increase in the (uncensored) adaptive propensity index (significant at the 1% level). Each point on the index of experience as enablers (Disaster Experience) was associated with a 0.15 point increase in the (uncensored) adaptive propensity index (significant at the 5% level). Each point on the self-efficacy index was associated with a 0.74 point increase in the (uncensored) adaptive propensity index (significant at the 1% level). Each point on the technical expertise index was associated with a 0.20 point increase in the (uncensored) adaptive propensity index (significant at the 1% level). The fifth significant constraint was negatively correlated with the dependent variable, suggesting that farmers who find agricultural information more accessible are less likely to change land use. Specifically, each point on the agricultural information index is associated with a 0.16 point *decrease* in the adaptive propensity index (significant at the 10% level).

Whether or not the farmers practised dairying was also included in the model as a binary independent variable. Dairy farmers were found to be significantly less likely to change land use. Specifically, dairying was associated with a 7.78 point reduction in the land use change propensity index (significant at the 1% level). This was added to ARLUNZ in as a constraint labelled 'Dairy Path Dependence'.

Table 7.4: Tobit regression results for the 11 salient adaptation constraints and a binary variable for land use.

simplifieddv	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
aspirationindex	-.0017661	.0442788	-0.04	0.968	-.0888219	.0852897
behaviouralindex	.2376453	.0607711	3.91	0.000	.1181643	.3571263
riskperceptionindex	.1621703	.1196286	1.36	0.176	-.0730292	.3973699
institutionsindex	.0410093	.0533884	0.77	0.443	-.0639567	.1459753
scaleindex	.0750571	.06064	1.24	0.217	-.0441659	.1942802
financialindex	.0061412	.0430869	0.14	0.887	-.0785712	.0908536
experienceplusindex	.1469286	.0606535	2.42	0.016	.027679	.2661783
selfefficacyindex	.7383285	.0927441	7.96	0.000	.5559861	.9206709
expertiseindex	.2002874	.0719356	2.78	0.006	.0588561	.3417186
informationindexag	-.1597418	.0844358	-1.89	0.059	-.3257494	.0062658
informationindexcc	-.2029454	.1481412	-1.37	0.171	-.494203	.0883122
max_edu	.1061606	.5793909	0.18	0.855	-1.032969	1.24529
1.landusedairy	-7.783705	2.267793	-3.43	0.001	-12.24237	-3.32504
_cons	-36.10563	12.9896	-2.78	0.006	-61.64424	-10.56702
/sigma	17.8219	.634996			16.57344	19.07035

6 left-censored observations at simplifieddv <= 0
397 uncensored observations
0 right-censored observations

In Tobit models, the underlying latent variable is unobservable, therefore there are no strictly formal measures of model fit (Hoetker, 2007). While a number of pseudo-R^2 measures exist, they are often reported inconsistently, lack statistical meaning, and are not strictly analogous to R^2 in OLS (Hoetker, 2007). In light of the recommendations of Hoetker (2007), pseudo measures of model fit are not reported in this study. As an indicative test, OLS regression analysis was performed on the same combination of indices, and measures of fit calculated. The OLS model had an R squared value of 0.26 and an adjusted R squared value of 0.23, suggesting that the independent variables explain roughly a quarter of the variation in the dependent variable. The model had a multiple R coefficient of 0.51. While the OLS results for each index are not reported here, they were very similar to the results of the Tobit regression analysis, as would be expected.

7.4 Model Verification and Validation

Model verification and validation are important processes in determining whether model results are credible. Verification is the process of establishing the correctness of the model structure, while validation tests the truthfulness of the model results relative to the real-world system it is approximating (Parker *et al.*, 2003). Verification generally involves checking that the model code is working as intended, and ensuring that the overall structure of the code adequately approximates the system or phenomenon of interest (Parker *et al.*, 2003). Verification is discussed further in the following section.

Performing a rigorous validation is important because, as Green (2013, p.2) pointed out: "…ultimately, the usefulness of a model depends on its plausibility". Formal validation can be challenging in complex modelling exercises, and as a consequence is not often attempted (Schreinemachers *et al.*, 2009; Heckbert *et al.*, 2010b). In their review of 48 bio-economic farm model studies, Janssen and van Ittersum (2007) found that less than half attempted to validate their results, while only four attempted quantitative validation. Despite inherent challenges, attempts are made to validate the version of ARLUNZ used in this study. Quantitative validation, described in Section 7.4.2, was only possible for specific model components, meaning that validation of the final model output was necessarily qualitative, as Section 7.4.3 explains.

7.4.1 Verification of ARLUNZ

The first step in verification was to ensure that the model design adequately approximated the system and phenomenon in question. The version of ARLUNZ used in this study was adjusted from the original version of the ARLUNZ model, for which much verification has already occurred (Morgan *et al.*, 2015; Morgan and Daigneault, 2015). Happe *et al.* (2006, p.22) suggest that this can be seen as a "take a previous model and add something" approach to verification. With this in mind, the important aspects on which to focus verification in this study are those new aspects of the model, specifically, the constraints on agent adaptation.

In line with the recommendations of Jager *et al.* (2000), the behavioural constraints added to ARLUNZ in this study were developed based on behavioural and microeconomic theories that are well established in the literature. In order to ensure that these constraints and the system within which they apply were understood, the qualitative fieldwork and analysis described in Section 5.5 was completed prior to the design of model constraints. The constraints added to the model were based explicitly on the findings of this qualitative work, as described in Chapter 6. This approach ensures that the origins and processes of the adaptation constraints in question are verified from the outset, and the simplifying assumptions used to add them to the model structure are transparent and open to criticism. The final structure of the model was also verified with three people considered to be experts in the agricultural economy of the Hikurangi Catchment during a follow up period of fieldwork, as will be described in Section 7.4.3.

Care was also taken throughout the modelling process to ensure the model code was working as intended. Simple model behaviours were sense-checked throughout the research, and the researcher was careful to become familiar with the internal logic of the original code, as well as to resolve any glitches and errors that prevented the model from running as intended. These glitches and errors arose frequently with the addition of new adaptation constraints, however the results presented are from verified model runs in which all of these known errors were resolved.

7.4.2 Validation

Complex models are unable to be validated in the traditional sense for a number of reasons. Validating models using data omitted during calibration assumes normality and linearity in the model processes, which are unlikely to occur in complex systems (Parker *et al.*, 2003). Furthermore, the foci of complex modelling studies, and the model processes themselves, are often abstract concepts which are difficult to measure quantitatively (Parker *et al.*, 2003; Jager *et al.*, 2000). When model outcomes are emergent, some have argued that formal validation is likely to be impossible (Heckbert *et al.*, 2010a). Because of this, there has been a necessary move towards qualitative forms of validation for the assessment of complex systems models (Huigen, 2004; Nolan *et al.*, 2009).

One approach to informal model validation is to test the credibility of model outputs under different parameterisations and structures. Configurations or parameter sets that do not resemble reality can then be discarded (Heckbert *et al.*, 2010a). Alternatively, at the parameter level, the sensitivity of the model to dramatic changes in important variables can be compared with expectations. At the structural level, Grimm *et al.* (2005) suggest the use of pattern oriented modelling in which multiple model structures are built, and those that are unable to reproduce the basic patterns of the system in question are rejected. However, pattern oriented modelling is most useful for simple systems (Grimm *et al.*, 2005), making it inappropriate in this case.

Another approach to validating complex models is to compare their outputs with observations. When models are built on established rules and produce outputs that are similar to what is observed in the real world they may be considered trustworthy. The obvious problem with this approach is that when the phenomenon of interest cannot be observed, such as the response of farmers to future climate change, it cannot indicate whether the model is producing valid results.

An alternative approach to model validation which may account for unobservable phenomena is cross-checking model outputs with stakeholders' behaviours, understandings, and expectations (see for example, Berger *et al.* (2010)). Moss (2008) compared this informal validation approach to more formal econometric validation techniques, concluding that the former is preferable in many cases. The main drawback of this approach, however, is that the understandings and expectations of stakeholders are likely to vary, and the model may be unable to sufficiently approximate two widely differing stakeholders (Heckbert *et al.*, 2010). Furthermore, even if all stakeholders share the same opinions and expectations, there is no guarantee they are right (Green, 2013).

Expert opinion can also provide valuable insights about the credibility of complex models (Bousquet *et al.*, 1998; Parker *et al.*, 2003; Gurung *et al.*, 2006). Experts are able to scrutinise model structures and sense-check model outputs. Working through the modelling procedure and discussing outcomes with experts does not necessarily limit findings to the expectations already held by the experts. Surprising findings can challenge experts' expectations, and careful assessment of model processes can lead to new theories or explanations of macro-phenomena. This approach does, however, run into the same problem as stakeholder validation, namely, experts can disagree, and they can also be wrong (Green, 2013).

While there is no generally accepted framework for establishing the validity of complex models (Heckbert *et al.*, 2010), each of the approaches described in this section can give some indication of model validity. However each of the approaches described also has serious drawbacks, and viewed alone could be seen as tenuous measures. It is clear that the validation of complex models would benefit from combining a number of these techniques in order to develop a fuller understanding of model performance (Janssen and Ahn, 2006). This study combined quantitative validation of model components where possible with qualitative validation based on expert opinion. The sensitivity of the model to changes in the magnitudes of constraints was also tested, as will be described in Section 7.6.

7.4.2.1 Quantitative Validation

While quantitative validation in the traditional sense was not possible for the overall model, it was possible to validate certain sub-components of the model. Specifically, two of the adaptation constraints which comprise the focus of this study were derived using econometric methods for which predictions can be formally compared to observations. The use of statistical tests to establish the validity of sub-components of complex models is common to Schreinemachers and Berger (2011), Schreinemachers *et al.* (2009), and Berger *et al.* (2010), and the results of this approach were described in Section 7.3.3.5. As Schreinemachers *et al.* (2009) point out however, the fact that the regression outputs and the empirical observations are not independent means that this remains an informal approach to validation. It reveals how well the econometric approximations explain variation in the observed phenomena rather than how well the model is able to project beyond the data upon which it was calibrated.

7.4.3 Qualitative Validation

The results of the model simulations were discussed with three experts in the agricultural economy of the study area during a follow-up period of fieldwork undertaken in January 2017. Two of these experts could broadly be described as agricultural support consultants, while the third was a farmer with historical ties to the area and an understanding of local cultural and regulatory processes. These three experts were asked to comment on each of the constraints modelled in this study. The mathematical representation of each constraint was first described, then each expert was asked to comment on whether they thought this constraint represented a real process, how well they thought the constraint was structured, and whether they thought the magnitude of the constraint was reasonable.

The three experts were also shown initial overall model results, comparing land use change in the optimised scenario with that under the constrained scenario. They were asked whether they thought that the land use changes simulated in the model were credible over the timeframe modelled and which scenario they thought produced the most credible dynamics. The following section describes the results of this overall model comparison, while Sections 7.4.3.2-7.4.3.7 provide an explanation of adjustments made to six constraints in light of this expert opinion. Sections 7.4.3.8 and 7.4.3.9 describe two constraints that were removed from the analysis because their conceptualisation was invalidated by the experts' insights. Mention is not made of constraints that the experts broadly agreed on.

7.4.3.1 Overall Model Comparison

Two of the three experts interviewed saw the changes in land use patterns as being credible over the timeframe modelled, while the third was unconvinced because he did not expect to see such a large proportion of the catchment converted to forestry in either scenario. In his words "80 years is a long time. I suppose I'm split. The challenge is for [drystock], I can see how it would initiate change, but I find it hard to believe everyone would just go into forestry."

Scepticism about the expansion of forestry simulated in the model runs was shared by one of the other experts, who commented "I would have picked there were going to be challenges in forestry in Northland". Asked whether he thought the model was underestimating the constraints on conversion to forestry, the unconvinced expert replied "I think so, yeah. Because I'd agree, I mean if the increasing yields are there then the dollars and cents in it would stack up, but in behind that you've got needing to have an immediate economic [turnover]…" As an alternative to forestry, the same expert reflected "knowing what I know about the catchment, I think dairy would probably be an easier option, mainly because the returns would be quicker…" One of the other experts also reflected that “If you had asked me what I thought was going to happen in 80 years’ time, I wouldn’t have picked drystock to have completely disappeared”.

In light of these observations, the constraint on conversion to forestry relating to the need to ensure a Minimum Cash Flow was increased. Initially, farmers were required to have at least 10% off-farm income to enable a conversion to forestry, however this was increased to 50% for the remainder of the analysis.

All three experts thought that the constrained scenario was the more credible scenario. Referring to the optimised scenario, one expert said “I’d find it hard to believe there’d be that much jumping around… even if things are 100% right it takes time, it takes time to shift”. Referring to the constrained scenario, another expert explained “Human nature overrides [economic signals], it’s that pig-headedness of ‘I’m a drystock farmer, I don’t grow trees’.” These responses give a level of confidence that, relative to an optimised scenario, the constrained scenario is seen as credible by experts in the economics of the studied region.

7.4.3.2 Lifestyle Preference

All three experts thought the preference for drystock farming with respect to lifestyle represented a real process. One of the experts pointed out that lifestyle should be linked to age, saying “the 60 year old [dairy] farmer doesn’t necessarily want to sell his farm, but doesn’t want to be doing intensive dairying”. Two of the experts interviewed thought that setting a lifestyle preference at 10% was overly conservative. In light of these responses, lifestyle preferences were scaled according to farmer age, with a minimum of 0 for farmers in the youngest age group (age = 1), and a maximum of 30% for farmers in the oldest age group (age = 9).

7.4.3.3 Kaitiakitanga

Two of the experts pointed out that it was not only Maori farmers who held the value of Kaitiakitanga. One of the experts estimated that the concept was held by between 20% and 25% of farmers in his experience. The other expert suggested that setting the magnitude of the constraint at 10% was low in his experience, suggesting that 15% to 20% could be more accurate. In order to remain conservative, the lower bound of these two estimates was used, meaning that 20% of farmers were programmed to be 15% less likely to accept advice to change to a more intensive land use.

7.4.3.4 Regulation

One of the experts pointed out that the regulatory limits placed on converting land from native forest to productive uses are not universal. According to him, "not all native forest is a protected natural area, and not all protected natural areas are protected under the district plan anyway… and then having said that, some farmers think it's there when it's actually not, and some farmers ignore it when it is there… But it's not a hard limit". Another expert provided counter evidence suggesting that it would be extremely hard to clear native bush, and cited the district council rules (Whangarei District Council, 2017) which state:

"Any damage, destruction or clearance of indigenous vegetation is a permitted activity if it complies with the following:

a) It is the removal of trees that are a danger to human life or existing structures (including network utilities); or

b) Clearance is for a new fence where the purpose of the fence is to exclude stock and/or pests from the area; or

c) It is beneath a canopy of a production forest; or

d) The removal of a tree or trees, or the gathering of plant matter is in accordance with Maori custom and values."

Based on these local regulations, it is seen as highly unlikely that large areas of native forest will be converted to productive uses in the future. Areas of the catchment classed as native forest were, therefore, programmed to be 95% less likely to change to a productive land use under this constraint. This level allows for exceptional circumstances permitting clearing of native forest, and a small degree of non-compliance.

7.4.3.5 Labour Constraints

Two of the experts interviewed pointed out that labour constraints were not solely determined within the area, and there was potential to bring in farm workers from overseas if the labour market was short. All three experts, however, thought that labour could constitute a real constraint within the catchment. One expert recommended increasing the level at which this constraint appeared to 30%. Conversion of land was therefore limited to a 30% expansion in area of any one land use in the catchment per model time step.

7.4.3.6 Social Information

All three experts thought that information from social networks was often inaccurate. However one of the experts who worked closely with the dairy industry pointed out that social information constraints were likely to be less apparent among dairy farmers because of the online accounting and reporting platform, Dairy Base. This expert further explained "it's based on accounts data, and I guess it's only based on what the farmer tells us they've produced, so maybe they could bullshit us, but they don't". Based on this, social information constraints are removed for farmers who practise dairy.

7.4.3.7 Conversion Costs

All three experts thought that conversion costs were an important adaptation constraint. While they all agreed that the costs of each specific land use change were set at a reasonable level, one of the experts pointed out that annualising these costs over 25 years was not justified. He thought that they should be annualised over ten to 15 years, explaining "I think 25's probably quite a long way out. Maybe too far out… it's real crystal-ball gazing, so I think the timeframe will be dragged back." In light of this, the more conservative estimate of 15 years was taken in place of the initial 25 years, and the conversion costs were adjusted accordingly.

7.4.3.8 Scale

While all three experts thought that farm scale could constrain farmers' decisions, it became clear that the interaction between scale and land use was more complex than originally proposed. Specifically, two of the experts thought that small scale dairy farmers may be forced to go to drystock, not because it could make more profit, but rather because it would lose less money. As one explained, "If you're losing money hand over fist because your cost of production is so high, then they can be forced to make changes… they're more likely to say 'bugger dairy, I'll just put a few beefies on'." It was acknowledged, however, that the original specification which favoured more intensive land uses would apply for farms that are close to, but below, the industry average. Intuitively, there is a point of scale as which the dominant motivation changes, however it is not clear that this point is knowable, and how the magnitudes of these competing motivations compare across different farm sizes. In light of this lack of confidence, scale constraints were removed from the remainder of the analysis.

7.4.3.9 Agricultural Information Constraints

While all three experts acknowledged the existence of agricultural information constraints, the direction of these constraints indicated by the Tobit regression model surprised them. As one expert explained “I would have thought that being more informed gives more confidence… because in theory knowledge builds confidence”. One of the experts linked this result to the dominance of subjective factors such as cultural identity and lifestyle preferences. This was echoed by another expert who said “I wonder if it’s just really subjective, because, I’m informing myself but it’s just not really where I want to be. So yes, I’m informed but it’s not enough to get me there.” Both of these explanations suggest that constraints related to agricultural information are dominated by other factors. They provide little explanation of why greater access to agricultural information would make a farmer less likely to change land use. In light of the uncertainty about why there was a negative correlation between agricultural knowledge and adaptive propensity, this constraint was removed from the model analysis.

7.5 Modelling Uncertainty

The accuracy of even the most verified and validated models is affected by both error and uncertainty. Error refers to the differences between actual and modelled values or processes that could potentially be identified but are not necessarily so (Berger and Troost, 2014). Error can be minimised through careful data collection and verification of model processes, however in reality, it is likely to substantially influence the results of complex models. Uncertainty, by contrast, refers to inaccuracies in data and model processes that are unknown because of limitations of our understanding of these data and processes (Berger and Troost, 2014). Uncertainty stemming from the models used in this study is discussed in the following section, while uncertainties in the yield projections used to force these models are discussed in Section 7.5.2. Path dependence is discussed in relation uncertainty in Section 7.5.3, while section 7.5.4 discusses the uncertainties inherent in emergent processes. Finally, Section 7.5.6 explains attempts to manage uncertainties in this study.

7.5.1 Structural Uncertainties

Uncertainty associated with the ARLUNZ model and the NZFARM sub-model stems from their inability to replicate highly complex SES with perfect accuracy. In reality, the socio-ecology of the Hikurangi catchment is vastly more complex than any computer model could simulate because it is affected by abstract processes such as interpersonal relations, complex micro-processes such as soil biology and pathogen diffusion, and highly unpredictable processes such as global markets and weather conditions. Many of these uncertainties are likely to be practically irreducible (Darnhofer, 2014).

The modified version of ARLUNZ used in this investigation is an attempt to simulate only what are understood to be the most relevant economic and behavioural dynamics, with a bias towards focusing on those which constrain land use change. To make the model tractable, many known processes with the potential to affect model outcomes are ignored. Moreover, it is likely that a vastly higher number of important social-ecological processes remain unknown. Ignorance and obliviousness of important model processes are likely to contribute substantial uncertainty to the modelling exercise undertaken in this study. While the overall level of structural uncertainty is impossible to estimate, the sensitivity analysis that will be described in Section 7.6 gives an understanding of the relative importance of model parameters, and by implication, an understanding of which aspects of the model are likely to contribute the most uncertainty.

Uncertainty also exists for the processes that are modelled explicitly. The processes modelled in ARLUNZ and NZFARM are interpreted simplifications of real processes. Even when these model processes appear to closely replicate real-world processes, this could occur for the wrong reasons, a situation called metaverisilitude (Parker *et al.*, 2003). While this possibility cannot be eliminated, it is also not seen as fatal to the utility of complex social-ecological models (Parker *et al.*, 2003).

The timeframe modelled in this study presents a specific problem that permeates all forms of climate change projections. The data with which models are built are captured under conditions that are expected to change considerably over the timeframe modelled. SES are highly complex and nonlinear, giving reason to expect that the dynamics and responses of these systems to stimuli would change under different environmental conditions (Evans *et al.*, 2013).

7.5.2 Climate Projection Uncertainties

Projections for the impacts of climate change on agricultural yields provide the central forcing to which farmers adapt within ARLUNZ. Climate projections are formed through a complex integration of theory and observation using models which are conceptually based but empirically calibrated. Even in their most sophisticated form, climate models are gross simplifications of reality. Uncertainty stems from regional biases in GCM behaviour (Hennessy *et al.*, 2007), theoretical challenges of downscaling methods (Boe *et al.*, 2009), and uncertainty over future greenhouse gas concentrations (Dessai and Hulme 2007). A number of these uncertainties are essentially irreducible (Dessai and Hulme, 2004). While recent increases in computing power have improved our ability to quantify these uncertainties, estimates of climate model uncertainties have widened in some cases (Dessai *et al.*, 2009).

GCM uncertainties are often seen to be substantial relative to other modelling uncertainties in complex impact assessments (Kingston &Taylor, 2010; Kingston *et al.*, 2010). Different GCMs form different projections for changes in climate at global and regional levels. Ideally, model studies should compare the impacts of climate projections from a range of different GCMs in order to understand the possible magnitude of GCM uncertainties in their results (Kingston *et al.*, 2010; Boe *et al.*, 2009). In this case, individual CGM yield change projections were not available. Yield projections are instead based on mean projections from an ensemble of six GCMs which were shown to perform well in the New Zealand region, namely: BCC-CSM1.1, GEM1-CAM5, GFDL-CM3, GISS-EL-R, HadGEM2-ES, and NorESM1-M.

GCM projections were downscaled to the 0.05 degree grid cell level for the whole of New Zealand by Tait *et al.*, (2016). These downscaled climate change projections were used as inputs for yield change projections at the same resolution produced for pastoral agriculture, forestry, and horticulture (Rutledge *et al.*, 2017). These projections are the most recent and comprehensive attempts to simulate agricultural yields in New Zealand under climate change.

7.5.3 Path Dependence

ARLUNZ is a complex, stochastic model in which heterogeneity and variation in agent attributes can substantially affect model outcomes. This leads to what are called 'nonconvexities' in the model outcome surface, in which model outcomes may reach peaks under multiple parameterisations or random seeds (Parker *et al.*, 2003). In these cases, model outcomes are path dependent because they rely on the initial model conditions (Huigen *et al.*, 2006; Parker *et al.*, 2003). The level of path dependence in the ARLUNZ model was examined by running the model multiple times using different random seeds, as will be explained in Section 7.6. The results of this exercise are described in Section 8.3.

7.5.4 Emergence

Emergence brings uncertainty to the interpretation of model outcomes because it is not feasible to formally determine the processes that lead to emergent outcomes (Happe *et al.*, 2006; Green, 2013). Even when a specific outcome is consistently generated when changing a single parameter, it is possible that the outcome was not affected by the parameter that was changed, but rather by another process, or multiple other processes linking the two (Green, 2013). It may be theoretically possible to trace the mathematical cause and effect pathways through the model, however in complex ABMs there are likely to be many potential pathways between stimulus and outcome and no way to determine which are the most relevant. With these uncertainties in mind, no attempts were made to explain model outcomes analytically in this study. The processes underlying adaptive land use change decisions were instead explored qualitatively by interviewing stakeholders.

7.5.5 Navigating Uncertainty

As the previous sections explain, uncertainty is an inevitable characteristic of this study. Scenarios are used by the IPCC as a key strategy for addressing uncertainty (Jones *et al.*, 2014). Scenarios are not predictions, rather they are presented as candidate descriptions of possible changes in systems over time. By presenting multiple scenarios in a consistent manner, an understanding of the uncertainties of the modelling exercise can be communicated.

With this in mind, the results of this study are presented as an attempt to model scenarios of adaptation constraints. The aim of the research is not to suggest what land use patterns in the Hikurangi Catchment may be under climate change, but rather to assess how adaptation constraints may affect outcomes relative to an optimised 'Ricardian' scenario. The constrained runs are presented as alternative scenarios, and variations between these scenarios can be interpreted as representing the uncertainties inherent to the modelling of adaptation constraints.

7.6 Experimental Design

A clear experimental design is needed in order to understand the impacts of the constraints on adaptation assessed in this study. Computational experiments vary certain model parameters and measure the effect these variations have on model outcomes (Morris, 1991). The large number of relevant constraints in this study means that the scope of the experiments had to be limited in a strategic way. The following three sections describe considerations in the experimental design, while Sections 7.6.4 and 7.6.5 describe the simulation experiments and sensitivity analysis undertaken in this study, respectively.

7.6.1 Foci of the Study

As explained in Chapter 1, this study aims to quantify the most important ways by which farmers' adaptive behaviours depart from optimised adaptation assumed under the prevailing Ricardian approach. The central focus of the modelling exercise is, therefore, to quantify the impacts of the relevant adaptation constraints, on an otherwise optimised adaptation scenario. The comparative measures are defined by the prevailing Ricardian approach, which generally assesses the effects of adaptation to change in monetary terms between two specific points in time (Seo *et al.*, 2009). As a result, while ARLUNZ has the ability to simulate a range of different economic and environmental measures, this study focuses largely on the differences in catchment revenue. The impacts of changes on other economic and environmental measures provide extensive grounds for further research.

7.6.2 Climate Change Scenarios

Climate change projections provide the forcing in response to which adaptation occurs in this study. Given considerable uncertainty about the impacts of climate change, particularly at small scales, it is important to understand the sensitivity of the model to different climate change projections. The projections of the Climate Change Impacts and Implications study (Tait *et al.*, 2016; Rutledge *et al.*, 2017) produced downscaled ensemble mean yield change projections for two Representative Concentration Pathways (RCPs): 2.6 and 8.5. These are the lowest and highest of the IPCC greenhouse gas concentration trajectories, respectively, representing radiative forcing of +2.6 and +8.5W/m^2 by 2100 relative to pre-industrial concentrations, respectively. It is possible that changes in precipitation or temperature could spike or dip at points within this range, particularly at small spatial resolutions. However as end-members of a range of concentration trajectories, RCPs 2.6 and 8.5 are likely to show the most variation attributable to differences in greenhouse gas concentration. The sensitivity of the model to assumptions about greenhouse gas concentrations is assessed by calculating and comparing results under both of these RCPs.

7.6.3 Stochasticity

The computing requirements of this study are further expanded because a number of the properties of the farmer agents and process of decision making within ARLUNZ use random seeds, making the model stochastic. As a result, a single model run is unable to describe the distribution of possible outcomes that would result from different random seeds, and could be an extreme value that represents this distribution poorly (Nickolic *et al.*, 2013; Thiele *et al.*, 2014). Nickolic *et al.* (2013, p. 110) point out that one should “never trust the outcome of a single run of an agent based model”. It is therefore necessary to run each model configuration multiple times with different random seeds in order to calculate second order metrics such as means and confidence intervals which describe the distributions of effects.

There is no consensus as to how many runs should be considered ‘sufficient’ (Thiele *et al.*, 2014; Railsback and Grimm, 2012). While as few as ten runs are sometimes applied for specific models, Thiele *et al.* (2014) caution that this is likely to be too few to credibly assess the distribution of outcomes for many models. Nikolic *et al.* (2013) suggest identifying the most variable parameters by performing 100 runs for each configuration using an efficient sampling strategy. The variance of the most variable parameters can then be assessed to interpret the number of repetitions after which the additional variance is negligible. In this case, the parameter space comprises 16 constraint parameters, meaning that it would require 1,600 model runs to run each configuration 100 times for a single parameter value. The size of the ARLUNZ model makes this infeasible because each full run takes approximately 4.1 core hours to complete. In this case, therefore, the scoping of variance was done over 32 runs for each parameter.

7.6.4 Simulation Experiments

Preceding the formal sensitivity analysis of adaptation constraints, more general simulation experiments were run. The use of more general simulation experiments is advocated by Thiele *et al.* (2014) who argue that they improve understanding of model behaviour. In this study, each of the adaptation constraints was applied in isolation to an otherwise optimised scenario in order to test how they affect adaptation in the absence of other constraints. In addition, a number of different combinations of constraints were tested. Groupings of constraints falling under the categories of generic constraints, specific constraints, and transaction costs were run with the other constraints turned off. The results of these initial simulation experiments are described in Section 8.2.

7.6.5 Sensitivity Analysis

The impacts of individual constraints were analysed by performing a sensitivity analysis in which the effects of varying parameter values on the outputs of the model were assessed. This provides a way to understand the relative importance of model parameters, as well as quantify their absolute importance (Thiele *et al.*, 2014). Sensitivity analyses also reveal the importance of parameter uncertainties. If varying specific parameters has little effect on model outputs, then uncertainties in these parameters are of low importance. If, alternatively, variations in parameter values greatly affect model outcomes, uncertainties in these parameters are shown to be more important (Thiele *et al.*, 2014). Sensitivity analysis can also identify programming artefacts and reveal the limits of the model's applicability, where specific parameter values produce outcomes that are clearly unrealistic (Parker *et al.*, 2003).

Sensitivity analysis methods can be separated into three broad groups: screening, local sensitivity analysis, and global sensitivity analysis (Thiele *et al.*, 2014). Screening methods are computationally efficient and can be used to rank the importance of parameters; however they are unable to quantify their importance (Thiele *et al.*, 2014). Local sensitivity analysis quantifies the effects of variations in input parameters on model outputs by adjusting parameters one at a time. While this can identify the importance of each parameter *ceteris paribus*, it does not account for possible interactions between simultaneous changes in multiple parameters (Thiele *et al.*, 2014). By contrast, global sensitivity analysis varies the values of multiple parameters simultaneously, providing information about the interactions between these parameters, but requiring vastly more model runs and computing resources to do so (Thiele *et al.*, 2014). Considering the size of the ARLUNZ model, a full global sensitivity analysis was not feasible within the limits of the current study. A local sensitivity analysis was, however, performed, as section 7.6.5.2 will describe.

While sensitivity analysis is widely seen as a necessary process for understanding the dynamics of complex models (Nickolic *et al.*, 2013; Thiele *et al.*, 2014; Railsback and Grimm, 2012; Ku, 2015), it remains uncommon in ABM studies. Thiele *et al.* (2014) conducted a survey of published ABM papers and found that only 12% of papers published in the Journal of Artificial Societies and Social Simulation and only 24% of papers published in Ecological Modelling contained some form of sensitivity analysis. This may be in part because sensitivity analysis requires massive repetitions of model runs, making it computationally expensive and time consuming. The size of the ARLUNZ model and the number of parameters in question meant that computing power and time constraints were important determinants of the experimental design in this case. These two constraints necessitated narrowing the parameter space from what would be assessed under a full factorial analysis. The sensitivity analysis performed in this study also required high-powered computing resources. It was run on the Darwin supercomputing cluster at the University of Cambridge. The model code was translated line-by-line into Linux/Unix format in order to do this. Adjustments were also made to the modelling file structure by Dr. Fraser Morgan and Dr. Adam Daigneault to allow for many experiments to be run in parallel. Even with this supercomputing resource, the analysis performed in this study still took more than a month to run.

7.6.5.1 Narrowing the Parameter Space

If computing power were not a limiting factor, sensitivity analysis would ideally explore each parameter of a model at a fine resolution across a broad range of values. Approaches such as the Design of Experiments methodology allow for this. As Thiele *et al.* (2014) point out, however, even relatively simple models may need to assess billions of parameter sets using this approach. Such an approach is generally not feasible for complex human-environment models (Ku, 2015). It is therefore necessary to focus the sensitivity analysis on a smaller subset of parameters. Therefore, while the ARLUNZ model comprises many other parameters, the sensitivity analysis conducted in this study focuses on the 16 parameters constraining adaptation described in Table 7.1.

7.6.5.2 Local Sensitivity Analysis

Following Thiele *et al.* (2014), parameter values were varied by 10%, truncated at their boundary values as reported in Table 7.5, giving a low estimate, and middle estimate, and a high estimate for each parameter. Because time steps were defined as being five years long, it was not possible to adjust the length of time that foresters are locked into their industry by 10%. This parameter value was increased and decreased by one full time step instead. The results of this local sensitivity analysis are described in Section 8.4.

Table 7.5: Low, middle and high estimates for the values of each adaptation constraint parameter.

Adaptation Constraint	Low Estimate	Middle Estimate	High Estimate
Minimum Cash Flow	Farmers with external income of less than or equal to 45% are restricted from changing to forestry.	Farmers with external income of less than or equal to 50% are restricted from changing to forestry.	Farmers with external income of less than or equal to 55% are restricted from changing to forestry.
Lifestyle Preference	Farmers 13.5% more likely to accept advice to change to drystock and 13.5% less likely to change away from drystock	Farmers 15% more likely to accept advice to change to drystock and 15% less likely to change away from drystock	Farmers 16.5% more likely to accept advice to change to drystock and 16.5% less likely to change away from drystock
Kaitiakitanga	Maori farmers 13.5% less likely to change to more intensive land uses	Maori farmers 15% less likely to change to more intensive land uses	Maori farmers 16.5% less likely to change to more intensive land uses
Risk Aversion	Each index point below 100 in the Behavioural Index is associated with a 0.00207% reduction in the likelihood of changing land use.	Each index point below 100 in the Behavioural Index is associated with a 0.0023% reduction in the likelihood of changing land use.	Each index point below 100 in the Behavioural Index is associated with a 0.00253% reduction in the likelihood of changing land use.
Cultural Identity	The likelihood of a farmer changing land use during their farm lifecycle is reduced by 9%.	The likelihood of a farmer changing land use during their farm lifecycle is reduced by 10%.	The likelihood of a farmer changing land use during their farm lifecycle is reduced by 11%.
Regulation	Areas of the catchment classed as 'native forest' in the baseline are 94.5% less likely to change to other land uses.	Areas of the catchment classed as 'native forest' in the baseline are 95% less likely to change to other land uses.	Areas of the catchment classed as 'native forest' in the baseline are 95.5% less likely to change to other land uses.
Disaster Experience	Each index point below 100 in the Experience Plus Index is associated with a 0.00135% reduction in the likelihood of changing land use.	Each index point below 100 in the Experience Plus Index is associated with a 0.0015% reduction in the likelihood of changing land use.	Each index point below 100 in the Experience Plus Index is associated with a 0.00165% reduction in the likelihood of changing land use.
Temporal Response Lags	Drystock to dairy: Likelihood of land use change adjusted by a factor between 0.865 and 0.955 proportional to each farmer's financial index score. Forestry to pasture: Likelihood of land use change adjusted by a factor between 0.712 and 0.82 proportional to each farmer's financial index score. Establishing horticulture: Likelihood of land use change adjusted by a factor between 0.82 and 0.856 proportional to each farmer's financial index score.	Drystock to dairy: Likelihood of land use change adjusted by a factor between 0.85 and 0.95 proportional to each farmer's financial index score. Forestry to pasture: Likelihood of land use change adjusted by a factor between 0.68 and 0.8 proportional to each farmer's financial index score. Establishing horticulture: Likelihood of land use change adjusted by a factor between 0.8 and 0.84 proportional to each farmer's financial index score.	Drystock to dairy: Likelihood of land use change adjusted by a factor between 0.835 and 0.945 proportional to each farmer's financial index score. Forestry to pasture: Likelihood of land use change adjusted by a factor between 0.648 and 0.78 proportional to each farmer's financial index score. Establishing horticulture: Likelihood of land use change adjusted by a factor between 0.78 and 0.824 proportional to each farmer's financial index score.
Labour Constraints	The number of new farmers that can enter dairy, forestry, or horticulture is limited to 33% of the total number in the industry in the current time step	The number of new farmers that can enter dairy, forestry, or horticulture is limited to 30% of the total number in the industry in the current time step	The number of new farmers that can enter dairy, forestry, or horticulture is limited to 27% of the total number in the industry in the current time step
Social Information	The information on profit gathered through social networks varied by a random factor with a mean of 100% (1) and a standard deviation of 9% (0.09).	The information on profit gathered through social networks varied by a random factor with a mean of 100% (1) and a standard deviation of 10% (0.1).	The information on profit gathered through social networks varied by a random factor with a mean of 100% (1) and a standard deviation of 11% (0.11).

Adaptation Constraint	Low Estimate	Middle Estimate	High Estimate
Conversion Costs	The following conversion costs are included in land use decisions: - Drystock to Dairy = $207.50 per ha - Anything to Forestry = $56.70 per ha - Forestry to pasture = $120.83 per ha - Anything to Horticulture = $3,118.82 per ha.	The following conversion costs are included in land use decisions: - Drystock to Dairy = $230.55 per ha - Anything to Forestry = $63 per ha - Forestry to pasture = $134.26 per ha - Anything to Horticulture = $3,465.35 per ha.	The following conversion costs are included in land use decisions: - Drystock to Dairy = $253.61 per ha - Anything to Forestry = $69.3 per ha - Forestry to pasture = $147.69 per ha - Anything to Horticulture = $3,811.89 per ha.
Dairy Path Dependence	Dairy farmers are programmed to be 7.002% less likely to change land use.	Dairy farmers are programmed to be 7.78% less likely to change land use.	Dairy farmers are programmed to be 8.558% less likely to change land use.
Forestry Path Dependence – code outside normal place	Foresters are locked in to their industry for 4 consecutive time periods.	Foresters are locked in to their industry for 5 consecutive time periods.	Foresters are locked in to their industry for 6 consecutive time periods.
Self-Efficacy	Each index point below 100 in the Self Efficacy index is associated with a 0.00666% reduction in the likelihood of changing land use.	Each index point below 100 in the Self Efficacy index is associated with a 0.0074% reduction in the likelihood of changing land use.	Each index point below 100 in the Self Efficacy index is associated with a 0.00814% reduction in the likelihood of changing land use.
Technical Expertise	Each index point below 100 in the Expertise index is associated with a 0.0018% reduction in the likelihood of changing land use.	Each index point below 100 in the Expertise index is associated with a 0.002% reduction in the likelihood of changing land use.	Each index point below 100 in the Expertise index is associated with a 0.0022% reduction in the likelihood of changing land use.
Climate Change Information Constraints	Index scores below a cutoff of 55 are calculated as constraints that decay over the first three time steps (multiplied by 1, 0.66 , 0.33, and 0 thereafter). Conversion rate is adjusted in proportion with the decayed farmer information index.	Index scores below a cutoff of 50 are calculated as constraints that decay over the first three time steps (multiplied by 1, 0.66 , 0.33, and 0 thereafter). Conversion rate is adjusted in proportion with the decayed farmer information index.	Index scores below a cutoff of 45 are calculated as constraints that decay over the first three time steps (multiplied by 1, 0.66 , 0.33, and 0 thereafter). Conversion rate is adjusted in proportion with the decayed farmer information index.

Chapter 8

Modelling Results

This chapter describes the results of the modelling exercise. It begins by presenting findings about the overall impacts of the full suite of adaptation constraints. Section 8.2 presents the results of tests comparing the different categories of constraints described in Section 4.8.1. Section 8.3 describes the impacts that individual constraints had on model outcomes, and assesses the variance contributed by stochastic elements of the model using different random seeds. Section 8.4 presents the results of the local sensitivity analysis and the final section summarises the modelling results.

8.1 Overall Impacts of Adaptation Constraints

This section describes the impacts of the full suite of adaptation constraints modelled in this study (referred to as the All Constraints specification) on model outcomes relative to a specification in which no constraints are applied (referred to as the Optimised specification). Each of the tests described were run 32 times using 32 different random seeds, which were kept the same for each of the experiments to compare results fairly.

The results of the Optimised specification are described first because these provide a 'baseline' against which various constrained specifications are compared. As explained in Section 2.5, and illustrated in Figure 7.2, the Optimised specification describes the model behaviour when assuming rational choice among farmers. Changes in land use in the catchment under the Optimised specification are shown in Figure 8.1, while the number of farmers that NZFARM recommended to change land use, and the number accepting these recommendations are shown in Table 8.1. The land use figures show large shifts in land use towards forestry and away from dairy and particularly drystock between the baseline period and 2035, while changes thereafter are difficult to distinguish. Table 8.1 shows that this massive land use shift occurs in the first time step, as farmers adjust perfectly to the coarse calibration of NZFARM described in Section 7.2.1. This adjustment is further explored later in this section, and is discussed in Section 9.2. Small changes in recommended land use continue after the first time step in response to climate change. Table 8.1 also demonstrates that farmers follow perfectly the advice of NZFARM in the Optimised specification.

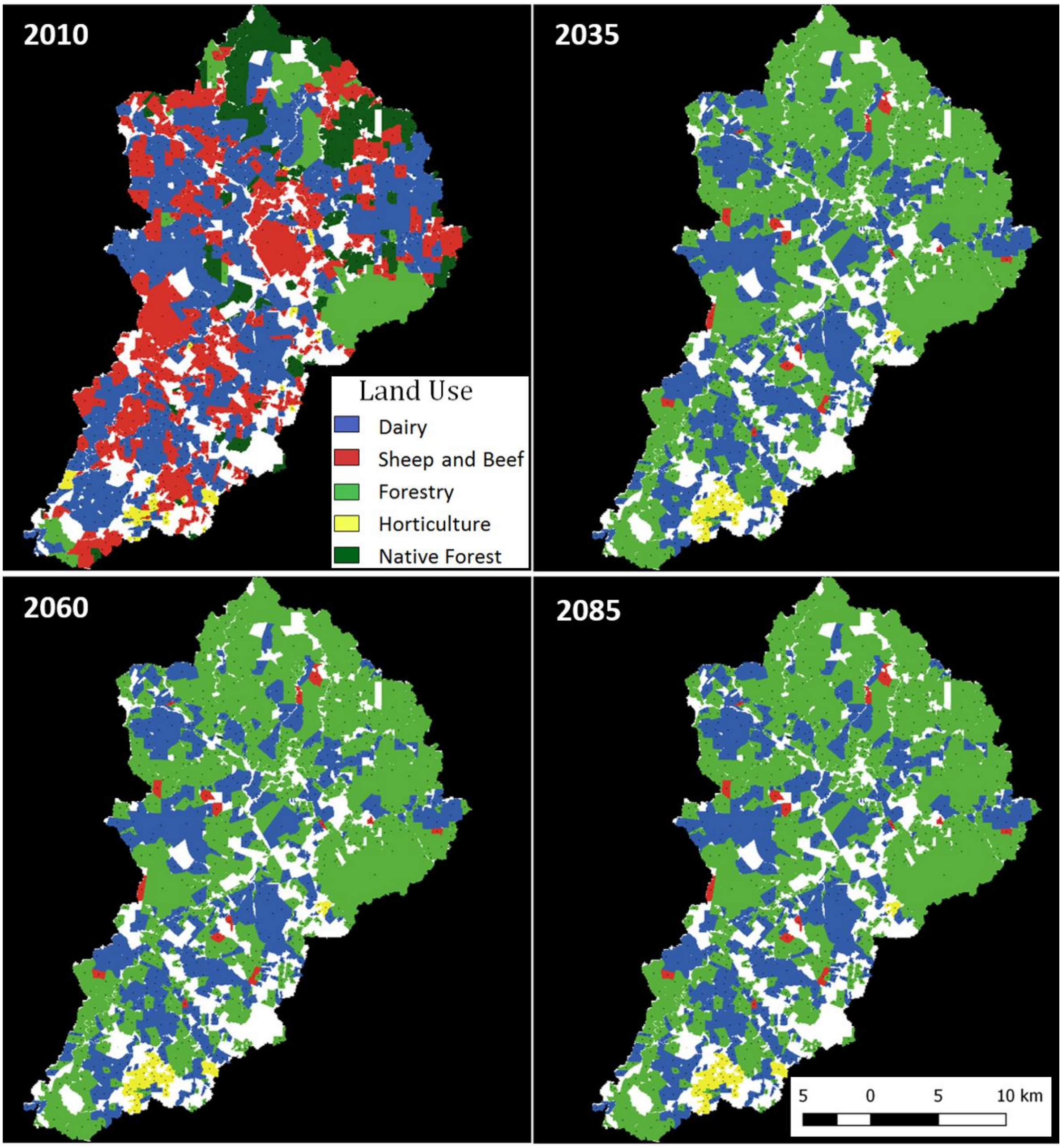


Figure 8.1: Modelled land use in the Hikurangi catchment at 25 year intervals from 2010 to 2085 under the Optimised specification for RCP 8.5. RCP 2.6 showed very similar results, and is therefore not reported here.

Table 8.1: Number of farmers that NZFARM recommends to change land use in each model time step, and number of farmers who accept this recommendation under the Optimised specification.

Year	Number of Farmers Recommended to change	Number of Farmers Accepting Recommendation	Acceptance Rate (%)
2015	711	711	100
2020	37	37	100
2025	35	35	100
2030	35	35	100
2035	37	37	100
2040	35	35	100
2045	35	35	100
2050	34	34	100
2055	34	34	100
2060	34	34	100
2065	35	35	100
2070	34	34	100
2075	34	34	100
2080	34	34	100
2085	34	34	100

The Optimised specification is compared first to the All Constraints specification because, as explained in Section 4.8, the constraints on adaptation apply together in reality, and they are likely to interact in important ways. Changes in land use in the catchment under the All Constraints specification are shown in Figure 8.2, while the number of farmers that NZFARM recommended to change land use, and the number accepting that recommendation are shown in Table 8.2. The land use images show a much slower and smoother progression of land use change away from drystock and towards dairy and particularly forestry than under the Optimised specification. Under the All Constraints specification, land use never reaches the 'optimal' land use pattern shown in Figure 8.1. The final land use pattern is far more heterogeneous, with many more farmers continuing to farm drystock than did so under the Optimised specification. Table 8.2 shows that, while NZFARM again recommends massive changes in land use in the first time step, only a small proportion of farmers accept these recommendations. This means that the number of changes recommended by NZFARM is again high in the second time step. The rate of acceptance of NZFARM's advice shows a declining trend over time, reflecting the tendency for less constrained farmers to change land use over time, leaving more constrained farmers among the group being advised to change by NZFARM. This results in the more gradual changes in land use over time evident in Figure 8.2.

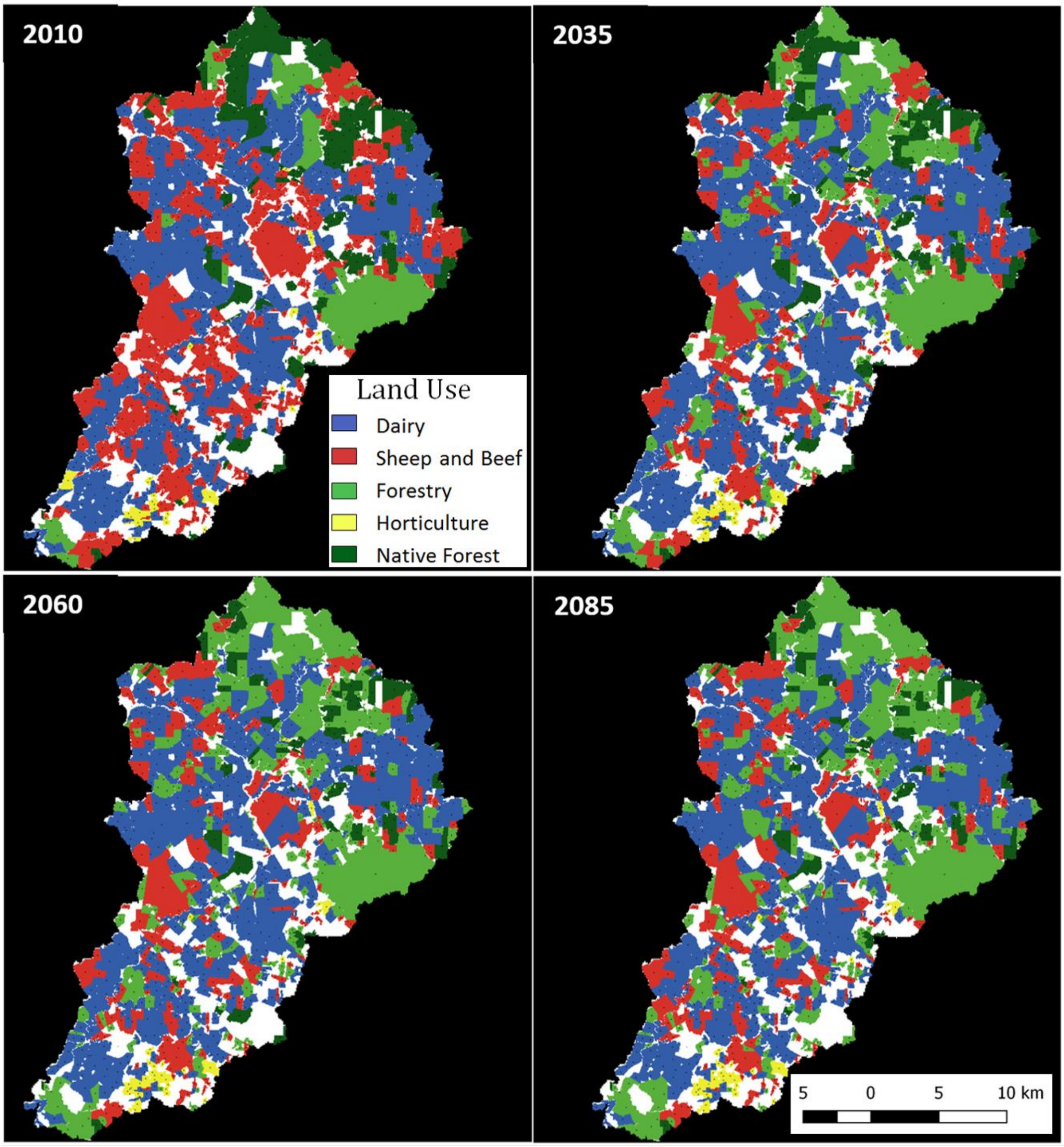


Figure 8.2: Modelled land use in the Hikurangi catchment at 25 year intervals from 2010 to 2085 under the All Constraints specification for RCP 8.5. RCP 2.6 showed very similar results, and is therefore not reported here.

Table 8.2: Number of farmers that NZFARM recommends to change land use in each model time step, and number of farmers who accept this recommendation under the All Constraints specification.

Year	Number of Farmers Recommended to change	Number of Farmers Accepting Recommendation	Acceptance Rate (%)
2015	711	91	12.80
2020	626	58	9.27
2025	576	52	9.03
2030	531	25	4.71
2035	512	21	4.10
2040	494	18	3.64
2045	482	11	2.28
2050	474	9	1.90
2055	467	10	2.14
2060	458	13	2.84
2065	450	11	2.44
2070	439	7	1.59
2075	434	6	1.38
2080	429	7	1.63
2085	428	2	0.47

These differences in land use patterns have substantial impacts on the total catchment profit each specification produces over the modelled time period. Table 8.3 compares the mean cumulative catchment profit over the modelled time period between the Optimised specification and the All Constraints specification for the IPCC's Representative Concentration Pathways (RCPs) 2.6 and 8.5, and a specification in which no climate change is applied. The profit estimates for each specification were compared using a paired two-sample t-Test. This demonstrated a highly statistically significant difference between the Optimised specification and the All Constraints specification for each of the three climate change scenarios. The All Constraints specification produced lower cumulative catchment profits in each case, ranging between 33.79% lower under RCP 8.5 and 30.66% lower under the specification with no climate change forcing.

In dollar terms, under RCP 8.5 the average annual profit per farm over the 75 year time period is $265,147 under the Optimised specification and $175,544 under the All Constraints specification, implying that these constraints reduce income per farmer by an average of $89,604 per year. The impact of these constraints is reduced to $77,799 per farmer per year under RCP2.6, and to $73,309 per farmer under no climate change forcing. These figures are not discounted; the implications of which are discussed in Section 9.4.3.

Table 8.3: Comparison of model results including 32-seed mean total catchment profits, percentage difference in means, paired t-Test one-sided p-values, and differences in average annual profit per farmer for RCP 8.5, RCP 2.6, and no climate change forcing.

	Model Specification	**Mean Total Catchment Profit ($)**	**Difference in Mean (%)**	**t-Test P(Optimised<= All Constraints)**	**Difference in Profit per Farmer ($)**
RCP 8.5	Optimised	1.83E+10	33.79%	0.00***	89,604
	All Constraints	1.21E+10			
RCP 2.6	Optimised	1.72E+10	31.15%	0.00***	77,799
	All Constraints	1.18E+10			
No CC	Optimised	1.65E+10	30.66%	0.00***	73,309
	All Constraints	1.14E+10			

*(significant at the 10% level) **(significant at the 5% level ***(significant at the 1% level)

The significant impact of adaptation constraints in the specification with no climate change forcing indicates that much of this impact accumulates in response to adjustments to NZFARM's low agreement with the baseline land use caused by its low-resolution calibration. The differences in mean total catchment profit between the Optimised and All Constraints specifications over time were therefore compared in order to isolate the impacts of adaptation constraints under each climate change scenario. Figure 8.3 shows the different trajectories of these impacts. The impacts of adaptation constraints are greatest under RCP 8.5, and the difference between this scenario and the no climate change scenario increases over time. Adaptation constraints have noticeably more impact under RCP 2.6 than under the no climate change scenario through much of the modelled time period; however this difference reduces towards the end of the century, reflecting the increasing impacts of climate change mitigation under this scenario. Adaptation constraints have a smaller impact on total catchment profit in the final time step under the RCP2.6 scenario than under the no climate change scenario. This is likely to reflect the benefits of greater incentives to change earlier in the modelled period dominating the reduced climate change signal by 2085 under this scenario. The differences between these impact trajectories were also compared using paired two-sample t-Tests. In each possible comparison these returned P (Optimised<=All Constraints) values of 0.00, indicating that the impacts of adaptation constraints in these three scenarios were significantly different at the 1% level.

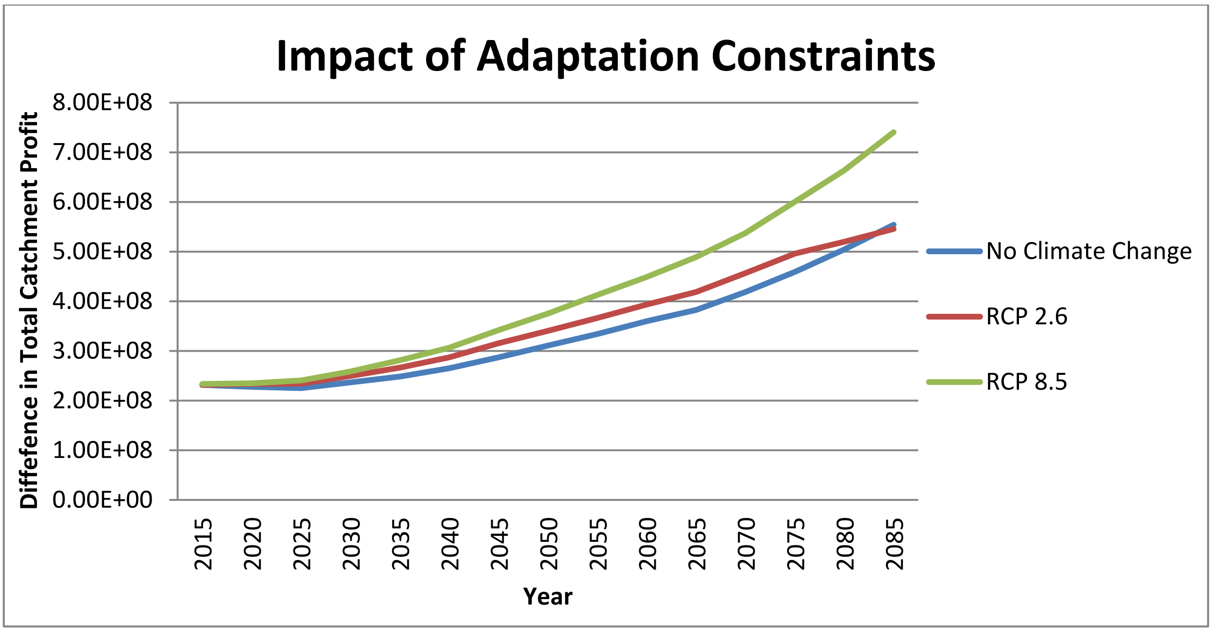


Figure 8.3: Cumulative impacts of adaptation constraints measured by the difference in total catchment profits between the Optimised and the All Constraints specifications under RCP 8.5, RCP 2.6 and a no climate change scenario.

Figure 8.4 shows mean total catchment profits over time with 95% confidence intervals for the All Constraints and Optimised specifications under RCPs 2.6 and 8.5. Substantial differences arise between the two specifications in the first model time step, and these differences increase over time in absolute terms under both RCPs. In all cases, RCP 2.6 shows slightly lower catchment profits, reflecting smaller projected yield increases. The 95% confidence intervals are very narrow around each of the specifications tested. This indicates low stochasticity within the model, which is explored further in Section 8.3.1.

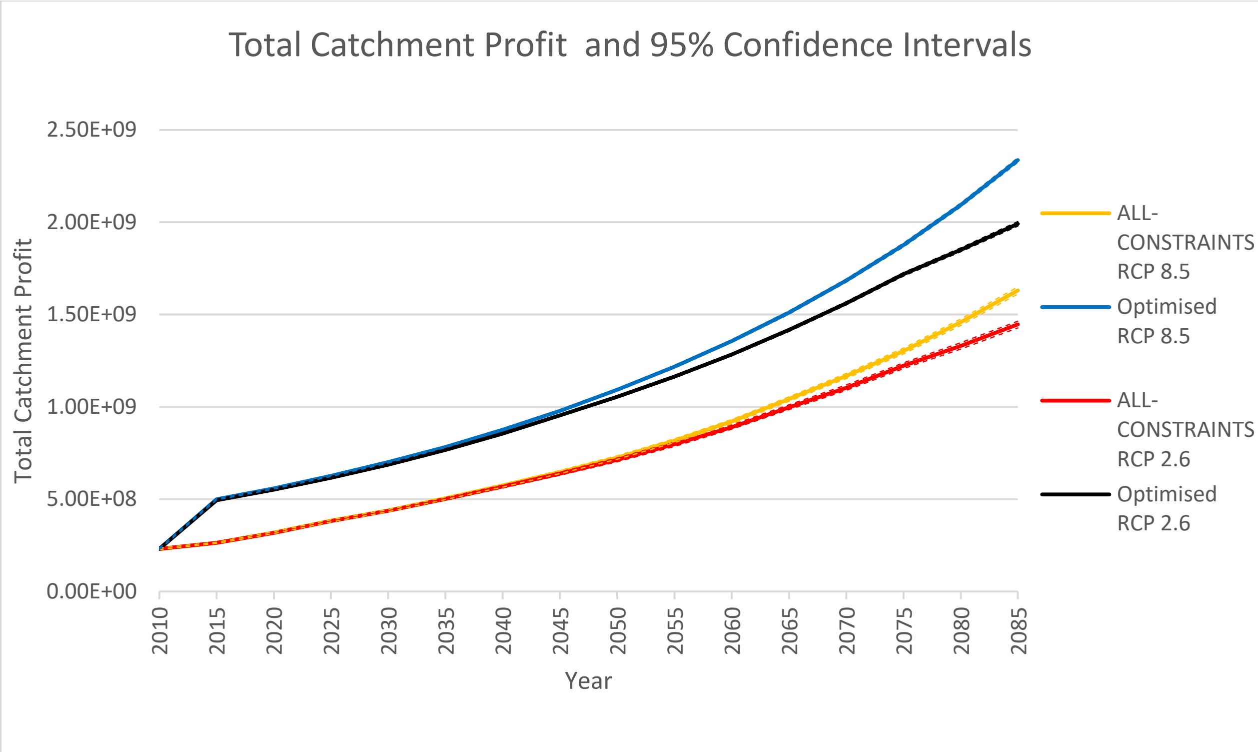


Figure 8.4: Mean total catchment profits between 2010 and 2085, with 95% confidence intervals for RCPs 8.5 and 2.6.

The relative difference in mean total catchment profits over time between the Optimised and All Constraints specifications is shown in Figure 8.5. The relative impact of adaptation constraints is greatest in the early part of the time period, and declines over time. This is likely to reflect the probabilistic nature of many of the constraints modelled. Each farmer makes 15 decisions about whether or not to change land use during the 75 years modelled. When NZFARM consistently provides a recommendation to change land use over this timeframe then this is more likely to be accepted than not over the time period if the chance of accepting the advice in any one time step is greater than roughly 7%. This may reflect random elements in farmers' decision making in reality eventually leading to change when a decision is reconsidered many times. It does, however, also assume that farmers reconsider their land use decisions every five years on average, which may not be the case.

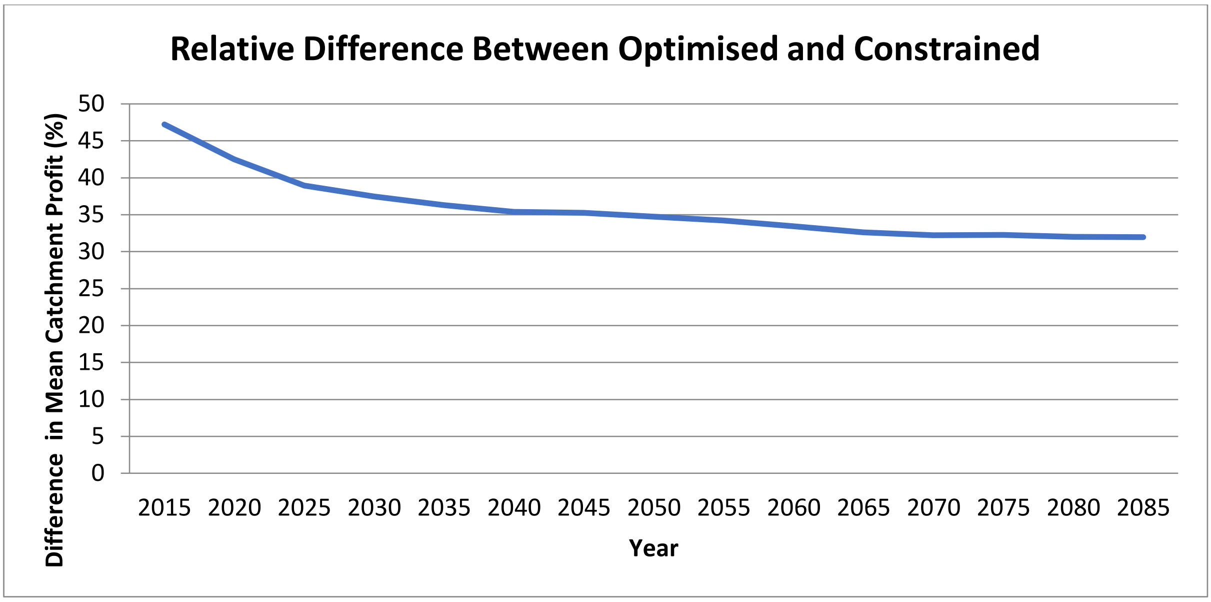
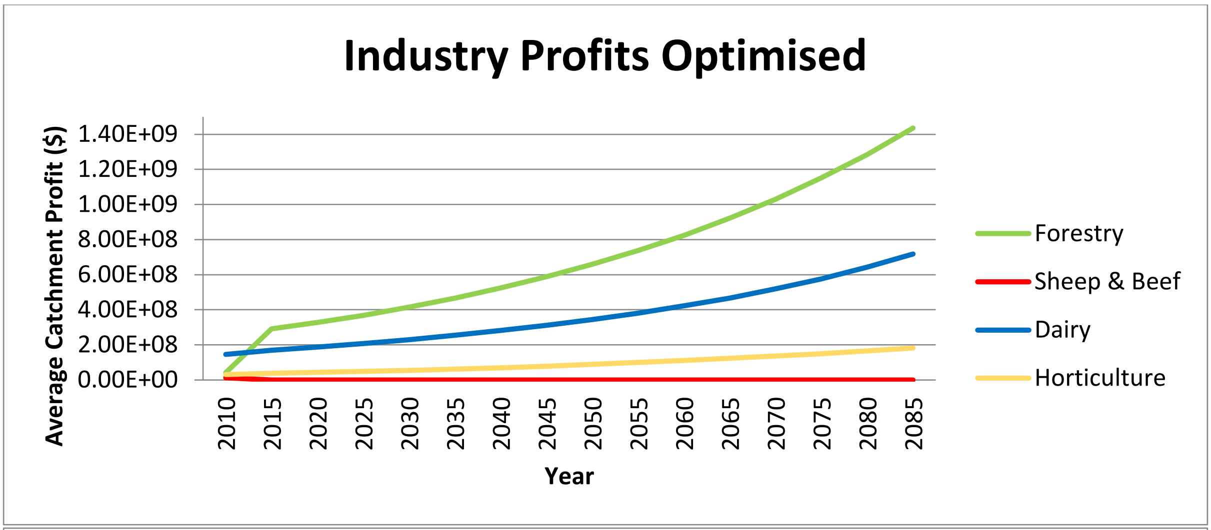


Figure 8.5: Relative difference in mean total catchment profit over time between the Optimised and All Constraints model specifications under RCP 8.5. RCP 2.6 showed very similar results and is therefore not reported here.

Figure 8.6 compares profit generated over time in each industry between the Optimised and All Constraints specifications. It demonstrates that the major difference between these two specifications is in forestry profits which amount to roughly double dairy profits under the Optimised specification but remain lower than dairy profits under the All Constraints specification. While the All Constraints specification shows slightly higher dairy and drystock profits, reflecting larger areas under these land uses, these increases are minimal compared to the loss of forestry profits relative to the Optimised specification. This suggests that the constraints on farmers changing their land use to forestry are likely to have the greatest impact on financial outcomes.



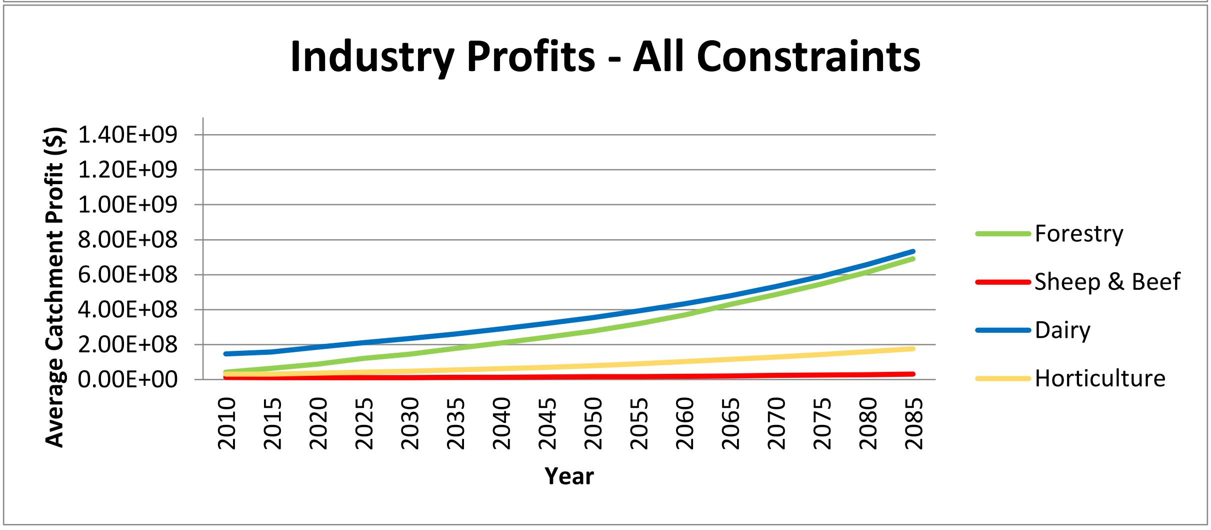


Figure 8.6: Average catchment profits for each land use under the Optimised and All Constraints specifications for RCP 8.5. RCP 2.6 showed very similar results and is therefore not reported here.

8.2 Categories of Constraints

The impacts of groups of constraints falling under the categories of Generic Constraints, Specific Constraints, and Transaction Costs (as described in Section 4.8.1) were tested in isolation and their results were compared with the Optimised specification. Table 8.4 compares the mean total catchment profit over the modelled time period for these comparisons. Specific Constraints had by far the greatest impact – reducing total catchment profit by an even greater extent than the All Constraints specification. This result reflects the impact of the sequencing of constraints in the model, as described in Section 7.2.1.5. In the Specific Constraints specification, stronger constraints such as Regulation and Self Efficacy appeared higher in each agent's decision making process because other smaller constraints were removed. This meant that these stronger constraints acted on a probability of accepting the advice to change that was closer to 1, meaning that their absolute impact on this probability was greater under the Specific Constraints specification than under the All Constraints specification.

Generic Constraints had a moderate impact, reducing catchment profits by close to 10% over the time period. This difference was significant at the 1% level. Transaction Costs had the smallest impact on catchment profits, and the difference between profits under this group of constraints and the Optimised specification was not statistically significant.

Table 8.4: Comparison of model results including 32-seed mean total catchment profits, percentage difference in means relative to an Optimised specification, paired t-Test one-sided p-values, and differences in average annual profit per farmer relative to an Optimised specification for the categories of Generic Constraints, Specific Constraints, and Transaction Costs.

Model Specification	Total Mean Catchment Profit ($)	Difference in Mean vs. Optimised (%)	t-Test P(Optimised<=model specification)	Difference in Profit per Farmer vs. Optimised ($)
Generic Constraints	1.66E+10	9.23	0.00***	24,583
Specific Constraints	1.21E+10	34.12	0.00***	90,880
Transaction Costs	1.82E+10	0.88	0.12	2,353

*(significant at the 10% level) **(significant at the 5% level ***(significant at the 1% level)

Figure 8.7 shows the mean total catchment profits over time for Generic Constraints, Specific Constraints, and Transaction Costs, compared to an Optimised specification. Specific Constraints have a persistently large impact on profit throughout the modelled-time period. Generic Constraints have a more modest impact on catchment profit, however the impact of these constraints is also persistent. Transaction Costs reduce catchment profits in the first time step, however they have little impact thereafter, and profits under this constraint category are very similar to those under the Optimised specification from 2020 onwards. This may reflect the decaying influence of climate change information constraints, which cease to have influence as time progresses.

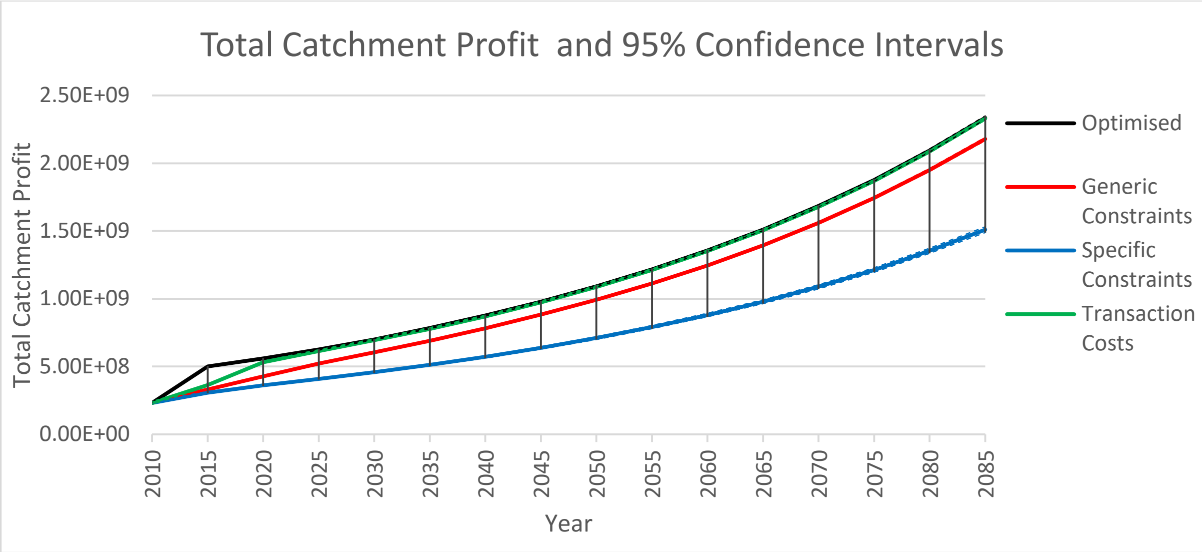


Figure 8.7: Mean total catchment profits between 2010 and 2085, with 95% confidence intervals for an Optimised specification and specifications using generic constraints, specific constraints, and transaction costs.

8.3 Impacts of Individual Constraints

The impacts of each of the individual constraints were also tested by running each in isolation across 32 random seeds under RCP 8.5. Table 8.5 compares the mean total catchment profit over the modelled time period under each individual constraint to the same 32-seed mean for the Optimised specification, ordered by level of impact. The impacts of these constraints varied markedly. Five constraints, namely Minimum Cash Flow, Regulation, Labour Constraints, Response Lags, and Forestry Path Dependence, showed differences with the Optimised scenario that were significant at the 1% level. Dairy Path Dependence showed differences with the Optimised scenario that were significant at the 5% level, while Self Efficacy and Social Information showed differences significant at the 10% level. The results from applying the remaining constraints did not differ significantly from the Optimised scenario.

In a number of cases, constraints that caused greater overall differences in total catchment profit registered higher p-values indicating low statistical differences. For example, while climate change information constraints resulted in average annual differences of $1,683 per farmer, comparing the datasets for mean profit per time step over the modelled time period indicated no significant difference from the Optimised specification. By contrast, Dairy Path Dependence resulted in average annual differences of only $185 per farmer, but these were found to be significant at the 5% level. This likely reflects the relative persistence of each constraint. Climate change information constraints were designed to decay over the first three time steps (to reflect an expansion in the communication and understanding of climate change impacts), meaning that after 2025, the climate change information constraints scenarios would produce identical catchment profits to the Optimised scenario, hence the lack of statistical difference when datasets for the individual time steps are compared. By contrast, Dairy Path Dependence is likely to impact catchment profits at any point during the modelled time period when farmers are being advised to change land from dairy to a different use.

Two constraints, namely Minimum Cash Flow and Regulation, had particularly large impacts on total catchment profits relative to an Optimised scenario. The Minimum Cash Flow constraint restricts conversion of land to forestry for any farmer earning less than 50% of their income from outside agriculture. This restriction had almost as much impact on total catchment profits as the All Constraints scenario, suggesting that it may be responsible for much of the impact of adaptation constraints identified in this study. The impact of this constraint reflects the dominance of forestry in catchment incomes under the Optimised scenario depicted in Figure 8.5. The Regulation constraint had roughly one fifth of the economic impact of the All Constraints scenario. This constraint made farmers 90% less likely to accept the advice of NZFARM to change land use if their initial land use was native forest. While not a hard restriction, the impacts of this constraint were likely to persist for many time-steps because of the small chances of accepting NZFARM's advice.

Table 8.5: Comparison of model results including 32-seed mean total catchment profits, percentage difference in means relative to an Optimised specification, paired t-Test one-sided p-values, and differences in average annual profit per farmer relative to an Optimised specification for each of the individual constraints modelled in this study.

Model Constraint	**Mean Total Catchment Profit**	**Difference in Mean vs. Optimised**	**P(Optimised<=model specification)**	**Mean Annual Difference in Profit per Farmer vs. Optimised**
Minimum Cash Flow	1.23E+10	32.52%	0.00***	$86,223
Regulation	1.69E+10	7.66%	0.00***	$20,412
Labour Constraints	1.79E+10	2.23%	0.00***	$5,931
Lifestyle Preference	1.81E+10	1.02%	0.028	$2,696
Climate Change Information	1.81E+10	0.63%	0.18	$1,683
Social Information	1.82E+10	0.57%	0.082*	$1,503
Self Efficacy	1.82E+10	0.54%	0.063*	$1,451
Risk Aversion	1.82E+10	0.19%	0.13	$494
Cultural Identity	1.82E+10	0.18%	0.12	$472
Kaitiakitanga	1.82E+10	0.14%	0.14	$367
Technical Expertise	1.82E+10	0.14%	0.13	$360
Response Lags	1.83E+10	0.12%	0.00***	$314
Disaster Experience	1.82E+10	0.11%	0.14	$299
Dairy Path Dependence	1.82E+10	0.07%	0.02**	$185
Forestry Path Dependence	1.83E+10	0.07%	0.00***	$177

*(significant at the 10% level) **(significant at the 5% level) ***(significant at the 1% level)

Figure 8.8 shows the mean total catchment profits over time for each of the constraints modelled individually in this study compared to an Optimised specification. The substantial impact of the Minimum Cash Flow constraint is the most striking feature of these data. This constraint shows some increases in profit in the first time step, likely as a result of the proportion of farmers with more than 50% of their income from outside farming switching to forestry. At this first time step, the impact of Minimum Cash Flow is only slightly larger than for climate change information constraints. However from 2015 onwards, Minimum Cash Flow has a substantial and persistent impact on total catchment profits, reflecting the hard limit preventing many farmers from ever converting to forestry. The Regulation constraint has a smaller but similarly persistent impact on catchment profits, while many of the other constraints have impacts that decay rapidly over the early time steps of the modelled period. This decay is likely to reflect the probabilistic nature of many of the constraints modelled, described in relation to Figure 8.5.

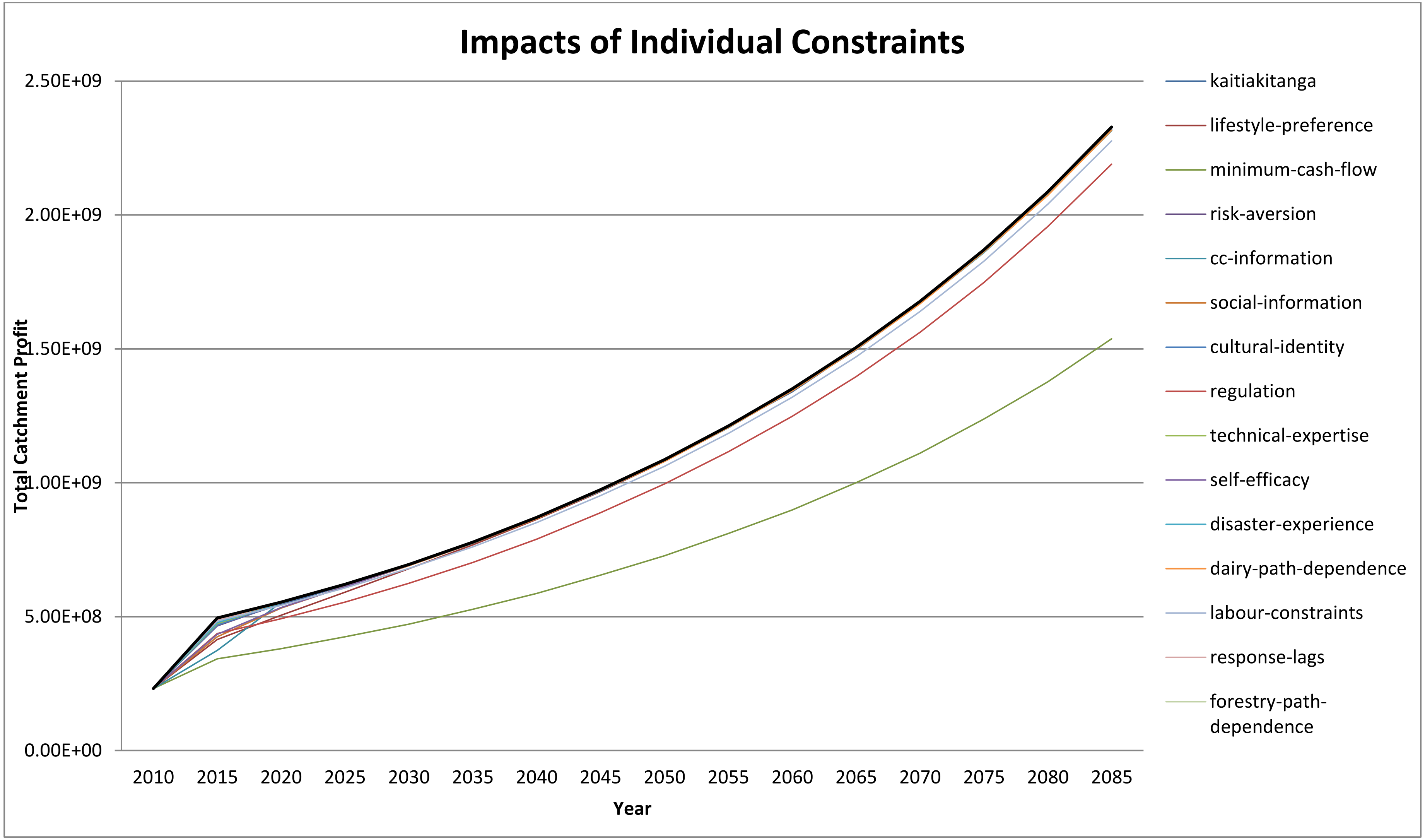


Figure 8.8: Mean total catchment profits between 2010 and 2085 for each of the individual constraints modelled in this study and an Optimised specification.

8.3.1 Scoping of Variance

As explained in Section 7.6.3, each of the adaptation constraints added in this study was run using 32 different random seeds under the most extreme climate change scenario in order to explore the variance contributed by random elements of the model. Figure 8.9 shows the impact that each additional run with a different random seed contributed to the running-mean of total catchment profit for each of the individual constraints modelled in this study. These data demonstrate that the model is not highly stochastic, and changing the random seed that the model is run with has little impact on the running mean. This impact declines with the addition of more runs, and does not exceed 0.5% for any constraint after the fourth random seed is added. The trends of the individual constraints show some co-variance. For example, the fourth random seed has a large impact on the running mean of most of the constraints tested, indicating that it may have created quite unusual initial model conditions. There are, however, also differences in the way that each constraint changes with the addition of extra model runs, reflecting idiosyncrasies in the impacts these constraints have on total catchment profits.

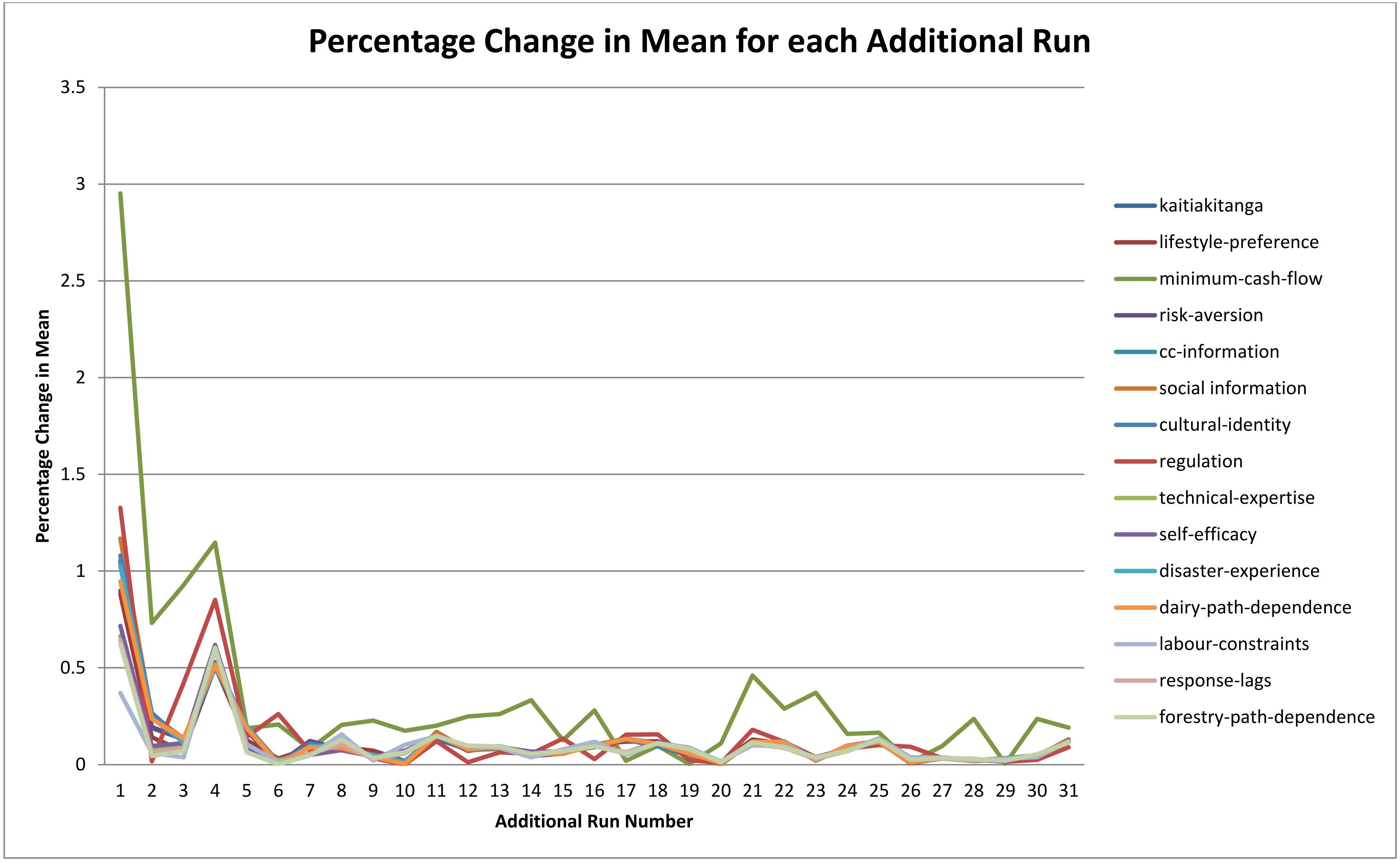


Figure 8.9: Percentage change in the running mean of total catchment profit for each additional model run and each individual constraint under RCP 8.5.

8.4 Local Sensitivity Analysis

Given the low levels of model stochasticity found in the scoping exercise, the number of random seeds run for each constraint was reduced to eight for the local sensitivity analysis. As specified in Table 7.5, the sensitivity of the model to the strength of each constraint was tested by varying each by 10% above and below their best-estimate values. The results of this local sensitivity analysis are presented in Table 8.6, ordered the size of the deviation their high estimate caused. The largest absolute impacts on the model results were, unsurprisingly, found for the constraints that had the greatest impacts on the model results. Deviations in the impacts of the two most important constraints, Minimum Cash Flow and Regulation, were, however, lower than the 10% adjustments to their values. The large impacts these two constraints have on the model can, therefore, be seen in relative terms as not particularly sensitive to the level at which they are set.

By contrast, a number of the constraints showed a greater than 10% difference in model results for a 10% change in their value. The constraints relating to Lifestyle Preference, Kaitiakitanga, Labour Constraints, and Cultural Identity each show greater than 10% deviations in impact for both the high and low estimate adjustments. The impact of these constraints on the model outcomes can therefore be seen as relatively sensitive to changes to the level at which each is set. However, the small total impacts of these three constraints meant that the absolute deviations caused by changing their values was modest.

A number of constraints showed highly non-linear sensitivity to changes in their values. Dairy Path Dependence, Risk Aversion, Response Lags, and Disaster Experience were substantially more sensitive to reductions in the level at which they were set than to increases in this level. By contrast, Technical Expertise, Social Information, Climate Change Information and Self Efficacy were substantially more sensitive to increases in the level at which they were set than to decreases. These differences may reflect a non-linearity in marginal land use decisions. For example, while increasing the Dairy Path Dependence value by 10% may have only affected the land use decisions responsible for a small land area, it appears that a 10% increase from the best-estimate value affected the land use decisions responsible for a much larger farm area. Given the modest impact many of these asymmetrical constraints had, the difference between increasing and decreasing their values could reflect different decisions made by a small number of farmers, or even a single very large farmer.

Table 8.6: Deviations in the absolute and relative impacts of each constraint on model outcomes when the constraint value was increased by 10% (high) and decreased by 10% (low).

	Deviation caused by low estimate (%)	**Deviation caused by high estimate (%)**	**Low-estimate Deviation as a percentage of impact**	**High-estimate Deviation as a percentage of impact**
Minimum Cash Flow	2.05	1.53	6.09	4.55
Regulation	0.5	0.35	6.78	4.75
Lifestyle Preference	0.15	0.2	12.30	16.39
Self Efficacy	0.075	0.11	14.15	20.75
Climate Change Information	0.066	0.11	8.15	13.58
Kaitiakitanga	0.066	0.061	21.29	19.68
Labour Constraints	0.48	0.46	19.92	19.03
Cultural Identity	0.045	0.039	12.16	10.54
Social Information	0.02	0.036	2.56	4.62
Technical Expertise	0.0024	0.016	1.71	11.43
Disaster Experience	0.035	0.0053	11.29	1.71
Response Lags	0.023	0.0046	8.21	1.66
Risk Aversion	0.016	0.0043	4.21	1.13
Dairy Path Dependence	0.035	0.0028	14.58	1.17
Forestry Path Dependence	0.00	0.00	0.00	0.00

8.5 Summary of Modelling Results

The results presented in this chapter reveal a number of insights about the economic impacts of adaptation constraints in the Hikurangi catchment. The full suite of adaptation constraints reduced total catchment profits by a highly statistically significant margin under RCPs 2.6, 8.5, and a scenario in which no climate change occurs. The impact of adaptation constraints in the no climate change scenario indicates that the low-resolution calibration of NZFARM is a substantial driver of adaptation in the model. The three possible climate change scenarios did, however, still produce results that were highly statistically different from one another.

The influence of adaptation constraints was found to decrease over time in relative terms. The proportion of farmers accepting NZFARM's advice to change land use was also found to decrease over time. Adjustments in land use were found to be much slower and smoother over time when the full suite of constraints was applied than it was under the Optimised scenario. Major differences in profit between the two scenarios were driven largely by differences in forestry area, with the Optimised scenario leading to rapid expansion of forestry area that was not matched in the All Constraints scenario.

Specific Constraints were found to have an even larger impact on total catchment profits than when the full suite of constraints was applied, although this can be explained by the different sequencing of constraints. Generic Constraints had a moderate and statistically significant impact on total catchment profits, while the small impact of Transaction Costs was not statistically significant.

The Minimum Cash Flow constraint had by far the largest impact of the individual constraints, reducing catchment profits by almost as much as the full suite of constraints did. The impact of this constraint, and four other constraints that had smaller individual impacts, was significant at the 1% level. One constraint caused differences that were significant at the 5% level, while two caused differences that were significant at the 10% level. The impacts of many of the constraints were found to decay over time, while those hard limits that did not decay over time were found to have the largest overall impacts.

The model was found to not be particularly stochastic, and the impact of additional model runs did not exceed 0.5% for any constraint after the fourth random seed was added. The results of the local sensitivity analysis also showed that the impacts that the two largest adaptation constraints contributed were not particularly sensitive to the level at which these constraints were set. While other constraints showed greater sensitivity in relative terms, their small overall impact limited the importance of these deviations in absolute terms.

Chapter 9

Discussion

This chapter discusses the findings and implications of this study in the context of their limitations and their situation with respect to previous research. It reflects on the aims of the study and discusses the evidence supporting the research hypothesis set out in Section 1.2. It starts by discussing the forcings to which agents in the model adapted. Section 9.2 relates the overall findings to the concept of the adaptation deficit outlined in Chapter 1. These findings are then related to previous literature on suboptimal adaptation, and their potential for generalisation is considered. Section 9.3 discusses the main implications of the adaptation deficit identified in this study, while Section 9.4 discusses insights about the dynamics of the adaptation modelled. Section 9.5 considers how these findings relate to system adaptedness and resilience, before Section 9.6 introduces a number of policy implications from this work. Finally, Section 9.7 re-visits and summarises the limitations of this study.

9.1 Impacts of Climate Change

The changes in land use patterns and total catchment profit under different climate change scenarios reported in Section 8.1 demonstrate the impact that climate change may have on agricultural productivity and land use in the Hikurangi catchment. The highest total catchment profits occurred under the strongest climate change scenario (RCP 8.5), while the more moderate RCP 2.6 produced significantly lower total catchment profits. The scenario in which climate forcing was removed produced significantly lower total catchment profits than either of the two climate change scenarios. This increase in total catchment profits under increasing climate change reflects projected increases in pasture, horticulture, and particularly forest productivity under climate change in New Zealand, consistent with the literature described in Section 4.3. These increases in productivity are likely to reflect substantial increases in thermal growing time under climate change, allowing for longer growing seasons (Wratt et al, 2008; Rutledge *et al.*, 2017). Projected increases in production are consistent in both direction and scale to Dynes *et al.* (2010) and Lieffering *et al.*, (2012), who explored the impacts of climate change on agricultural productivity in New Zealand.

While benefits to agriculture in New Zealand under climate change appear likely, it should be remembered that these reflect geographical characteristics that are not common globally. The IPCC (2014) conclude with *high confidence* that agricultural losses have been more commonly reported than benefits. While the investigation and reporting of climate change impacts may be biased towards assessing damages, the sheer number of studies reporting damages across numerous regions suggests that the positive impacts of climate change found in this study may be the exception rather than the rule. Whether change leads to benefits or losses is, however, not particularly important in assessing the adaptation deficit, because constraints on adaptation impose costs both when change is needed to avoid damages and when change is needed to realise opportunities (Kelly *et al.*, 2005).

It should also be noted that projected benefits have three important caveats. Firstly, increases in productivity under longer growing seasons assume that plant growth is limited only by temperature and rainfall. In many cases more nutrients such as nitrogen and phosphorous will be needed to realise these benefits in New Zealand (Dynes *et al.*, 2010). Secondly, these projections do not account for likely increases in climatic extremes, which are likely to have major impacts on agriculture (Dasgupta *et al.*, 201). Thirdly, the projected increases in productivity reflect annual averages, in which large increases in productivity in the winter and spring may mask decreases in the summer and early autumn (Lieffering *et al.*, 2012). Changes in tactical management decisions are likely to be necessary to manage these different seasonal changes and to realise overall benefits (Lieffering *et al.*, 2010; Fitzgerald *et al.*, 2009).

9.2 The Adaptation Deficit

The central aim of this study was to estimate the potential scale of the adaptation deficit. While finer details of the impacts of individual adaptation constraints are important (these are discussed in Section 9.4.1), the current section focuses exclusively on the impact of the All Constraints specification relative to the Optimised specification. This focus is justified because sufficient empirical evidence was gathered to warrant the inclusion of each of the adaptation constraints modelled, and these constraints would generally apply together in the real world.

The results reported in Section 8.1 support the central hypothesis of this thesis.

Including empirically derived constraints on adaptation *does* significantly affect economic outcomes under climate change in the study catchment.

The impact of these constraints is highly statistically significant. These constraints were found to reduce average annual profits per farmer over the modelled time period by $77,799-$89,604 depending on the greenhouse gas concentration assumed. While these values are not discounted and reflect growing incomes over the modelled period, the modelled reduction in total profits over the time period was also large in relative terms, equalling roughly one third of total catchment income relative to the Optimised specification over the modelled time period. These estimates can be taken as a rough first estimate of the scale of the adaptation deficit in the study catchment, defined by Noble *et al.* (2014, p.839) as "the gap between the current state of a system and a state that would minimise adverse impacts from existing climate conditions and variability". By the definitions of Burton (2004) and Burton and May (2004), this adaptation deficit includes both current inefficiencies in land use, and inefficiencies in how land is used over the modelled timeframe. It also demonstrates that analyses that ignore adaptation constraints are contributing to an adaptation myth (Repetto, 2009) which understates the challenges of adaptation. The adaptation deficit estimated here is subject to a number of caveats and uncertainties, which are discussed further in Section 9.7. Two specific uncertainties warrant mention at this point.

Firstly, it is acknowledged that the timeframe over which model runs occurred contributed substantial uncertainty. Beyond that associated with the *ceteris paribus* assumption, the long timeframe presents important complexities endogenous to the agricultural economy modelled. For example, one might expect the average farm to change hands multiple times over the 75 years modelled, meaning the dynamics of succession are likely to be important (Troost and Berger, 2016). While this study considered these dynamics on a simplistic level, with cultural constraints making land use change relatively more likely at the point of succession, the dynamics of this process were not considered in detail. This internal complexity, coupled with the likelihood of substantial changes in external forces, means that uncertainty in the results increases over the modelled time-period. As explained in Section 8.3, the constraints modelled in this study had the largest impacts in the first few time-steps of the model, meaning that the increasing uncertainty later in the modelled time period is likely to have a reduced impact on the core findings of this research than if the impacts of the adaptation constraints were constant over time.

Secondly, as explained in Section 8.1, the significant changes in land use that occur under the specification with no climate forcing indicate that a substantial proportion of adaptation is occurring in response to NZFARM's low agreement with the baseline land use pattern in the catchment. Under each scenario, the optimisation function of NZFARM, based on data from the whole of New Zealand, is recommending substantially different land use patterns in the first time step, before climate change provides any substantial forcing. This large adjustment has two possible explanations. As explained in Section 7.2.4.1, this adjustment may reflect poor calibration to the local environment in the catchment, and may reflect localised factors not captured in national level data that favour different land uses. The adjustment could also be explained as an adjustment to a *current* adaptation deficit (Parry *et al.*, 2009; Burton, 2004; Burton and May, 2004) in which the baseline patterns of land use are not well adapted to maximise profit under current conditions. Parry *et al.* (2009) suggest that the current adaptation deficit in agriculture is likely to be high, implying substantial gaps between current agricultural practice and that which would maximise economic benefits. They suggest that a relevant estimate of the size of the current adaptation deficit could be seen as equal to the cost of achieving current development goals, which was estimated at roughly US$40-60 billion globally in 2009. This is substantially larger than current estimates of the annual costs of climate change adaptation in the sector, which are discussed further in Section 9.3.1.

While a Ricardian model such as NZFARM would theoretically account for current adaptation deficits by including land use inefficiencies in its baseline data, it is possible that social, cultural, economic, and environmental characteristics of the study area make it less well-adapted to the current climate than the national average – requiring greater adjustments to reach this. Census data from Northland lend some support to this theory. For example, the median age of people in Northland is 4.7 years older than the rest of the country, and the Maori population is higher (Statistics New Zealand, 2013), meaning that the constraints relating to labour, lifestyle, and kaitiakitanga may have affected the initial land use mix more than they did elsewhere in the country. The proportion of people with formal qualifications is also 6.5% lower, and the median income is 18% lower than the national average (Statistics New Zealand, 2013), meaning that constraints relating to technical expertise, response lags, and minimum cash flow may have similarly shifted the baseline land use away from what NZFARM would consider optimal. These statistics suggest that the current adaptation deficit may be higher in Northland than the national average, suggesting that at least part of the adjustments seen in the model's first time step may relate to this local deficit.

It is perhaps most likely that the initial adjustments in land use reflect elements of both coarse model calibration and adjustment to a current adaptation deficit, however it would be difficult to estimate the extent of each without re-calibrating the NZFARM model for the catchment in question. Even if this were done, the extent of the current adaptation deficit would remain unknown, as this calibration exercise would include local land use inefficiencies in the newly-defined optimal land use. Despite uncertainty about the provenance of these adjustments, they are retained in the model analysis because, as explained in Section 7.2.4.1, Ricardian models could be expected to assume similar adjustments when applied to higher resolutions than the data on which they are designed.

9.2.1 Relation to Previous Literature

This study identifies a significant adaptation deficit, which accords with the general findings of previous studies. For example, Gsottbauer and van den Bergh (2011, p.24) reason that economic performance under climate change may be severely affected by sub-optimal decision making, and conclude that "if individuals are not reaching their individual optimum or efficient outcome… society as a whole is unlikely to arrive at a socially optimal outcome." De Bruin and Dellink (2011, p.34) assessed the impacts of individual adaptation constraints on utility and found that "especially restrictions to the effectiveness of adaptation at more extreme levels of climate change can be very harmful." It also accords well with the findings of Burke and Emerick (2016) who found little difference in farmers' long-run adaptation to changes in climate relative to short-term responses in the United States. Noting data on responses to long-term temperature changes of up to 1.5°C, they concluded "we find limited evidence that agricultural productivity has adapted to these environmental changes, with fairly negative implications for the future impacts of climate change on the agricultural sector" (Burke and Emerik, 2016, p.110).

The identification of a substantial adaptation deficit also accords well with the findings of Kerr and Olssen (2012). These identified substantial delays, and by implication, costs, in farmers' strategic responses to changes in commodity prices in New Zealand. They also provide further evidence to support the inclusion of Constant Elasticity of Transformation (CET) functions within the NZFARM model, in order to represent constraints on the rate at which land use change can occur (Daigneault *et al.*, 2012; 2013; 2014).

9.2.2 Potential for Generalisation

The adaptation deficit discussed in the previous section was based on an empirical investigation of adaptation constraints in a single case study catchment. The potential for generalising these findings therefore warrants discussion. Care was taken in the design of this study to try to enhance the potential for generalisation. The study focused on the agricultural sector in New Zealand because farmers there have a long history of exposure to shifting economic conditions meaning that they are likely to be relatively adaptable. Furthermore, as a developed country the individual adaptive capacity of farmers in New Zealand is likely to be high relative to the global average. These characteristics reduce the risk of identifying greater adaptation constraints than exist in agriculture globally.

Within New Zealand, this study focused on the Hikurangi catchment because it closely matches the land use profile of New Zealand as a whole, with a mixture of dairy farming, drystock farming, forestry, and horticulture. Therefore the constraints specific to changes between these land uses are likely to apply to much of the country. Furthermore, the level of abstraction in the model used in this study was intentionally high in order to focus on the general dynamics of adaptation constraints and avoid over-calibration to the specific catchment in question. The poor calibration of the NZFARM model discussed in the previous section actually makes the model more applicable to the rest of the country, because the optimisation function is based on national level data. This leaves much potential to extend the current study to other areas in New Zealand to test its conclusions under different conditions.

Despite these attempts to preserve generalisability, the idiosyncratic geographies of climate change, adaptation opportunities, and adaptation constraints make generalisation challenging. Climate change poses different hazards to different people in different places, meaning that the actions people must take to adapt to climate change are diverse (Noble *et al.*, 2014; Klein *et al.*, 2014). Furthermore, adaptation opportunities, and the constraints and limits on their realisation, differ greatly by context (Klein *et al.*, 2014; Adger *et al.*, 2007; Mortreux and Barnett, 2009). For example, in their review of papers focused on adaptation constraints, Biesbroek *et al.* (2013, p.1124) found that "each study identifies a unique configuration of factors and conditions that pose [constraints] to adaptation in their specific context". Differences in the adaptation constraints people face are not solely contextual. Many reflect differences in the behavioural tendencies of individuals and groups influenced by social and cultural forces. For example, standardised behavioural experiments have found dramatically different behaviours when played by people from different cultures (Gowdy, 2008). Relevant to the current study, Peerlings *et al.* (2014, p.736) found substantial differences in the regional indicators of resilience among farmers in Europe. They reason that "This could be due to regional differences in legal structures and social and cultural values that may affect the possibility of adopting certain strategies". There is even clearer evidence of differing adaptation constraints relating to religion in different contexts. For example, Mortreux and Barnett (2009) found that many people on the Pacific Island of Tuvalu did not consider migration in response to climate change because of a belief that the promises that God made to Noah in the Bible meant that sea level would not rise under climate change. Gawith *et al.* (2015) found similar complacency in the face of water stress among both Hindu and Buddhist communities in Nepal. These studies amplify the conclusions of Davidson (2016) and Mortreux and Barnett (2009) who stress the need to consider specific social, cultural, economic, religious, and political contexts in order to understand behavioural responses to change.

While the range of contextual factors relevant to adaptation constraints varies in complex ways, a common differentiation is made between developed and developing countries. With respect to climate change, Brooks *et al.* (2005, p.153) point out that "The factors that make a rural community in semi-arid Africa vulnerable to drought will not be identical to those that make areas of a wealthy industrialised nation such as Norway vulnerable to flooding". As explained in Section 4.5, climate change adaptation has been more frequently reported in developed countries than in developing countries (Berrang-Ford *et al.*, 2011). This may reflect the fact that, in general terms, many major constraints on adaptation are likely to be more prevalent in developing countries. For example, the constraints on individual adaptation are seen to be particularly restrictive in developing countries because of a range of impediments on personal capabilities (Field *et al.*, 2014). Because of these differences in the nature of adaptation constraints, de Bruin *et al.* (2009) point out that even if adaptation constraints have only minor impacts globally, they may still cause severe loss and damage when they constrain vulnerable people and communities.

The impacts of individual adaptation constraints can also vary substantially between very similar contexts. For example, Biesbroek *et al.* (2013) point out that adaptation constraints found to be important in Sweden are different from those found to be important in Norway. Some of these differences are likely to reflect different research foci and methods, as Biesbroek *et al.* (2013) also found that multiple studies in the same country also identify different individual constraints.

Notwithstanding the diversity of constraints found in different places, a number of individual constraints are frequently reported across a range of different contexts (Biesbroek *et al.*, 2013). Certain aspects of human behaviour are also broadly applicable. For example, Gowdy (2008) points out that while some aspects of behaviour were found to differ between cultures taking part in a standardised behavioural experiment, none of the cultures studied displayed the economic rationality assumed to drive Homo Economicus.

Furthermore, while substantial diversity is also found in the drivers of climate vulnerability and adaptive capacity, Brooks *et al.*, (2005) found that a number of drivers were important in many geographical and socioeconomic contexts. These often related to development factors and capabilities such as health and poverty, and they were conceptualised as ‘generic’ determinants of vulnerability and adaptive capacity, while those relevant to a particular context were labelled ‘specific’ determinants of vulnerability and adaptive capacity (Brooks *et al.* 2005). Brooks *et al.* (2005) focused their analysis on the generic determinants of vulnerability based explicitly on the rationale that these can be generalised to a wide range of contexts.

This conceptualisation fits well with the classification of constraints as ‘generic’ or ‘specific’ that was devised by Arnell and Charlton (2011) and adopted in this thesis, as explained in Section 4.8.1. Similar to the approach of Brooks *et al.* (2005), it is argued that the Generic Constraints modelled in this study are likely to be broadly applicable in a range of contexts, while each individual context is likely to have its own unique collection of Specific Constraints. The Specific Constraints modelled in this study were found to have a substantially larger impact on catchment profits than the Generic Constraints, indicating that adaptation is constrained to a large extent by factors that are specific to the context of the Hikurangi catchment. Generic Constraints were, however, found to reduce catchment profits by close to 10% over the modelled time period, a difference that was significant at the 1% level. This indicates that an initial bundle of constraints that can be expected to apply to a broad range of contexts were found to significantly reduce economic prosperity in the Hikurangi catchment under climate change. This implies that the main finding of this study can be generalised, and adaptation constraints can be expected to significantly reduce economic prosperity in many contexts under climate change relative to an optimised scenario.

This finding should, however, be interpreted carefully. While the Generic Constraints identified in this study may be widely applicable, they are likely to manifest in different ways in different contexts (Klein *et al.*, 2014; Adger *et al.*, 2007). Furthermore, while the addition of Specific Constraints is by definition unlikely to ameliorate the impacts of Generic Constraints, as this study shows they may have far greater impacts than their generic counterparts, meaning that accepting only the generalizable findings of this study may lead to substantial underestimates of the impacts of adaptation constraints in many contexts. Any attempt to fully describe adaptation constraints requires careful consideration of the local context in question.

These findings demonstrate the need for more case studies assessing the range of constraints on adaptation across different contexts. These case studies should then be compared and synthesised in order to more fully identify which constraints can be considered generic, and to test the likely impact that they may have. The impacts of specific constraints should also be considered across multiple cases in order to understand the range of impacts that they may have in different contexts, which can then be added to meta-estimates of the impact of generic constraints to estimate upper-bound uncertainty.

9.3 Implications of the Modelled Adaptation Deficit

The extent of the adaptation deficit identified in this study has considerable implications for estimates of the cost of adaptation, the benefits of mitigation, and the residual loss and damage from climate change. The following four sections explore the main implications of the adaptation deficit identified in this study. Section 9.3.1 describes the implications of this adaptation deficit for adaptation cost estimates, while Section 9.3.2 explains its implications for the economics of climate change mitigation. Section 9.3.3 highlights how this adaptation deficit might affect the residual loss and damage from climate change. Finally, Section 9.3.4 speculates about how consideration of the adaptation deficit might impact Integrated Assessment Models.

9.3.1 Implications for Adaptation Cost Estimates

When constraints on adaptation are severe, the economically optimal level of adaptation is likely to change. In purely economic terms, the optimal level of adaptation is when the marginal cost of adaptation is equal to the marginal benefit that adaptation provides (Chambwera *et al.*, 2014). The constraints modelled in this study are likely to make it more costly to achieve the same adaptation benefits, implying that assessments of the economics of adaptation that ignore these constraints are likely to recommend inefficiently high levels of adaptation. This situation is shown in the right hand panel of Figure 9.1, which shows a theoretical representation of adaptation economics used in the IPCC's Fifth Assessment Report (Chembwera *et al.*, 2014).

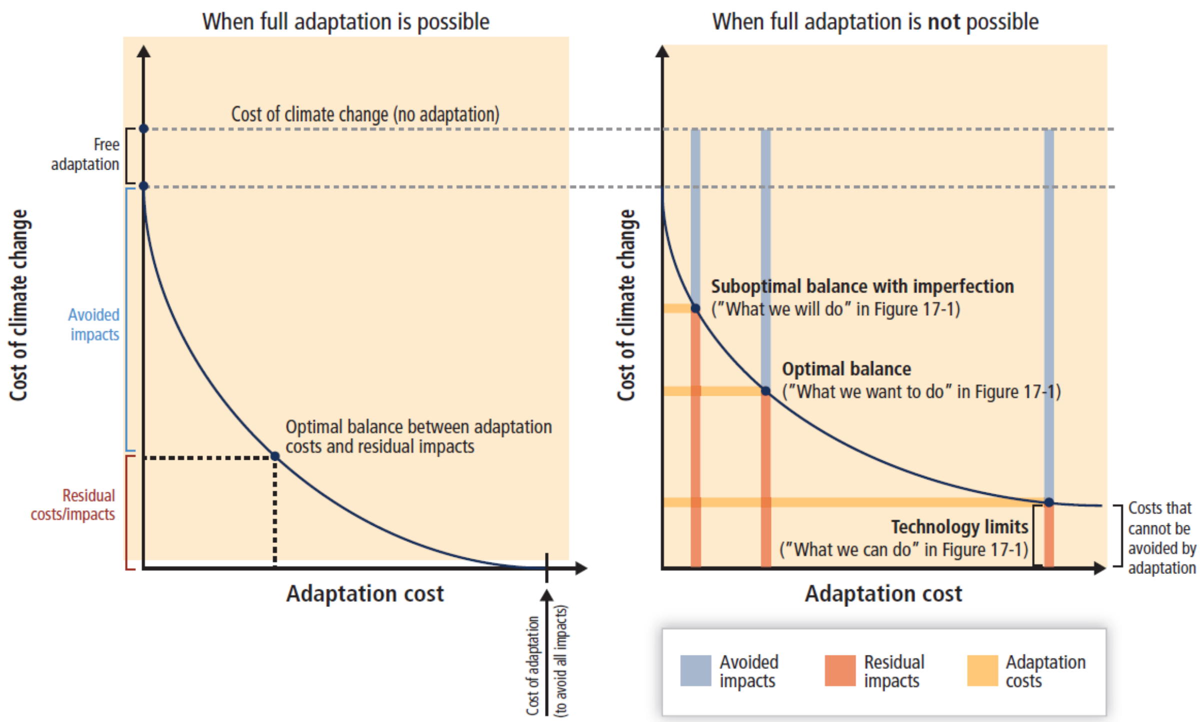


Figure 9.1: Hypothetical representation of a cost curve comparing adaptation effort and residual damages with and without adaptation constraints and limits. Source: Chambwera *et al.* (2014).

As explained in Section 4.6.1, estimates of the global costs of adaptation range from US$28-67 billion per year in 2030 to US$70-100 billion per year in 2050 (UNFCCC, 2007; Chambwera *et al.*, 2014). As part of the estimates for 2030 formed by the UNFCCC (2007), adaptation costs were estimated by assuming a 10% 'climate mark-up' on the costs of agricultural research and extension services, and a 2% 'climate mark-up' on the costs of farm infrastructure (Parry *et al.*, 2009). Beyond the question of whether or not these mark-ups are reasonably quantified, the current study shows that this method ignores important adaptation costs including financial support for land use change, adjustment costs and productivity lags when changes occur, and social preferences relating to cultural heritage, cultural identity, and lifestyle. The impacts of the constraints identified in this study imply that these costs are likely to be substantial, and would almost certainly result in larger adaptation costs than those estimated by the UNFCCC.

This inference accords well with Parry *et al.* (2009) who argue that the 2030 estimates of adaptation costs are likely to be substantial underestimates. When separated by sector, the estimated cost of agricultural adaptation in the UNFCCC estimates is between US$11.3-12.6 billion per year in 2030 (between 17% and 45% of total adaptation costs). Parry *et al.* (2009) point out that this amounts to roughly one fortieth of the costs of meeting increased demands for food under population increase, whereas for adaptation in the water sector this ratio is roughly 1:3. They reached the pointed conclusion that "These are important differences which deserve analysis." (Parry *et al.*, 2009, p.15).

According to Chambwera *et al.* (2014), the newer World Bank (2010) estimates for adaptation costs are more comprehensive than the earlier UNFCCC (2007) estimates. These suggest that adaptation costs may amount to US$70-100 billion per annum by 2050. However these estimates also contain clear methodological deficiencies. For example, the metric used to determine the costs of agricultural adaptation in the World Bank study was the number of malnourished children, and adaptation costs were assumed to accumulate to the point where the number of malnourished children under climate change is returned to the baseline number (Nelson *et al.*, 2010). This framing excludes any adaptation costs that do not affect food security (which arguably includes most changes in non-staple crops, livestock, and forestry), and also excludes any costs associated with adaptations to realise opportunities (which includes all of the adaptations modelled in this study, for example). Furthermore, while acknowledging their importance, the World Bank estimate does not include costs undertaken by the private sector in agriculture (Nelson *et al.*, 2010). These oversights suggest that the updated World Bank estimates of the costs of climate change adaptation in agriculture are again likely to be substantial underestimates.

Parry *et al.* (2009) suggest that top-down approaches to estimating the costs of adaptation could be usefully compared with bottom-up estimates of the costs of individual adaptation options. They show that a bottom-up assessment of the costs of increased crop irrigation demands (Fischer *et al.*, 2007) amounted to roughly 65% of the total cost of adaptation in the agricultural sector included in the UNFCCC (2007) estimates. They conclude that "if we were to extend this approach with costings for other explicit adaptation measures, it could be that the additional adaptation costs for the agricultural sector will exceed the [UNFCCC estimates]" (Parry *et al.*, 2009, p.34). The findings of the current study support such an approach, with the added recommendation that bottom-up assessments of adaptation costs also consider the additional costs caused by the constraints that these adaptations are likely to face.

9.3.2 Implications for Mitigation Response

While climate change was found to provide benefits in the Hikurangi catchment, negative impacts are expected to dominate positive impacts globally. In principle a Homo Economicus living in the Hikurangi region may advocate increasing levels of greenhouse gas emissions in order to exacerbate climate change. However the discussion in this section takes a global perspective, assuming net damages from climate change when exploring the implications of adaptation constraints for mitigation policy.

Changes to the effectiveness and costs of adaptation, and to the overall levels that can be expected to occur, affect the optimal levels of climate change mitigation. As explained in Section 1.1.2, adaptation and mitigation are complementary risk management strategies (Klein *et al.*, 2014; de Bruin *et al.*, 2009). In purely economic terms, both mitigation and adaptation can be expected to face increasing marginal costs, meaning that an economically efficient response to climate change would combine these two responses rather than pursue either in isolation (de Bruin *et al.*, 2009). In many decision making structures, the potential costs of climate change are the dominant consideration in the level of mitigation deemed necessary. These costs are estimated using integrated assessment models and depend on the assumed cost and effectiveness of adaptation options (de Bruin and Dellink, 2011). As explained in Section 2.4, adaptation is generally optimised in these assessments. The findings of this study suggest that adaptation is likely to be significantly constrained in reality, meaning that studies assuming optimal adaptation may have produced unreasonably high estimates of the benefit and unreasonably low estimates of the costs of adaptation. The extent of the adaptation deficit described in Section 9.2 suggests that overestimates of the benefits of adaptation could be higher than 30%. The methodological uncertainties described in the previous section suggest that underestimates of the costs of adaptation may also be substantial, however these are not estimated here.

Both of these deviations imply that the optimal level of mitigation will be higher if adaptation constraints are considered. The constraints on adaptation explored in this study imply that adaptation to climate change is likely to be costly, difficult, and for some strategies, unattainable. Under these conditions, an effective way to minimise total damages would be to increase mitigation effort to reduce the speed and extent of climate change impacts (Klein *et al.*, 2014; Field *et al.*, 2014). While beyond the scope of the current study, these results imply that assessments of optimal mitigation responses to climate change should be adjusted to account for sub-optimal adaptation.

As explained in Section 4.11, de Bruin and Dellink (2011) modelled the benefits of adjusting mitigation efforts in response to information about sub-optimal adaptation. They found that constraining adaptation below optimal levels leads to a roughly linear positive increase in the benefits of mitigation effort. These benefits did, however, depend on the nature of sub-optimality, with more transient constraints represented in their 'delay' scenario providing smaller benefits from changing mitigation levels than more persistent constraints relating to the overall quantity of adaptation permitted. In this study, many of the smaller individual constraints were reasonably transient in nature, and their impacts were minor after the first few decades of the modelled time period. Therefore the benefits of increasing mitigation in response to these constraints may be small. The impacts of the two strongest constraints, Regulation and Minimum Cash Flow, persisted throughout the modelled time period, implying that the benefits of adjusting mitigation levels in response to these constraints may be substantial.

9.3.3 Loss and Damage

The adaptation deficit also has important implications for the residual impacts of climate change, referred to as loss and damage. It is widely acknowledged that, as a result of current greenhouse gas concentrations described in Section 1.1.2, and the limits to adaptation described in Section 4.7.1, some level of loss and damage from climate change is unavoidable (Klein *et al.*, 2014; Field *et al.*, 2014; Noble *et al.*, 2014; Hallegatte *et al*., 2016). The extent of the adaptation deficit identified in this study indicates that the residual loss and damage from climate change may be greater as a result of constraints on our ability to adapt. While increases in mitigation effort can minimise the increases in loss and damage resulting from the adaptation deficit, they are not capable of reducing them to the level that was possible if adaptation could be optimised. The residual costs of climate change, the costs of adaptation, and the costs of mitigation are therefore all likely to be higher as a result of constraints on adaptation.

Parry *et al.* (2009) call for greater research evaluating residual loss and damage. An indication of the growing awareness of residual loss and damage in integrated assessment models is the inclusion of limits to the effectiveness of adaptation options in the latest iteration of the Policy Analysis for the Greenhouse Effect (PAGE) model (Hope, 2011). The results of this thesis demonstrate that the constraints on adaptation should be added to the limits to possible adaptation in order to fully evaluate loss and damage under climate change.

9.3.4 Impact on Integrated Assessment Models

The implications of adaptation constraints for adaptation costs, mitigation responses, and loss and damage described in the previous three sections also have implications for estimates of the overall impacts of climate change formed by Integrated Assessment Models (IAMs). IAMs provide estimates of the global costs of climate change, upon which decisions about global responses, in the form of both adaptation and mitigation, are made (Gsottbauer and van den Bergh, 2011). For example, the influential findings of the Stern (2007) review were based in part on simulations using the PAGE2002 model (Hope, 2011). Despite their influence, however, existing IAMs have many well-documented shortcomings (Dasgupta *et al.*, 2014). Relevant to the current study, IAMs simulate adaptation poorly. Many do not explicitly specify the type of damages occurring, while those that do generally assume optimal responses which equalise the marginal costs and benefits of adaptive responses (de Bruin *et al.*, 2009; de Bruin and Dellink, 2011). As the findings of this thesis demonstrate, people are unlikely to adapt to climate change in an optimal manner. Moreover, even if people did try to equalise the marginal costs and benefits of adaptation, current uncertainties in the estimation of these costs are likely to provide spurious incentives.

There appears to be a growing awareness of the need to consider the possible impacts of sub-optimal adaptation. For example, the most recent update to the PAGE model (PAGE2009) assumes that adaptation is only half as effective at reducing damages as the previous version (PAGE2002) did (Hope, 2011). According to Klein *et al.* (2014) this, combined with other adjustments, results in strong increases in the simulated economic costs of climate change. In an effort to further explore sub-optimal adaptation, de Bruin and Dellink (2011) assessed the impacts of a range of hypothetical constraints on adaptation using the DICE model, as explained in Section 4.11. They found that these constraints had substantial but differing impacts on utility, as reported in Figure 4.7. However no empirical justification was given for the specification or quantification of the constraints they assessed, making the results theoretical rather than applied. The current study assesses the impacts of empirically specified and quantified adaptation constraints, and finds that in the agricultural sector of the Hikurangi catchment, these may have greater economic impacts than those estimated by de Bruin and Dellink (2011). This thesis was limited in its focus and scope, but in keeping with the recommendations of Parry *et al.* (2009) it demonstrates that a range of bottom-up assessments of the constraints on adaptation could be combined in order to constrain adaptation within suitable IAMs such as DICE or PAGE. This may help to clarify the true potential adaptation has to reduce the costs of climate change.

9.4 Dynamics of Adaptation

In addition to estimating the adaptation deficit, the findings of this study reveal a number of important insights about the dynamics of adaptation. The impacts that individual constraints had on adaptation are discussed in relation to previous literature in the following section. Section 9.4.2 then discusses findings about the speed of adaptation in relation to previous findings. Section 9.4.3

considers how the findings of this study might be affected by time preferences in the form of discount rates. Finally, Section 9.4.4 considers the social and cultural implications of the changes in land use simulated.

9.4.1 Impacts of Individual Constraints

This study focuses on the impacts of groups of adaptation constraints because the combination of, and interactions between different constraints can either amplify or dampen their impacts (Eisenack *et al.*, 2014). Assessment of the impacts of each constraint in isolation can provide useful insight into their relative importance and the dynamics of their impacts, which may assist in formulating responses to them. These results are, however, discussed under the caveat that none of the constraints modelled occur in isolation in the real world, and interaction with other constraints may either dampen or exacerbate their impacts. While examining these interaction effects is beyond the scope of the current study, it is a potentially important area for further research.

The different approaches to assessing adaptation constraints in this study suggested different things about their relative importance. The literature reviewed in Section 4.9.2.1 suggested that financial constraints would be among the most commonly reported. While financial constraints were indeed commonly referenced during the interviews conducted with farmers in the Hikurangi catchment, the single most referenced constraint was found to be farmer motivation and aspiration. Despite this, the impact of lifestyle preferences in the model simulations was less than that found for constraints relating to labour, regulation, and minimum cash flow. The need to have an external minimum cash flow to sustain a shift into forestry was found to have by far the greatest impact of any adaptation constraint, and was likely responsible for the majority of the impacts of the All Constraints scenario.

While cross-comparison is challenging because of differences in foci and methods, a number of previous studies have also assessed the impacts of individual constraints on adaptation. For example, Chhetri *et al.* (2010) investigated the impacts of path dependence in agricultural adaptation to climate change by comparing an optimised model of adaptation to a logistic model of adaptation to simulate delays in technology dispersal. They found that agricultural profits were significantly lower (by 1.36-1.62%) in the logistic scenario than the optimised scenario in their first 20 year time step, however the two were not significantly different in their second or third 20 year time steps. The path dependence assessed by Chhetri *et al.* (2010) most closely resembles the response lags constraint in the current study, however it may also overlap with the social information and climate change information constraints to some extent. When divided over the three time-periods modelled, the impact of path dependence on agricultural profits identified by Chhetri *et al.* (2010) is roughly comparable to the impact of response lags, social and climate change information constraints modelled in this study. Furthermore, the rapid decay towards insignificance bears similarity to a number of the constraints assessed in this study, as shown in Figure 8.7.

Another study focused on individual adaptation constraints came from Acosta-Michlik and Espaldon (2008), who used a variant of the 'consumat' approach of Jager *et al.* (2000) to assess vulnerability to climate and commodity market changes in the Philippines. While they did not quantify the impacts of adaptation constraints, their analysis identified financial constraints and lack of information as the most important contributors to vulnerability in the Philippines, and by implication, the most important constraints on adaptation included in the consumat approach. The importance of financial constraints is echoed in the current study by the large impact of the minimum cash flow constraint relative to the other constraints studied. The importance of information is less clear in the current study, with social information significantly affecting total catchment profit and climate change information constraints having no significant impact. The monetary impacts of these two constraints was, however, moderate, and they may have had a greater impact if they were considered in combination.

De Bruin and Dellink (2011) assessed a range of constraints on adaptation which they specified based on the results of previous literature. They presented their findings as reductions in a utility index, meaning that it is difficult to directly compare the level of impact constraints had in their study to those found in the current one. However, the relative importance of different constraints which were presented in Figure 4.7 provides a useful comparison. While their 'Obsolete' scenario was found to be their most harmful constraint, there is no analogue for this constraint in the current study because climate is assumed to change within the range of current projections, and the potential for substantially higher rates of change was not considered. 'Delay' was the second most harmful constraint in their analysis, and it most closely resembles the 'Response Lags' constraint in the current study, while also overlapping with Climate Change Information and Labour Constraints. Response Lags were found to have a small but highly statistically significant impact on mean total catchment profits, reflecting their modest but persistent influence. Combined with the larger impacts of Climate Change Information and Labour Constraints (the latter of which was also highly statistically significant), the relatively large impact of 'Delay' in the analysis of de Bruin and Dellink (2011) appears consistent. De Bruin and Dellink (2011) also found a modest but noticeable impact when restricting the 'Quantity' of adaptation that could occur at any one time. The specification of this constraint most closely resembled Labour Constraints in this study. However these were justified on the basis of different rationales, as described in Section 6.3.1.4. Labour Constraints were found to have the third largest total impact on catchment profits in this study. This demonstrates a notable difference in terms of relative importance between the two studies, although this may simply reflect different rationale, specification, and quantification of each constraint.

A more obvious difference exists between de Bruin and Dellink's (2011) 'Funding' constraint and the Minimum Cash Flow constraint assessed in the current study. De Bruin and Dellink (2011) define their funding constraint as the difficulty of financing adaptation effort, and simulated it by placing limits on expenditure in each time period. They found this had the least impact on their utility index of any of the constraints they investigated. In the current study, the Minimum Cash Flow constraint was designed to reflect the financial difficulties of changing land use to forestry, defined as a threshold of external income below which this change was not possible. This was found to have by far the greatest impact on total catchment profit of any of the constraints investigated here. Differences in the relative impacts of these two financial constraints could reflect the levels at which they were set in each study. They could also reflect the fact that the 'Funding' constraint of de Bruin and Dellink (2011) restricted the rate at which adaptation could occur, while the Minimum Cash Flow constraint placed a hard limit on farmers who were unlikely to be able to sustain a shift into forestry. The large impact of the Minimum Cash Flow constraint is also likely to reflect the economic importance of forestry expansion in the current study.

9.4.2 Speed of Adaptation

The speed at which adaptation takes place is known to greatly impact its benefits (IPCC, 2014; Porter *et al.*, 2014; Kerr and Olssen, 2012; Simões *et al.*, 2017). The results presented in Figures 8.3 and 8.4 and Tables 8.2 and 8.3 in the previous chapter demonstrate that adaptation in the form of land use change occurred much more slowly in the All Constraints scenario than it did in the Optimised scenario. Evidence that agricultural land use change takes place more slowly than would be economically optimal is common in the literature (see Kerr and Olssen (2012) for a summary). For example, based on data from New Zealand, Kerr and Olssen (2012) built a time series model to estimate land use change in response to commodity price changes. Their findings, shown in Figure 9.2, show that land use areas in dairy and forestry respond similarly to changes in the price of milk and timber, respectively. Their shares initially expand quickly in response to price increases, however this expansion slows considerably towards its modelled equilibrium area. These responses suggest that it takes approximately two and six years for 50 and 75% of the dairy area adjustment to occur, respectively. Adjustments in forestry were found to be slower, requiring six years to reach 50% of equilibrium and 12 years to reach 75% of equilibrium. Expansion of drystock area was found to be non-monotonic and even slower, requiring 12.5 and 18.5 years to reach 50 and 75% of the long run equilibrium, respectively.

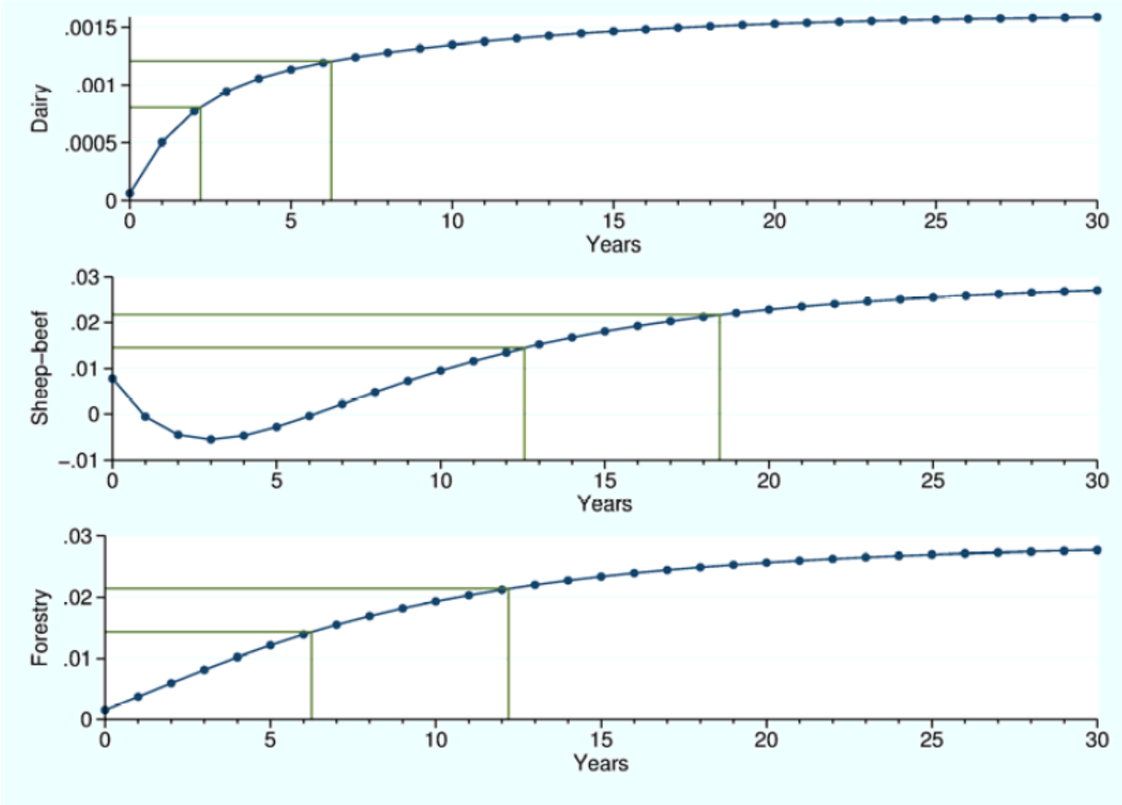


Figure 9.2: Land share responses to a permanent one standard deviation increase in prices for each respective commodity. The lines show adjustments to 50% and 75% of long run equilibrium land use areas. Source: Kerr and Olssen (2012).

Kerr and Olssen (2012, p.4) find their results to be consistent with similar studies worldwide, and conclude that “in New Zealand it can take many years before the full land-use impact of changes in economic returns is realised”. This finding is consistent with the results of the All Constraints scenario in the current study. As explained in Section 7.4.3.1, this also aligns with the interpretation of the three experts interviewed as part of the qualitative validation exercise, all of whom thought that the rapid land use change in the Optimised scenario was unrealistic.

The slowness of adaptation in the All Constraints scenario implies an important departure from the assumed dynamics of meeting adaptive potential. As explained in Section 2.3.1, adaptation occurs largely on evolutionary timescales in ecological systems, while human systems, through understanding and foresight, are known to be capable of anticipatory adaptation (Redman and Kinzig, 2003; Galopin, 2006; Nelson *et al.*, 2007; Adger *et al.*, 2009a). The findings of this study suggest that adaptation is likely to occur slowly in response to climate change. This accords well with the findings of Berrang-Ford *et al.* (2011) who through a meta-analysis of studies into adaptation show that the majority of adaptive action remains reactive. Even in the highly competitive and organised business sector, reactive adaptation may dominate (Simões *et al*., 2017). For example, in an assessment of organisational adaptation to climate change, Berkhout *et al.* (2006, p.135) found that “Organisations rarely adapt ‘autonomously’… routines are adapted incrementally in response to feedback about outcomes”. This implies that agricultural adaptation may not be particularly sensitive to future risks (Hoffmann *et al.*, 2007). In a broad sense, these findings suggest that while human beings are capable of ‘learning the easy way’ through proactive adaptation, we may be more prone to ‘learning the hard way’ in reality. This seems to confirm the view of Heyd and Books (2009, p.277) who suggested the lack of response to climate change represents “a fundamental and broadly based *cultural inadequacy*, characterised by an inability to fully comprehend or act on certain risks associated with environmental variability and change, even when information on these risks is widely available” (emphasis in original). Our adaptive behaviour seems likely to be more ‘Darwinian’ than it is ‘planned’. As the findings of this study demonstrate, the difference between the two is likely to be highly significant.

9.4.3 Discounting

Discounting of future flows of costs and benefits is an important consideration in many studies assessing long-run policy issues such as climate change (Gsottbauer and van den Bergh, 2011). This study focused on assessing the potential scale of the adaptation deficit rather than providing information about how best to address it. Direct policy advice based on discounted net present values is not considered to be justified given the limitations of this study, discussed in Section 9.7. The values reported in Chapter 8 were, therefore, not discounted in any way, and do not account for time preferences relevant to decision making today. It is, however, worth considering briefly how time preferences might affect the findings of this study.

Views about the appropriate discount rate to apply to future costs and benefits vary markedly and constitute a large source of uncertainty in long-run economic impact studies. Many economic models use exponential discounting in which the importance of costs and benefits in the future declines rapidly over time. The exponential discount factors applied in major studies of climate change economics have ranged between 1.5% and 0.1% based on different rationales and value judgements made by the authors (Chambwera *et al.*, 2013). However, many economists have argued that empirical evidence more strongly supports hyperbolic discounting in which future costs and benefits retain more importance over time (Gifford *et al.*, 2011; Gsottbauer and van den Bergh, 2011).

De Bruin *et al.* (2009) assessed the impacts of a range of discount rates on the costs and benefits of adaptation and mitigation responses to climate change. They found that the higher discount rates increase the importance of near-term impacts relative to long-term impacts, making adaptation a more beneficial response option than mitigation. By contrast, the lower discount rates make mitigation the more relevant response option. A further important finding of de Bruin and Dellink

(2009) was that constraints on adaptation that occur sooner imply greater costs at *any* discount rate. The fact that the adaptation constraints modelled in this study had the largest relative impacts in the near term, as shown in Figure 8.3, implies that the discounted relative impact of these constraints may be higher than the non-discounted relative impacts reported. This difference would be greater under higher discount rates than under lower discount rates, meaning that adaptation constraints are likely to be particularly important if our concern for future costs and benefits declines rapidly as time horizons increase.

9.4.4 Social and Cultural Implications

While this study has focused largely on assessing the economic impacts of adaptation constraints, it is also important to consider the social and cultural implications of its findings. As Adger *et al.* (2005) point out, legitimacy, which they define as the extent to which changes are acceptable to those whom they affect, is an important element of successful adaptation. As explained in Section 2.3.1, central to understanding what constitutes ‘good’ or ‘desirable’ adaptation, is understanding what people and societies value (Klein *et al.*, 2014; Adger *et al.*, 2009b). These values are difficult to quantify and are different for different people at different levels of organisation (Adger *et al.*, 2005; Stern, 2007).

The findings of the qualitative fieldwork relating to farmers’ motivations and aspirations, reported in Section 6.3.1.1, give an indication of what farmers value with respect to land use. Table 6.3 demonstrates that while profit is an important factor, it was not as frequently cited as lifestyle in relation to motivation and aspiration. Table 6.3 also demonstrates that environmental protection, pride in the land, and diversification were important drivers of farmers’ land use decisions. With the findings of Section 6.3.1.1 in mind, it seems that the large scale conversion to forestry and reduction in drystock area projected in Figure 8.4 would represent a substantial overall decrease in the value people derive from the lifestyle aspects of farming in the catchment. In the words of one farmer who had worked in forestry “It’s a hard game played by hard men with hard things to play with. Cattle are a lot easier, a lot easier on men and a lot easier on family.” The response of one of the experts interviewed during the qualitative validation exercise gave further insight into the social implications of projected land use change. Referring to the forestry expansion shown in Figure 8.4, he said “Either way the social implications of that change by 2090 are huge. Basically, I mean what they’ve seen elsewhere in the country, the depopulation of the country as forestry comes in. There’d be little schools through there that would disappear.” These findings also reflect Daigneault *et al.* (2012) who found that many farmers in New Zealand are primarily interested in farming animals, and respond negatively to the prospect of converting land to forestry.

These insights suggest that adaptation under the optimised scenario, depicted in Figure 8.4, might not be considered 'good' or 'successful' adaptation by the people it would affect. While promising greater monetary returns, the wholesale conversion to forestry may diminish the lifestyle value farmers derive in the catchment, and may have social and community consequences which are undesirable. Therefore, while the constrained specification delivers lower total catchment profits, it may be more desirable from many people's perspectives. While others in the catchment may view profit as more important than these lifestyle or social conditions, this diversity of views was accounted for in the All Constraints specification. The probabilistic specification of the lifestyle constraint allowed for diversity in people's perspectives, meaning some could place a high importance on profit while others favoured land uses that afforded what they regarded as a good lifestyle.

While this analysis provides some understanding of the social implications of the adaptation scenarios modelled, it is clearly narrow. This study did not explicitly focus on the social and cultural dimensions of climate change, therefore it is likely to be blind to many important social and cultural implications. It is, however, clear that the massive shifts in land use envisaged in the scenarios explored in this study would impact the population structure and the social fabric of the catchment, with probable cultural flow-on effects related to attachment to place and cultural identities. Furthermore, this shallow consideration of social implications was not included in the overall findings presented in the previous chapter, meaning that these findings likely undervalued cultural and social impacts in a broad sense (Adger *et al.*, 2009b). While it would be a challenging and complex undertaking, a targeted investigation of the social and cultural implications of land use change scenarios on the Hikurangi catchment would provide valuable context to the findings of this study.

9.5 Adaptation and Resilience

As explained in Section 2.3, this study focused on adaptation as the operational determinant of resilience. Farmers have been found to adapt in order to work towards resilience (Darnhofer, 2014; Kenny, 2011); however adaptation can equally be employed to pursue system adaptedness. As Section 2.3.3 highlighted, the use of empirical data on the priorities, aspirations, and behaviours of farmers, means that the constrained scenarios modelled in this study implicitly incorporated resilience as an objective. By ignoring these constraints, the optimised scenario used in this study maximised system adaptedness. Insights about the relative merits of these two scenarios are discussed in the following two sections.

9.5.1 System Adaptedness

The objective function of the optimised specification of ARLUNZ in this study pursues system adaptedness. As explained in Section 2.3.3, system adaptedness can be defined as "the level of effectiveness in the way a system relates with the environment" (Nelson *et al.* 2007, p.400). System adaptedness can be assumed to be the objective of most economic models of adaptation based on optimisation. In this study it defines the adjustments in land use under climate change forcing that maximise total catchment profit.

While the maximisation of profit is often seen as a good thing in simplistic economic terms, it may seriously undermine resilience. The vast uncertainties of climate change projections described in Section 7.5.2, coupled with even greater uncertainties about other important social and economic stressors, mean that the current conditions under which agriculture is practised are likely to change dramatically and frequently in the future. Maintenance of the ability to respond to a wide range of changes is, therefore, likely to be fundamental to maintain prosperity in the future (Darnhofer *et al.*, 2010). Maximising adaptation can create externalities, diminish response diversity through sunk costs, and increase vulnerability to changes in conditions through over adaptation to the current range of conditions (Nelson, 2011). Extensive evidence suggests that most systems experience trade-offs between the degree of adaptedness to current conditions, and the flexibility to adjust to change (Nelson *et al.*, 2007, 2011; Darnhofer, 2014; Adger, 2000; Basset-Mens *et al.*, 2009). These drawbacks of system adaptedness, and its trade-off with resilience, mean that while system adaptedness may maximise immediate monetary returns, it can be a poor measure of success and may not be a desirable objective (Nelson *et al.*, 2007). The broader concept of resilience avoids these drawbacks.

9.5.2 Resilience

In contrast to system adaptedness, the objective of resilience explicitly includes maintenance of the capacity for further adaptation, learning, and transformation. In this study, the constrained model scenarios implicitly assume resilience as the objective of adaptation, although the constraints still mean that they pursue this goal imperfectly. As Darnhofer (2014) observed, farmers generally work towards resilience, meaning that the constrained scenarios are likely to be better representations of farmers' adaptive objectives than the Optimised scenario.

The volatility of the environmental and economic conditions affecting agriculture means that working towards resilience is likely to be a better approach for farmers than attempting to maximise system adaptedness (Darnhofer *et al.*, 2010). As explained in Section 2.3.4, Darnhofer (2014) suggests that *less* time and effort should be spent on identifying slacks and improving the efficiency of current farming systems and more on maintaining a diversity of response options. Indeed, this behavioural response was observed by Smit (1994, in Smit and Skinner, 2002) when farmers in New Zealand diversified their land uses and businesses and reduced farming intensity to provide flexibility in response to the removal of state support and publicly funded insurance in the late 1980s.

Comparing the scenarios modelled in this study, particularly with respect to the diversity of land use over time in Figures 8.3 and 8.4, the All Constraints scenario is clearly more consistent with the maintenance of resilience than the Optimised scenario. The overwhelming dominance of forestry throughout the modelled time period in the Optimised scenario leaves the economy of the catchment highly exposed to fluctuations in timber prices, unforeseen changes in climate, and pests and diseases specific to forestry described in Section 4.2. By contrast, the much more mixed land use in the catchment that persists throughout the modelled time period under the All Constraints scenario means the agricultural economy of the catchment would be less vulnerable to adverse changes in forestry. While this may make it slightly more vulnerable to negative changes in dairy and drystock, it also makes it more easily able to capitalise on any positive changes in these land uses. Though it provides lower total catchment profits, the All Constraints scenario may describe a more desirable pattern of adaptation than the Optimised scenario in the face of volatile and uncertain future conditions.

This leads to the interesting conclusion that, rather than implying failure in farmers' abilities to successfully manage change, some of the constraints on adaptation modelled in this study may result in a more desirable system state than that which could be achieved by Homo Economicus. Constraints such as risk aversion and scepticism of climate change information appear to reflect resilience as a motivation. Applying these reasoned constraints to an otherwise optimised scenario could, in principle, define a more desirable system state than the Optimised scenario. In this scenario, farmers would work towards resilience in an optimal manner. While system adaptedness is defined as an 'optimised' scenario in this study, a scenario in which only reasoned adaptation constraints maintained in order to enhance resilience are applied can be thought of as a 'desirable' scenario.

However many of the constraints modelled in this study are still likely to undermine farmers' efforts to achieve resilience. For example, it would be hard to argue that the constraints relating to lifestyle preferences or a lack of technical expertise are intended to maintain resilience. These constraints mean that the level of adaptation will remain below what would occur in the 'desirable' scenario. The difference these constraints make could be thought of as a 'resilience deficit'. The goal of addressing adaptation constraints should therefore be to minimise the resilience deficit rather than the adaptation deficit.

There are notable drawbacks to focusing on resilience. The discussion so far has considered the desirability of the overall state of the agricultural economy of the Hikurangi catchment. This focus ignores the social distribution of benefits and costs (Eakin *et al.*, 2009), and has the potential to privilege future system stability over the immediate needs of vulnerable groups (Eakin *et al.*, 2009). Each of the individual farmers who made land use more diverse in the All Constraints scenario than the Optimised scenario was foregoing higher profits that they could have made in forestry. While for some this may be a conscious and reasoned choice, the impact of the Minimum Cash Flow constraint suggests that for many this may have represented a major financial frustration. This reaffirms the point that some constraints on adaptation based on the goals of the people they affect are perfectly acceptable, while others have a negative influence from all relevant perspectives. It is therefore important to consider carefully how to respond to the constraints on adaptation, a subject that is discussed briefly in the following section.

9.6 Policy Implications

This study did not set out to try to determine how best to respond to adaptation constraints. This task goes beyond what is feasible within the project's restrictions, and would require different approaches to data collection and analysis focused on policy application. Findings about the adaptation deficit and about the relative importance of individual constraints are, however, clearly policy relevant, and this section provides a brief discussion of the implications of this study for climate change policy and adaptation investment.

9.6.1 Mainstreaming Adaptation within Development

As explained in Section 1.1.3, the term 'adaptation deficit' was developed to explain considerable damages caused by climate related impacts under current conditions, and it can be closely linked to economic development (Burton, 2004; Burton *et al*., 2002; Hallegatte *et al*., 2016). Fankhauser and McDermott (2014) investigated empirically the link between economic development and climate adaptation. They found that economic development increased both demand and supply-side aspects of climate adaptation and concluded that "inclusive growth policies… should be an important component of international efforts to close the adaptation deficit" (p. 9).

While early work on the economics of climate change suggested that economic development alone would be sufficient to ensure adaptation (Schelling, 1992), more recent work stresses that this is not necessarily the case (Fankhauser, 2017). Economic development can either increase or decrease vulnerability and exposure to climate change depending on how individuals and communities allocate resources and situate assets (Fankhauser, 2017; Chambwera *et al*., 2014). For example, better flood protection may increase development in flood prone areas (Hallegatte, 2012). There is a clear need to take a strategic approach to development that is conscious of the changing risks associated with climate change (Hallegatte *et al*., 2016).

A broad and growing literature highlights the need to include adaptation to climate change in the broader process of economic development (Burton *et al*., 2002; Burton, 2004; Noble *et al*., 2014; Klein *et al*., 2014; Chambwera *et al*., 2014; Hallegatte *et al*., 2016; Simões *et al*., 2017). In the climate change literature, this addition is generally referred to as 'mainstreaming' climate change within development policy, and it provides a way of simultaneously addressing both current and future adaptation deficits (Burton, 2004). In the development literature, this process is often referred to as 'climate-resilient development' (Fankhauser, 2017) or 'climate informed' development (Hallegatte *et al*., 2016). In a practical sense, the most effective approach to climate change adaptation is often by influencing the decisions and priorities of development planners (Fankhauser, 2017). While in principle, the difference in costs between 'climate resilient development' projects and standard development projects could be taken as costs of adaptation to climate change, Fankhauser (2017) suggests that this cost may be inseparable in practice.

9.6.2 Appropriate Intervention

The findings presented in Section 8.1 demonstrate that the removal of adaptation constraints would lead to significantly higher profits in the Hikurangi catchment. While the previous section argues that the Optimised scenario should not be the goal, it is also clear that substantial benefits could be realised by removing certain adaptation constraints. Governments, through legislative and policy tools at the national and particularly the local level, are likely to be key actors in minimising adaptation constraints (Biesbroek *et al.*, 2013; Simões *et al*., 2017). This is particularly the case when adaptation entails elements of public goods that are likely to be underprovided by private interests (Adger *et al.*, 2009a).

Government intervention to relieve constraints on adaptation is only appropriate under certain conditions. According to Ignaciuk (2015) government interventions in the adaptation process may be justified from an economic perspective when they (i) generate knowledge relevant to the adaptation process; (ii) facilitate the transfer of knowledge; (iii) correct for externalities; (iv) relieve financial constraints on adaptation; (v) facilitate risk sharing; (vi) remove undesirable institutional or legislative constraints; or (vii) facilitate multilevel and multi-scale collaboration. These conditions provide a wide remit. However the discussion presented in the previous section makes it clear that intervention should not occur when departures from economic optimality are based on reasoned and purposeful preferences, or when these departures are enacted to maintain resilience. In the case of the current study, Table 9.1 lists the constraints for which intervention may be appropriate and those for which it is unlikely to be. Climate change information constraints were not categorised because, while climate projections are potentially useful, scepticism about their accuracy may strengthen response diversity. Disaster experience was also difficult to categorise, because it is not clear how interventions in this constraint would take place. Regulation was not categorised either, because some regulations may be formulated with the intention of maintaining resilience, while others may be unhelpful restrictions in a broader sense.

Table 9.1: categorisation of the constraints modelled in this study based on whether they warrant intervention.

Constraints that may Justify Intervention	**Constraints for which Intervention may be Inappropriate**
Minimum Cash Flow	Kaitiakitanga
Social Information	Lifestyle Preference
Technical Expertise	Risk Aversion
Self-Efficacy	Cultural Identity
Dairy Path Dependence	Forestry Path Dependence
Labour Constraints	
Response Lags	

9.6.3 Potential Policy Tools

As defined in Section 2.3.2, adaptation constraints determine farmers' adaptive capacities. However, as the previous discussion highlighted, effectively addressing adaptation constraints requires a targeted approach (Moser and Ekstrom, 2010; Simões *et al*., 2017). While the general process of sustainable development is likely to loosen many adaptation constraints (Klein *et al.*, 2014), more specific interventions may also be warranted. In a broad sense, Pike (2008, p.6) suggests that successful government intervention in response to adaptation constraints can be achieved by 'encouraging' change through incentives and disincentives, 'enabling' change by providing tools and resources, 'engaging' with farmers to influence motivations and attitudes, and 'exemplifying' beneficial adaptive behaviour. More specifically, governments can employ a broad range of economic and legislative tools to encourage and enable behavioural change. These include, among others, insurance schemes, price signals and artificial markets, regulatory restrictions, and research and development initiatives (Chambwera *et al.*, 2014). Table 9.2 suggests a range of policy tools that could potentially address the adaptation constraints modelled in this study that have been judged to justify intervention.

Table 9.2: Potential policy tools for addressing the constraints for which intervention is warranted.

Constraint	**Potential Remediation Tools**
Minimum Cash Flow	- Public and/or private finance schemes to provide levels of up-front and working capital to new forestry enterprises (Howden *et al.*, 2007; Schreinemachers *et al.*, 2009). - Encouragement of ways to earn income during stand growth such as through the sale of carbon credits (Hahn, 2000).
Social Information	- Facilitate the transfer of accurate information about adaptation approaches through fora such as Dairy Base (see Section 7.4.3.6) (Howden *et al.*, 2007; Gsottbauer and van den Bergh, 2011; Simões *et al*., 2017).
Technical Expertise	- Invest in education and rural extension services to provide training for a range of different land uses (Gsottbauer and van den Bergh, 2011).
Self-Efficacy	- Invest in education and rural extension services to provide training for a range of different land uses (Gsottbauer and van den Bergh, 2011).
Dairy Path Dependence	- Avoid/dismantle artificial incentives for dairy expansion and intensification (such as New Zealand's Irrigation Acceleration Fund).
Labour Constraints	- Loosen restrictions on work visas when labour shortages occur.
Response Lags	- Offer low-interest financial support to expedite the process of land use change (Howden *et al.*, 2007; Schreinemachers *et al.*, 2009)

It is important to acknowledge that these policy tools may be less effective than is often hoped. Many policy interventions rest on the assumption of rational choice, which, as highlighted throughout this thesis, does not characterise human behaviour well in practice (Gsottbauer and van den Bergh, 2011). The formulation of effective policy responses to adaptation constraints must, therefore, take the factors that determine farmers' behaviour as a starting point (Ford and Berrang-Ford, 2011). For example, Niles *et al.* (2013) found that farmers in California responded far more favourably to incentives provided by climate change mitigation policy than they did to disincentives, and recommended focusing on the former approach as a consequence.

In addition to behavioural anomalies, moral hazard issues often present themselves when policy tools provide incentives or subsidies (Ignaciuk, 2015). For example, studies have shown the system of payments under the Australian Government's National Drought Policy (1992) discouraged self-reliance and preparedness for future drought conditions and climate change (Adger and Barnett, 2009). Interventions in monetary incentives must, therefore, be carefully designed and implemented.

Recommendations for interventions must also be conscious of the political economy of climate change policy. To improve the likelihood that these recommendations are heeded, they must take into account political constraints in policy formulation (Hahn, 2000). As Hahn (2000, p.392) points out, "one of the primary lessons of political economy is that economic efficiency is not likely to be a key objective in the design of policy". Governments are more likely to act in the interests of the most influential actors in society (Adger *et al.*, 2009a). Policy recommendations may be more effective if they are conscious of potential political biases.

This discussion provides an introduction to the types of adaptation constraints that may warrant intervention, and the range of policy tools that could be used to address them. It does not explore the costs or benefits of these interventions. Given the impacts of the adaptation constraints identified, this is likely to be an important area for further research. While beyond the scope of the current study, such research could build on the methods developed here, and test mechanisms to alleviate adaptation constraints within ARLUNZ.

9.7 Limitations

The findings of this study are presented with acknowledgement of a range of limitations. Many of these limitations have been noted throughout the thesis, therefore this section provides a summary, highlights their implications, and suggests possible approaches to addressing them in further work. The following section discusses the limited focus and scope of this study, and how further work could extend its findings. Section 9.7.2 re-visits the *ceteris paribus* assumption, and explores possible approaches to considering other important contextual factors. Sections 9.7.3 and 9.7.4 discuss uncertainty and complexity associated with the methods employed in this study and how these limitations affect the overall presentation of results.

9.7.1 Focus and Scope

The focus of this study on the agricultural sector in a single case-study catchment in New Zealand limits the potential to generalise its findings, as discussed in Section 9.3. While the impacts of climate change on agriculture are likely to be very important (Howden *et al.*, 2007; Meinke *et al.*, 2009; Mendelsohn and Dinar, 2009; Smit and Skinner, 2002; Rosenzweig *et al.*, 2014), large impacts will occur in a range of other sectors (IPCC, 2014). In order to fully consider the possible impacts of climate change, and how these may be affected by adaptation constraints, other important sectors such as human health, infrastructure, and ecosystem function must be included. Furthermore, as suggested in Section 9.3, each of these sectors would need to be considered across a range of different contexts, and their results synthesised in order to determine the range of impacts and identify the extent to which certain impacts and constraints can be generalised.

Furthermore, within its focus on agriculture in the Hikurangi catchment, this study only considered the constraints on land use change as an adaptation option. As explained in Section 2.5.2, this is similar to the treatment of adaptation in Ricardian studies, and therefore it provides a reasonable approach to critiquing their assumptions. It does, however, overlook both more subtle tactical adaptation approaches such as irrigation and fertiliser use, and more radical transformational changes such as shifts to entirely different industries. Considering a broader range of adaptation options, while beyond the scope of this study, would improve our understanding of the constraints on adaptation to climate change, and provides extensive grounds for further work.

Uncertainty is also contributed by the resolution at which climate change impacts and adaptation are considered in this study. For example, yield changes for the major land uses were considered as annual average adjustments. This overlooks the possible impacts of changes in seasonality and short term variability including extreme events which are expected to occur under climate change (IPCC, 2013). These may pose greater challenges to farmers than changes in annual mean conditions (Porter *et al.*, 2014). For example, Lieffering *et al.* (2012) found changes in seasonal pasture growth were likely to be the most striking impact of climate change in their three hill-country case study sites in New Zealand. They concluded (p. 185) by saying "the likely changes in seasonality which we have shown, present substantial challenges to farm management in dealing with both excess feed and feed shortages". These challenges were not considered in the current study because it was not feasible to include such temporal detail within the modelling analysis. Parry *et al.* (2009) suggest that adaptation to changes in variability is conceptually different from adapting to changes in mean climate. It is also likely that adaptation to changes in variability would encounter different constraints from those assessed in this study. These considerations should also be assessed by further work.

9.7.2 Ceteris Paribus Condition

As Section 2.5.2 highlighted, farmers are likely to have to adapt to a wide range of influences other than climate change, and these will often dominate the influence of climate change at any one time (Beijeman *et al.*, 2009; Burton and Peoples, 2008; Field *et al.*, 2014; Cradock-Henry, 2011; Adger *et al.*, 2009c). Factors such as economic and regulatory conditions, social and technological pressures, changing labour and commodity prices, and globalisation combine to form a multi-stress environment within which adaptation in agriculture occurs (Klein *et al.*, 2014; Smit and Skinner, 2002; Cradock-Henry, 2011; Adger and Barnett, 2009; Darnhofer *et al.*, 2010; Ford and Berrang-Ford, 2011; Reed *et al.*, 2013). This study focused on adaptation to climate change *ceteris paribus* because many of the other factors influencing adaptation are poorly understood and unable to be predicted (Bateman *et al.*, 2013; Field *et al.*, 2014; Daigneault *et al.*, 2012; Iglesias and Garrote, 2015). By ignoring important contextual factors however, it is acknowledged that this study is likely to have overestimated the importance of climate change as a driver of adaptation in agriculture. For example, Ford and Berrang-Ford (2011) suggest that the rate of change in non-climate drivers may outstrip the rate of climate change, therefore there may be no need to increase the rate of adaptation, but rather ensure that climate change is considered in adaptation decisions. Because of this, individual constraints specifically related to climate change, such as climate change information constraints, may be less important in reality than they were found to be in this study.

At the current time there is some limited potential to move beyond the *ceteris paribus* assumption when modelling climate impacts and adaptation. For example, changes in markets and commodity prices, and feedbacks with changes in productivity under climate change could in principle be modelled by coupling the NZFARM model with Computable General Equilibrium (CGE) models of the global economy (Daigneault *et al.*, 2012; Mendelsohn and Dinar, 2009). It is, however, extremely difficult to predict how climate change will affect international markets and flows of commodities globally, meaning that the results of global CGE models should be treated with great caution (Mendelsohn and Dinar, 2009). One possible approach would be to develop a range of scenarios based on CGE projections, and test the sensitivity of models assessing the impacts of adaptation constraints to this range of scenarios in order to develop an understanding of how other factors may affect the influence of adaptation constraints in the future.

This study also ignored the possible burdens and opportunities of climate change mitigation policy in agriculture. As explained in Section 1.1.2, achieving the objectives of the Paris Agreement is likely to require large scale land based carbon sequestration (Anderson and Peters, 2016). This may increase the demands on, and hence the value of forestry as an emissions sink. It may also provide considerable potential to derive cash flow from forestry during the growth phase, possibly ameliorating the strongest constraint modelled in this study. In other land uses, however, the need to reduce greenhouse gas emissions may place further burdens and constraints on farmers. The modelling of mitigation requirements and opportunities, while beyond the scope of this study, is an important area for further research.

It is also acknowledged that the dynamics of succession present important uncertainties over the time period modelled in this study. Troost and Berger (2016) explore the process of succession in more detail in a European context, and suggest advances in how to model it using ABM. This demonstrates a valuable extension of the method employed here. Improvements in the modelling of succession could reduce the endogenous uncertainties associated with exploring the agricultural economics of the Hikurangi catchment over a long time period, and may be a valuable area for further work.

9.7.3 Uncertainty

Uncertainties in the data collection and modelling processes were described in Chapters 5 and 7, respectively. The purpose of discussing these uncertainties again here is to highlight the fact that they are likely to combine in complex ways. Their combination is not a matter of simple addition; rather, these uncertainties interact with one another and may cause feedbacks, resulting in what are termed 'cascades' of model uncertainty. Figure 9.3 shows a diagrammatic representation of a cascade of uncertainty relating to climate change impact studies. As the diagram highlights, the envelope of uncertainty is greatest when considering adaptation responses because these depend on uncertain local impacts, projected by uncertain impact models, which are themselves forced by uncertain regional scenarios and climate models, which depend on uncertain projections about future atmospheric greenhouse gas concentrations that hinge on uncertain estimates of global development pathways and rates of technological development. Importantly, the fact that the combination of these uncertainties is functional rather than linear means that the overall level of uncertainty is highly uncertain in itself (Pappenberger *et al.*, 2005). The cascade of uncertainty in this study goes beyond that imagined in Figure 9.4 to include uncertainties about the constraints on adaptation responses. Therefore, even among highly uncertain climate change impact assessments, the current study must be particularly cautious in its approach, methods, and presentation of findings.

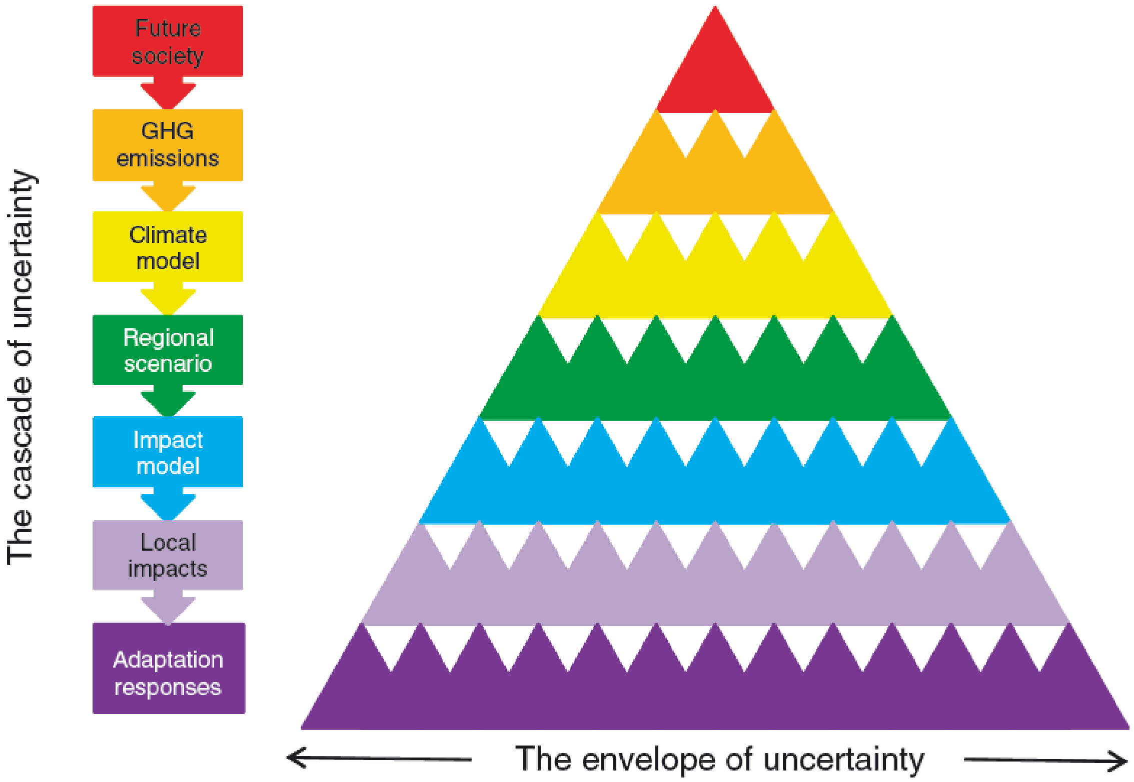


Figure 9.3. Diagrammatic representation of a typical cascade of uncertainty inherent in climate change impact studies. Figure taken from Wilby and Dessai (2010).

Dessai and Hulme (2007) assessed the robustness of policy-level adaptation decisions to the uncertainties of climate change projections in East Anglia. They used a one-at-a-time approach to sensitivity analysis to test the impacts of individual uncertainties in the modelling process, with all other parameters held constant. They found that uncertainties stemming from GCMs and regional climate models presented the greatest uncertainties to adaptive planning, followed by hydrological modelling and climate sensitivity. Their analysis stopped short of assessing the interplay between uncertainties, as would become evident using a global sensitivity analysis approach. Dessai *et al.* (2009) note that studies that seek to estimate overall levels of uncertainty have often found large overall uncertainty ranges. They further cautioned that estimates of these ranges are likely to increase as increasing computing power allows for fuller exploration of the uncertainty space.

Effort was made throughout this study to minimise the level of uncertainty to the extent this was feasible. As described in Section 5.1, the mixture of qualitative and quantitative approaches was employed to cross-check results and to understand processes underlying constraints as well as their prevalence within the population. This allowed the quantitative modelling assessment to be grounded in a more complete qualitative understanding of the adaptation challenges faced in the study catchment.

Effort was also taken to explore the extent of uncertainties contributed by certain aspects of the study approach. The impact of different RCPs was explored in the findings presented in Section 8.1. This demonstrated that individual results were sensitive to different assumptions about the concentration of greenhouse gas in the atmosphere. However the overall conclusion that adaptation constraints significantly impact economic outcomes in the Hikurangi catchment was not sensitive to these assumptions. The impacts of different adaptation constraints were also explored through a local sensitivity analysis, described in Section 7.6.5 and presented in Section 8.4. This demonstrated that the impacts that the two largest adaptation constraints contributed were not particularly sensitive to the level at which these constraints were set. While other constraints showed greater sensitivity in relative terms, their small overall impact limited the importance of these deviations in absolute terms.

When considering the trustworthiness of models simulating complex social systems, Johnson (2000, p.39) cites Catsi (1997) to identify six key questions upon which the validity of these models can be evaluated. These are now posed and addressed in turn.

1) Operational: Is the model able to provide answers to the questions for which it has been built?

The modified version of ARLUNZ was able to provide clear answers to the key research questions posed in Section 1.2. Specifically, the adaptation constraints modelled in this study were found to significantly affect the agricultural economy of the Hikurangi catchment under climate change.

2) Empirical: Does the model agree with observed data that are relevant to the problem under consideration?

The findings of this study were consistent with the general findings of previous assessments of sub-optimal adaptation, as explained in Section 9.2.1. Furthermore, the identification of substantial constraints on adaptation is consistent with the scarce observations of adaptation, described in Section 4.5.

3) Theoretical: Does the model contradict any established theories?

The model contradicts the assumption that rational choice is a reasonable model of human decision making in studies that model adaptation. These criticisms are, however, not new, and those who apply the rational choice assumption in models of human adaptation are aware of, and often acknowledge, its shortcomings (Mendelsohn and Dinar, 2009; Seo *et al.*, 2009; Bateman *et al.*, 2013). This study can be seen to provide an empirical quantitative and qualitative confirmation of a widely established criticism.

4) Consistency: Does the model contain any logical contradictions?

While uncertainties of resolution and abstraction are likely to produce logically implausible results at the farmer level within ARLUNZ, all of the higher level results reported in the previous chapter were logically consistent with one another, and with established theories about adaptive behaviour.

5) Faith: Do specialists in the area being modelled agree that the model produces believable results?

As explained in Section 7.4.3, the model was qualitatively validated with three experts in the agricultural economy of the modelled catchment. Two of these experts thought the simulated changes in land use in the catchment were credible over the modelled timeframe. The third expert was sceptical about the extent to which forestry would expand in the catchment, which was subsequently constrained further. Importantly, all of the three experts thought that the All Constraints scenario produced more credible results than the Optimised scenario.

6) Testing: Can the model be tested in the real world?

This final question proves problematic. Without the long term climate forcing on which this study focuses, the constraints specific to this forcing cannot be tested (Evans *et al.*, 2013). It is possible that a number of the identified constraints that were not specific to climate change could be tested against other stressors, such as commodity price changes (see for example Kerr and Olssen, 2012), however it may be difficult to identify which constraints are specific to which stressor, therefore the impacts of constraints on adaptation to commodity price changes may be tenuous indicators of the impacts of constraints on adaptation to climate change.

9.7.4 Complexity

Beyond the known uncertainty of the methods employed in this study there exists substantial complexity, much of which is effectively unknowable. This complexity contributes ‘deep’ uncertainty (Marshall, 2013), which means that it is not feasible to predict all potential future states of the system, nor fully explain the current state of the system based on its individual components (Marshall, 2013). Jasanoff (2007) suggests that the reduction of uncertainty is likely to be asymptotic for most complex problems. These deep and persistent uncertainties mean that surprises are likely within the system (Marshall, 2013). As a result, Darnhofer (2014, p.466) advises that there should not be “the presumption of sufficient knowledge, but the recognition of our ignorance; not the assumption that future events are expected, but that they will be unexpected.”

The results of this study are presented as, and should be interpreted as, indicative scenarios. They do not aim to predict how land use will change in the Hikurangi catchment in the future, rather they are presented as plausible representations of possible future states upon which the impacts of empirically derived adaptation constraints can be explored. The uncertainties described in this Section underscore the limitations of the model. They also emphasise that the model findings should be used cautiously and only in a limited capacity when considering possible policy insights, as acknowledged in Section 9.6. As explained in Section 2.6, this study follows a pragmatic constructionist epistemology. The results should therefore be understood in light of the pragmatic simplifications needed to produce them and with reference to the purpose of exploring the impacts of adaptation constraints. The results should be understood to stem from limited knowledge of the SES of the Hikurangi catchment, and they are open to scrutiny and revision as this knowledge develops.

While deep uncertainties and complexity limit the findings of this study, and indeed many studies involving climate change and human behaviour, their position in relation to existing understanding of adaptation is a worthy final point to consider. As explained in Sections 2.4 and 9.4, the ways in which adaptation is understood has extremely important implications for how best to respond to climate change. The current default assumption is that rational choice adequately approximates adaptive decision making in agriculture. The current study suggests that the constraints on adaptation should be accounted for in simulation of agricultural adaptation to climate change. While this finding is subject to deep uncertainties, it is worth considering whether these are likely to be greater or less than those accepted when assuming rational choice. We have accepted the uncertainties of the rational choice assumption to-date. This thesis argues that we should reconsider this tolerance. It also demonstrates an approach to modelling adaptation that better simulates human decision making.

Chapter 10

Conclusions

10.1 Objectives and Structure

The central aim of this thesis was to estimate the adaptation deficit through an empirical analysis of the constraints on adaptation in agriculture. A review of existing knowledge of adaptation constraints in agriculture informed the design of a mixed methodological approach to empirically assessing the constraints on adaptation in New Zealand's Hikurangi catchment. Semi-structured interviews were used to gain an understanding of the origins and processes of a range of constraints identified by farmers. An extensive survey of rural decision makers was used to assess the impact that these adaptation constraints had on the propensity of farmers to adapt to climate change. Mathematical rules were designed based on this information and these rules were programmed into an agent-based model of agricultural adaptation to climate change in the Hikurangi catchment.

The model was first run under a specification with no adaptation constraints in order to form a 'baseline' scenario. This scenario represented the Ricardian approach that dominates current economic assessments of agricultural responses to climate change. Under this approach, farmers were assumed to maximise system adaptedness.

The model was then run under a range of specifications in which adaptation constraints were applied. These scenarios treated farmers' adaptive behaviour as constrained, and implicitly assumed resilience as the objective of adaptation. The differences between these constrained scenarios and the Optimised scenario were then compared in order to answer the central research question of this thesis, namely:

Does including empirically derived constraints on adaptation produce significantly different economic outcomes?

In answering this question, this work met a number of other objectives. Most importantly, it demonstrated a method for empirically estimating the economic impacts of adaptation constraints. In doing this it moved beyond previous work by using empirical evidence to analyse adaptation constraints, rather than relying on arbitrarily weighting theoretical constraints. It was novel in the context of research into adaptation constraints because it combined both qualitative and quantitative methods. It also assessed a broader range of constraints within a more defined context than previous studies, and analysed their effects in isolation and in combination. Finally, it demonstrated the efficacy of agent-based modelling in the assessment of adaptation constraints.

10.2 Summary of Findings

Many of the adaptation constraints identified in the literature were evident among farmers in the Hikurangi catchment. Eleven constraints were specified based on interview responses from farmers. Twelve indices representing adaptation constraints were formulated based on survey data. Of these, five were found to have a consistent and significant correlation with adaptive propensity. The magnitudes of these five constraints were set based on their coefficients revealed in the Tobit model. Consequently, sixteen constraints were considered in the modelling exercise in this study.

Adjustments in land use were found to be much slower and smoother under the All Constraints scenario than under the Optimised scenario. The speed of the All Constraints scenario echoes evidence in the literature suggesting that land use change takes place slowly in response to economic stimuli, and much adaptation is likely to remain reactive. Furthermore, when shown land use changes under these two scenarios, all three experts interviewed in the qualitative validation exercise thought that the All Constraints scenario was more credible than the Optimised scenario.

The All Constraints scenario reduced total catchment profits by a highly statistically significant margin relative to the Optimised scenario under all of the climate change scenarios modelled. This answered the central research question of this thesis with the clear conclusion that:

Including empirically derived constraints on adaptation *does* significantly affect economic outcomes under climate change in the Hikurangi catchment.

In dollar terms, these constraints were found to reduce average annual profit per farmer over the modelled time period by $77,799-$89,604, depending on the greenhouse gas concentration assumed. This amounted to roughly one third of farmers' income relative to the Optimised specification and provides a rough first estimate of the scale of the adaptation deficit.

The impact of adaptation constraints when no climate change forcing was applied indicates that a substantial proportion of adaptation occurred in response to NZFARM's low agreement with the baseline land use pattern in the catchment. This is likely to be caused by poor calibration to the study catchment; however it may also reflect adjustment to a current adaptation deficit in the region. Isolating the differences caused by climate change, the three possible climate change scenarios were found to produce results that were highly statistically different from one another.

There were substantial disparities in the impacts of individual constraints. Five of the individual constraints had impacts on total catchment profit that were significant at the 1% level, one had an impact that was significant at the 5% level, and two had impacts that were significant at the 10% level. The impacts of many of the constraints were found to decay over time, while those hard limits that did not decay over time were found to have the largest overall impacts. The impacts that the two largest adaptation constraints had on the model were not particularly sensitive to the level at which these constraints were set, while other more sensitive constraints had small impacts on the model in absolute terms.

While generalisation is not possible for the Specific Constraints, the Generic Constraints investigated in this study are likely to exist in a broad range of contexts. Generic Constraints were found to reduce catchment profits by close to 10% over the modelled time period, an impact that was statistically significant at the 1% level. Because this initial bundle of broadly applicable adaptation constraints was found to significantly affect economic outcomes, the main finding of this thesis may apply more generally. However the generalisable findings of this study are likely to be substantial underestimates of the impacts of adaptation constraints in most contexts. It is worth remembering that the Specific Constraints modelled in this study had far greater economic impacts than the Generic Constraints.

10.3 Implications

The findings of this study demonstrate that the extent to which people will adapt to climate change is likely to be significantly below the level that would maximise financial benefit. Therefore, the dominant economic models of adaptation, which assume people to maximise their financial benefit, have likely been underestimating the costs and overestimating the benefits of adaptation. Such assessments, therefore, are likely to have been recommending inefficiently high levels of adaptation. Given that adaptation and mitigation are complementary risk management strategies, these assessments are also likely to have been recommending inefficiently low levels of mitigation. When adaptation is understood to be costly, difficult, and in some cases unattainable, the clear rationale for minimising the speed and extent of climate change becomes clearer still.

A further implication of the adaptation deficit identified in this study is that, even if our response in terms of mitigation and adaptation were adjusted perfectly, the dominant models of agricultural adaptation are likely to have been underestimating the loss and damage climate change will cause. This underestimation may have been particularly large in developing countries where adaptation constraints are thought to be more restrictive. This provides further compelling justification for increasing mitigation effort.

The dynamics of adaptation modelled in this study suggest that people are likely to be slow to adapt to climate change. This implies that the current reactive bias that has been observed by a range of studies can be expected to persist. While human beings are capable of anticipatory adaptation, it seems likely that our response to climate change may be more Darwinian in nature. The size of the adaptation deficit identified in this study highlights the importance of this difference.

While the differences between the scenarios modelled in this study highlight a significant loss of financial potential, the optimised scenario might not be seen as the most desirable. While promising greater economic returns, the wholesale conversion to forestry projected under the optimised scenario may diminish the lifestyle value farmers derive in the catchment, and may have undesirable social consequences. Furthermore, this land use change might seriously undermine the resilience of the economy of the Hikurangi catchment. This implies that some of the constraints modelled in this study, particularly those purposefully maintained to enhance resilience or lifestyle objectives, may lead to a more desirable system than could be achieved were they all removed. A scenario in which these beneficial constraints are maintained could be seen to be optimised for resilience, and defines a ‘desirable’ scenario.

However many of the constraints modelled in this study are likely to be undesirable from all relevant perspectives. These constraints mean that, without intervention, the level of adaptation will remain below what would occur in the ‘desirable’ scenario. The difference these undesirable constraints make could be thought of as a ‘resilience deficit’. A range of policy tools are available to address adaptation constraints. This study implies that they should be used to minimise the resilience deficit rather than the adaptation deficit. Future policy work would benefit from distinguishing explicitly between beneficial constraints, and those contributing to the resilience deficit.

10.4 Areas for Further Research

As explained in Section 9.7.4, the findings of this study are presented within a pragmatic constructionist epistemology which acknowledges substantial uncertainty. These findings exist in a reflexive equilibrium, and they are open to scrutiny and revision as our understanding of the dynamics of adaptation matures. A range of potential research areas could contribute to this task.

While this study demonstrated a method for empirically estimating the impacts of adaptation constraints, the approach taken could be extended in a number of ways. Most obviously, further work could consider a range of adaptation options beyond land use change. As a first step, tactical adaptations, such as those considered by Fitzgerald *et al.* (2009) and Lieffering *et al.* (2012) could be considered in parallel with the strategic adaptation of land use change. The modelling of transformational adaptation strategies such as exit from agriculture could be seen as a research horizon. Further insight could also be achieved by considering the impacts of different adaptation scenarios on other economic and environmental conditions. The ARLUNZ model would be well suited to this task as it is already capable of assessing the impacts of land use change on greenhouse gas emissions and nutrient leaching.

The method demonstrated in this study could also be extended by increasing the resolution at which climate change impacts and adaptation are considered. Specifically, people's responses to changes in both seasonality and the prevalence and magnitude of extreme climatic events warrant further consideration. The simulation of farmer decision making may also be improved by further understanding exogenous influences on farmers' decision making and processes that underlie it. Improvements in the modelling of succession could also reduce the internal uncertainties of the model over long time horizons.

The potential impacts of adaptation constraints in agriculture demonstrated in this study provide a strong rationale for considering adaptation constraints in other sectors. There are likely to be many important and unique constraints on adaptation to climate change in sectors such as health, infrastructure, and environmental quality. At a broad level, the approach taken in this study could be applied to estimate adaptation deficits in these other important sectors.

Beyond the approach taken in this study, there is a need to more carefully explore which adaptation constraints can be considered 'generic' and which are likely to be specific to certain contexts. The impacts of Generic Constraints should be tested in a range of contexts in order to understand the minimum impact that adaptation constraints are likely to have. The impacts of Specific Constraints should also be considered in multiple contexts in order to understand the range of additional impacts they may have. These case studies should then be compared through meta-analyses in order to form higher level understandings of the impacts that adaptation constraints may have.

As explained in Section 9.2.2, the relatively poor calibration of the NZFARM model leaves considerable potential to extend the current study to other areas in New Zealand. The characteristics, groupings, and impacts of adaptation constraints could therefore be examined in a range of different contexts in New Zealand with relative ease. However, the need for further case studies outside New Zealand, and particularly in developing countries, is clear.

There is also the need for further research into the impacts that the adaptation deficit might have on integrated assessment models. As Section 9.3 discussed, the adaptation deficit is likely to have important implications for the cost of adaptation, the best level of mitigation, and the likely extent of loss and damage. The findings of multiple bottom-up approaches to assessing the impacts of adaptation constraints could, in principle, be incorporated within top-down integrated assessment models. These could take a form similar to the Constant Elasticity of Transformation functions applied within NZFARM by Daigneault *et al.* (2012a,b; 2013; 2014). Much like the study of de Bruin *et al.* (2009), this approach could then be used to test the broader relevance of adaptation constraints when mitigation responses and different discount rates are considered. This could help to clarify the true potential that adaptation has to reduce the costs of climate change. This could, in turn, improve estimates of optimal mitigation levels.

The findings of this study also demonstrate the need to further understand what can be considered 'good' or 'desirable' adaptation. The Optimised scenario may be undesirable even from the perspectives of those actors who would gain financially from it. However, it is also clear that some adaptation constraints are detrimental from all relevant perspectives. Differentiating between desirable and detrimental constraints would require further research into the social and cultural dimensions of climate change adaptation. It would also require careful consideration of the aims of adaptation. As the discussion in Section 9.5.2 highlights, this is unlikely to be system adaptedness, and might be better understood as resilience. Therefore, interventions to address adaptation constraints should aim to minimise the resilience deficit rather the adaptation deficit.

With this aim in mind, further work exploring possible policy tools for relieving undesirable constraints is justified. This work could build on the methods used in this study. Potential mechanisms for alleviating undesirable constraints could, in principle, be tested within the ARLUNZ model. The highly significant impacts of adaptation constraints found in this study suggest that benefits of judicious intervention could be substantial.

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