



Adaptation knowledge for New Zealand's primary industries: Known, not known and needed



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A B S T R A C T

Climate sensitive primary industries including pastoral farming, high-value horticulture and viticulture are central to Aotearoa-New Zealand's economy. While advances have been made in understanding the impacts and implications of climate change critical knowledge gaps remain, particularly for adaptation. This study develops and applies a novel methodology to identify and characterise adaptation knowledge for primary industries. The basis for the review is ten years' of research and action under the Sustainable Land Management and Climate Change (SLMACC) program, supplemented with a systematic review of the published literature. Reports ($n = 32$) and literature ($n = 22$) are reviewed and assessed using the Adaptation Knowledge Cycle to characterise analytical and empirical foci. The detailed assessment of knowledge for Impacts, Implications, Decisions or Actions enables a robust and rigorous assessment of existing knowledge, identifies critical research gaps and emerging needs. Results show research to date has focused almost exclusively on understanding the impact of climate variability and extremes on land management. There are significant empirical (e.g. location and sector) and methodological (e.g. integrated assessments, scenarios, and vulnerability assessment) gaps, for at risk regions and sectors, and limited understanding of the decisions and actions necessary to enable successful adaptation. To inform future adaptation planning, additional work is required to better understand the implications, decision-making processes and obstacles to action. More detailed understanding of location-, season-, time- and sector-specific responses to climate change is also necessary. Findings advance our understanding of adaptation knowledge and reflect on diversity of information necessary to enable and sustain resilient rural futures and provide a conceptual and methodological basis for similar assessments elsewhere.

1. Introduction

Climate-sensitive primary economic activities such as pastoral farming, arable cropping and horticulture are likely to be affected by changes in climatic conditions, increased climate variability and extremes (Bizikova et al., 2012; Cradock-Henry, 2017; Howden et al., 2007). The impacts of warmer temperatures, decreased rainfall and more frequent droughts will be felt through declining yields and rising production costs, with implications for economic development, food security and well-being (Bailey and Buck, 2016; Lipper et al., 2014). Furthermore, these changes are likely to occur in conjunction with other socio-economic and global changes, such as trade liberalisation or protectionism, water availability, and conflicts over land use (Belliveau et al., 2006; Burton and Peoples, 2014; Eakin et al., 2009).

As a small, relatively wealthy, and export-led country, this is especially relevant for Aotearoa New Zealand (New Zealand). The

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Table 1
Common definitions of adaptation.

Source	Definition
Intergovernmental Panel on Climate Change (IPCC)	Adaptation is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (IPCC 2014)
United Nations Framework Convention on Climate Change (UNFCCC)	Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change (UNFCCC website)
United Nations Development Program (UNDP)	Adaptation is a process by which strategies to moderate, cope with and take advantage of the consequences of climatic events are enhanced, developed, or implemented (UNDP, 2005)
United Kingdom Climate Impacts Program (UKCIP)	Adaptation is the process or outcome of a process that leads to a reduction in harm or risk of harm, or realisation of benefits, associated with climate variability and climate change (UKCIP, 2003)

primary sector in New Zealand is already exposed to a number of risks and stressors, as demonstrated by recent experience with earthquakes, biosecurity incursions, and fluctuations in commodity prices (Burton and Peoples, 2014; Cradock-Henry and Fountain, 2019; Harrington et al., 2014; Spector et al., 2018). Weather-related risks pose a significant challenge to producers (Kenny, 2011). The effects of climate change will create new risks, some of which will act as persistent pressures and others as short, sharp shocks.

The increased frequency of such events will challenge management systems in the primary sector with implications across the New Zealand economy and society (Stroombergen et al., 2006). The primary sector contributes 7% of GDP and accounts for 79% of export earnings (Statistics New Zealand., 2018). Approximately half the land base is in productive pasture and arable cropping, including 1.8 million hectares of productive forest plantation. The primary sector is a significant economic driver, employing 350,000 people, and is fundamentally important to many local and regional economies (Patterson et al., 2006).

Successful adaptation to climate change in rural environments and enterprises is vital to securing a sustainable future for New Zealand. At the most general level, climate adaptation is what people do to avoid and recover from unusual or extreme climate events (Table 1). Adaptation in the primary industries encompasses diverse strategies that can be used by individual farmers and land managers, sectors, industries and regions to adequately respond to climate change. It involves adjusting practices, processes and capital in response to the actuality or threat of climate change, as well as responses in the decision environment, such as changes in social and institutional structures or altered technical options that can affect the potential or capacity for these actions to be realized.

Primary industries that are able to anticipate and reduce identifiable risks and are buffered against unexpected risk are more likely to be successful (Bizikova et al., 2012; Jakku et al., 2016; Kenny, 2011; Meinke et al., 2009; Moss et al., 2013). Therefore, it is necessary to review existing research, determine what information is available and identify gaps in understanding to support adaptation planning (Ford and Pearce, 2010).

This paper is the first systematic review of adaptation research for New Zealand's primary industries. The review is based on analysis of 32 adaptation projects funded through the Sustainable Land Management and Climate Change (SLMACC) program between 2007 and 2017, as well as a systematic review of the published literature. Outputs were assessed against the Adaptation Knowledge Cycle to characterize contribution to adaptation knowledge by analytical focus: Impacts, Implications, Decisions or Actions.

In section two, we describe the methodology including data sources, collection and analysis. Results are then discussed in terms of existing knowledge, gaps and research priorities. Based on this synthesis, the paper makes a unique contribution to the literature, combining a review of project-specific outputs with systematic review for a comprehensive knowledge assessment for this particular domain. Finally, the summary and conclusions present implications of the research and point to future research directions.

2. Review methodology

A mixed method approach was used and involved framing structured questions, identifying relevant work, assessing studies, summarizing evidence and interpreting findings (Khan et al., 2003). Two data sources provide the basis for the review: project reports from ten years of a government-funded climate research program and a systematic literature review. To enhance comparability between the two sets of data, we used a simple heuristic – the Adaptation Knowledge Cycle – to assess each research output according to its analytical focus: Impacts, Implications, Decisions or Actions. The following section discusses each component in more detail.

2.1. Review of impacts and adaptation projects

The Sustainable Land Management and Climate Change (SLMACC) research programme was established in 2007 and is administered by New Zealand's Ministry for Primary Industries (MPI) (MPI, 2018). The fund aims to address the impacts of – and adaptation to – climate change, mitigation of agricultural greenhouse gases and improvements of forest sinks, under the paradigm of sustainable land management (Rys, 2013). Research supported by the fund is intended to help New Zealand achieve its broader climate change targets through better understanding of the impacts of climate change, thereby improving risk management and increasing the resilience of the primary sector to climate change (MPI, 2018).

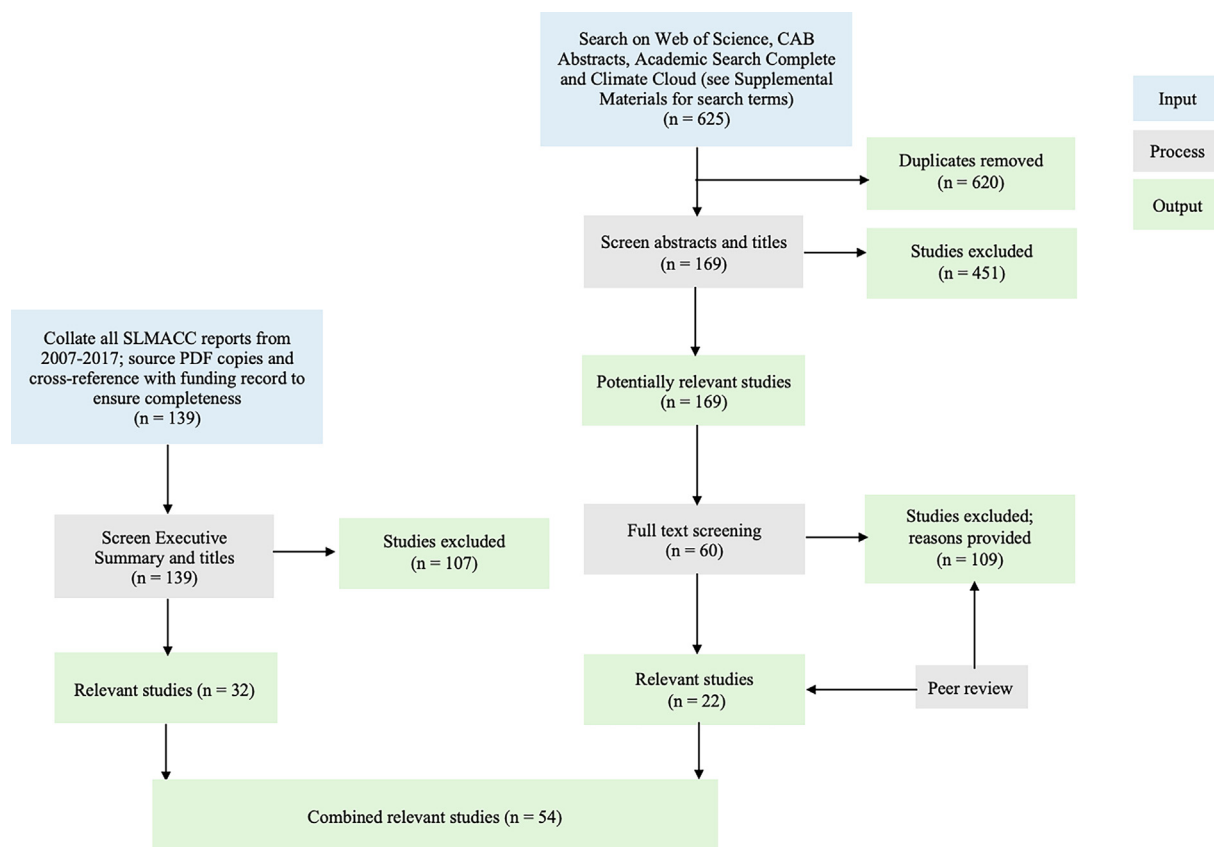


Fig. 1. Visualisation of the review process.

Since its inception, over NZ\$50 M (US\$35 M) has been invested through 139 projects categorised as follows: GHG mitigation ($n = 58$), impacts and adaptation ($n = 32$), forestry and carbon markets ($n = 29$) and technology transfer and cross-cutting issues ($n = 20$) (Fig. 1). As part of a wider review of the impacts of the program, the lead author was contracted to review the 32 impacts and adaptation projects (MPI, 2018). The authors were provided with copies of the project reports (see Supplementary Materials), and descriptive summaries were generated for each project. The summaries contain project-related details on the key organisations, named partners, project duration, main target audience and lead author.

2.2. Systematic literature review

A systematic review of the published white literature on climate change adaptation in New Zealand primary industries was also carried out to complement the review of project reports (see Supplementary Materials). ‘Systematic review’ (SR) is a methodological approach to synthesise and summarise the state of knowledge on a given topic or research question (Berrang-Ford et al., 2015; Bilotta et al., 2014; Booth et al., 2012). A strict methodology is used to collect, appraise and compile knowledge from all pertinent studies to ensure objective, transparent, traceable and upgradable outputs (Petticrew and Roberts, 2006). This approach provides a clear method to extract and analyse data, and to organise and identify both duplicated research and gaps in knowledge (Fedorowicz et al., 2011).

Systematic reviews were once limited to health care but are now more frequently published in environmental and social sciences (Adams et al., 2016; Berrang-Ford et al., 2015; Bilotta et al., 2014; Brisbois and de Loë, 2016; Flood et al., 2018; Haddaway and Pullin, 2014; Spector et al., 2018). In the climate change literature, SRs have been applied to gain in-depth understanding of place- and sector-specific knowledge (Ford et al., 2011; Lwasa, 2014; McDowell et al., 2014; Pearce et al., 2018; Wiréhn, 2018). Such reviews are considered to be a vital tool for surveying large bodies of knowledge and providing a baseline from which to measure advances in understanding (Flood et al., 2018).

The literature search was confined to peer-reviewed journal articles listed on databases selected in consultation with a research librarian. Three databases were used: ISI Web of Science, Climate CAB Abstracts, and Academic Search Complete. The search was limited to peer-reviewed manuscripts published between 2007 and 2017, to correspond to the parameters of the project reports. Results were cross-referenced with an earlier unpublished gaps analysis. The Climate Cloud – a repository for New Zealand-based climate change research – was also consulted using a targeted key word search.

Inclusion/exclusion criteria were used to screen the relevance of each article. Only articles focused on adaptation in the primary

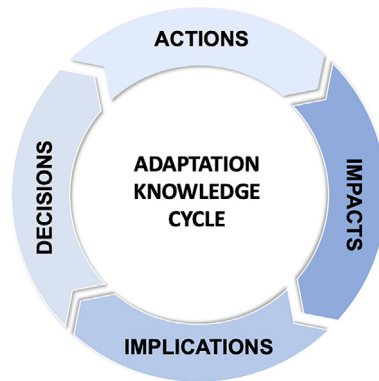


Fig. 2. Adaptation Knowledge Cycle.

sector in New Zealand were included. All references were initially downloaded to Endnote online or Mendeley. After screening criteria were applied, 22 research papers met the requisite criteria as shown in Fig. 1. Additional detail on the systematic review methodology is provided in the [Supplemental Materials](#).

2.3. Adaptation knowledge cycle and analysis

To further assess the specific outcomes related to adaptation research, the authors developed an analytical framework of what we consider to be the key characteristics and attributes of adaptation-relevant information: the Adaptation Knowledge Cycle (Fig. 2) (Cradock-Henry et al., in review).

This adaptation-specific typology was used to assess research outputs according to their analytical focus: Impacts, Implications, Decisions or Actions (I-I-D-A). Based on our previous work (Lawrence et al., 2016), it provides a simple heuristic to rapidly assess the contribution of a particular output to the adaptation knowledge base (Cradock-Henry et al., in review). **Impacts**-focused research provides a description of first-order impacts of climate change on the primary production system. This research identifies impacts but stops short of articulating how these impacts might flow through to challenge existing practices and lead to actions on the ground. **Implications**-focused research examines the knock-on or cascading effect of specific climate impacts on the primary production system and implications for management. Research with a **Decisions** or **Actions** focus provides information to make adaptation decisions by identifying when, where, and what decisions need to be made; or it supports changes in behaviour and implementation of on-the-ground actions for adaptation.

To apply the typology, we summarised each output, for projects – we also reviewed any related materials that might have been produced, and in some cases interviewed project leads. Each output was discussed as a team and assigned a value (I-I-D-A). Not all outputs fit neatly within the boundaries of the framework. However, to facilitate interpretation, each was assigned to a single category.

Reports ($n = 32$) and literature ($n = 22$) were reviewed, data extracted, classified and categorised in several ways. This provides a robust analysis describing the development of primary sector-focused climate change adaptation literature in New Zealand, thematically organising research outputs and identifying knowledge gaps.

The following data characteristics were identified and recorded for each adaptation research output (i.e. SLMACC project reports and published, peer-reviewed literature).

- **Thematic analysis:** Research outputs were read by at least two authors, and categorised according to thematic areas such as drought, biosecurity (including pest diseases), variability and extremes. Key characteristics of each output were recorded, and each item was summarised as part of an annotated bibliography.
- **Sector:** For each item the sectoral focus was identified. Where projects or papers addressed multiple sectors or activities in an area, they were classified as cross-sector; otherwise outputs were categorised as pastoral, dairy, arable, or horticulture and viticulture.
- **Georeferenced:** The impacts of climate change will be felt in different parts of the country. Eastern regions of New Zealand, for example, are likely to become hotter and drier, while western regions may become wetter. To gain insight into the prevalence of geographical locations and spatial gaps in the research, the scale (national/regional) and location of each research output was recorded. Results can be used to identify where most research is geographically focused and suggest spatial gaps where attention might be needed.

The tools and methods described here were used in combination to conduct this review. The review team met regularly and discussed all outputs, and proposed a preliminary list of themes that were common across the projects. All relevant outputs were then re-examined considering these themes. Each theme was then reported on using these data as evidence and examples.

3. Results and discussion

The following section discusses key themes from the 54 research outputs (including published papers and SLMACC reports published between 2007 and 2017) that form the basis of the review. Additional detail about each research output can be found in the [Supplemental Materials](#).

3.1. Impacts and adaptation: what do we know?

Over the last decade, new knowledge on climate change adaptation for New Zealand primary industries has been generated, improving our understanding. Adaptation research has made significant advances with respect to drought and the impacts of climate change for pasture-based farming. There is less information available on biosecurity, cross-sector adaptation, climate variability and extremes. Arable cropping, horticulture and viticulture are also under-researched.

3.1.1. Drought

Higher temperatures and decreased rainfall is expected to result in more frequent and severe droughts in eastern regions of New Zealand ([Harrington et al., 2014](#); [Kenny, 2011](#); [Reisinger et al., 2014](#)). While much of the drought-related research is focused on modelling drought frequency, severity and climate extremes ([Harrington et al., 2014](#); [Tozer et al., 2011](#)), this theme extends into broader considerations of the implications for a range of sectors and activities.

Overall, drought is the most-well-studied impact of climate change on the primary sector and includes work on impacts and understanding the implications for drought, as well as on-farm adaptive strategies and decision-making. Drought is the only topic for which there is information on Impacts, Implications, Decisions and Actions.

Drought will have an impact on wheat phenology ([Sylvester-Bradley et al., 2012](#)) and pasture production ([Zhang et al., 2007](#)). Pasture-based farming will need to adapt to variable soil moisture and prolonged drought, with implications for animal health toward and beyond mid-century. There are some empirical studies of adaptation in eastern regions, including the use of historical analogues documenting farmers' experiences and coping strategies in previous droughts. There is also work on tools to support on-farm decision-making and enable adaptation preparedness. [Cradock-Henry and Mortimer \(2013\)](#) developed a model of a drought-adapted farm, incorporating psycho-social, environmental and economic indicators for monitoring and evaluation. Other practical monitoring tools are included in a review of climate-smart agriculture to counter the impacts of drought, high temperatures, and heavy rainfall ([McKusker et al., 2014](#)).

3.1.2. Pastoral farming

New Zealand's pastoral farming activities – including dairy and livestock – are predominantly pasture based, with rain-fed farm systems on highly productive and well-drained soils. The majority of research with relevance for pastoral farming is focused on characterizing future impacts and implications. There are several studies that address the need for greater flexibility in pasture-based farming to adapt to existing climate variability and future extremes, as noted in the previous section.

There is a well-developed body of research on changing atmospheric conditions and the impacts on ryegrass, sub-tropical species and invasive weeds ([Dodd et al., 2009](#); [Tozer et al., 2011](#); [Crush, 2014](#)); pasture stress ([Guo and Trotter, 2008](#); [Lieferring and Newton, 2008](#); [Newton et al., 2008, 2011](#)) and productivity ([Fowler et al., 2008](#)). Higher temperatures, extreme rainfall events and higher winds associated with climate change are also likely to make pastures more susceptible to flooding, nitrogen leaching, drought, soil erosion and pests ([Hayman et al., 2012](#); [Lee et al., 2013](#); [Orwin et al., 2015](#)).

With this reliance on pasture feeding, farms will need to manage seasonal variability and long-term climate change, becoming more flexible and resilient ([Cradock-Henry and McKusker, 2015](#)). There is evidence in the literature that pasture-based dairy systems have relatively high levels of adaptive capacity, and there are opportunities to continue to improve production efficiencies, particularly where rainfall change is small. Potential adaptation strategies include the strategic use of supplementary feed, reduced stocking rates, irrigation, or sowing alternative plant species with greater drought tolerance ([Kenny, 2011](#); [Cradock-Henry and Mortimer, 2013](#); [Lee et al., 2013](#); [Cradock-Henry and McKusker, 2015](#)).

There is no research on the ability of pastoral farming to adapt to the increase in range across all climate impacts nor on the impacts of compounding hazards. For example, in the Hurunui the adverse effects of extended drought conditions were exacerbated by the November 2016 earthquake ([Cradock-Henry et al., 2018a](#); [Stevenson et al., 2017](#)). At the time of the earthquake, pastoral farmers in North Canterbury had been under considerable stress due to long-term (> 3 years) drought conditions. Impacts of the earthquake compounded existing stresses relating to personal well-being, animal health, productivity and yield ([Stevenson et al., 2017](#)). Furthermore, research to date has focused exclusively on the pasture component of the pastoral system. Heat stress may become problematic as we approach mid-century however there are no studies on the impacts of climate change on animal health, for example.

3.1.3. Biosecurity

Climate change will create significant biosecurity challenges for New Zealand's primary industries ([Kenny, 2011](#)). The review however, found only one SLMACC project on the topic ([Kean et al., 2015](#)). Warmer conditions may allow new exotic pests, weeds and diseases – currently prevented by New Zealand's current climatic conditions – to establish themselves ([Kenny, 2011](#)). The potential establishment of subtropical pests and current seasonal immigrants is of greatest concern, along with taxa that are already recognised as high risk ([Kean et al., 2015](#)). Climate is just one of several factors that affect invasion potential, and others – such as import

pathways, border management and host suitability – may also change in the future (Kean et al., 2015).

3.1.4. Cropping

There is some research on arable cropping, published studies however focus exclusively on understanding impacts (Beddington et al., 2012; Clark and Tait, 2008; Howlett et al., 2013; Trolove et al., 2008). Climate change will have mixed impacts on arable cropping (Wiebe et al., 2015; Zhang et al., 2007). Higher temperatures will allow earlier sowing of crops, and they will generally reach maturity faster – depending on sowing time. Higher temperatures could lead to decreased yields, but the fertilising effect of higher levels of carbon dioxide will potentially offset this, resulting in yield increases for temperate crops such as wheat and barley (Trolove et al., 2008).

This assessment however, is based on a small body of literature (Clark and Tait, 2008; Howlett et al., 2013; Trolove et al., 2008). In terms of adaptation in the sector, climate change may present new opportunities; for example, longer growing seasons and increased forage crop yields achieved through radical changes in forage germplasm and management (Trolove et al., 2008), if the sector can adapt to the increased frequency of heavy rainfall and wind events. It is important to note that the impacts of climate change will affect all primary industries, and many impacts will be coincident (e.g. warmer temperatures may also result in more intense storms, and/or new pests and diseases). The extent to which arable cropping – or any other sector – will be able to adapt or realise opportunities will be contingent on other factors (Challinor et al., 2018; Howden et al., 2007; Meinke et al., 2009). For example, dryland farming may increasingly precarious as temperatures rise and precipitation decreases. Farmers may require irrigation to ensure security of supply. Without irrigation systems in place, seed companies are often reluctant to sign purchase contracts to market and distribute due to the uncertainty.

3.1.5. Viticulture and horticulture

Wine is New Zealand's fastest growing primary industry, worth NZ\$1.7 billion (US\$1.0 billion) (New Zealand Winegrowers, 2018). High-value horticulture – including commercial vegetable production – is also expanding rapidly. Adaptation research for horticulture has focused largely on kiwifruit production and other fruit crops. Climate change is expected to have impacts for management and production outputs (Cradock-Henry, 2017; Tait et al., 2017). For some fruit crops, warmer temperatures may result in higher yields and fruit size, but this may be offset by increased water demands and increased competition for available water; changes in frost frequency and loss of winter chilling (Cradock-Henry et al., 2018b); and an increase in pests and disease (e.g. apple black spot) (Beresford and McKay, 2012), or pollination (Howlett et al., 2013).

For the wine industry, work on regional climate change in grape-growing regions such as Marlborough has provided new insight into climate variability and viticulture productivity. Regional climate scenarios provide the basis for understanding impacts (Sturman and Quéno, 2012), however, additional work is needed to identify adaptation options and assess the sector's adaptive capacity (Cradock-Henry and Fountain, 2019).

3.1.6. Pan-sector adaptation research

Successful adaptation will require in-depth understanding of the linkages between different industries, due to complex interdependencies – such as reliance on irrigation, and land use restrictions (Berry et al., 2006; Kiem, 2013; Kiem and Austin, 2013; Vermeulen et al., 2012). There has been no work to date on interactions between climate change and the diversity of primary industries. Clark and Nottage (2012) examine impacts, implications, decisions and actions individually for land-based industries (dairy, sheep and beef, cropping, horticulture, and forestry), and their report provides review and synthesis of existing scientific, professional and experiential knowledge. The research also engages with advanced risk analysis by applying production modelling to individual production units to create primary sector adaptation scenarios.

3.1.7. Climate variability and extremes

Daily temperatures and rainfall extremes in New Zealand have changed over the last 70 years. The probability of extreme warm days has increased and the probability of extreme cold days has decreased during this time (Ministry for the Environment, 2018). There is also clear evidence of a decreasing number of frosts, and some evidence for increasing numbers of very warm days, with regional variations. These changes have significant impacts on the primary sector through their impact on water availability during drought, increased soil erosion due to heavy rainfall events, heat stress for crops and animals, and increasing the likelihood of pests and disease (Reisinger et al., 2014).

There has been some project work on the impacts of extreme events on erosion (Basher et al., 2012), flood (McMillan et al., 2010), and wind (Mullan et al., 2011). There is one study on implications: catchment-scale modelling to predict the effects of climate change on weather elements, surface water flows, and groundwater flows (Bright et al., 2008). No published literature on the impacts of climate variability and extremes and the primary industries was identified in the literature review.

3.2. Knowledge gaps: what do we not know?

The results of the review and synthesis reveal empirical and methodological knowledge gaps for understanding adaptation in New Zealand's primary industries. Empirical gaps are those where additional data collection, modelling and analysis could narrow knowledge gaps for different sectors, places and/or issues. The resulting improved knowledge and empirical experience could assist decision-making on climate change adaptation and policies. The adaptation research we reviewed uses a narrow range of investigative techniques. We describe opportunities to address these methodological gaps to enhance our understanding of climate

change adaptation and support new knowledge for adaptation decisions and actions.

3.2.1. Empirical gaps

New Zealand's climatic and topographical diversity creates regional and local variation in physical climate factors (e.g., rainfall, diurnal temperature range, maximum temperatures, length of growing season, frost days) and soil types (e.g., volcanic sedimentary, peat soils etc). The success of certain primary industries in particular places can be attributed in part to the favourable combination of climate, soils, biosecurity system, a reliable supply of water and access to necessary physical infrastructure, and economic and social capital to provide inputs (labour, goods and services) and move the products along the value chain to market (Baskaran et al., 2009; Jay, 2007; Moller et al., 2008).

This also means, however, that each region and industry has the potential to be differentially affected by climate change because of biological, socio-cultural and economic characteristics. For example, changes in temperature may affect northern regions more than the southern regions, accelerating demand for regionally based seed solutions. Eastern New Zealand is expected to become drier, which will have implications for irrigated dairying and other water intensive industries, while western regions may be faced with heavier rainfall events, leading to problems with flooding and soil erosion. Northern parts of the East Coast may face the combined pressures of water limits and pasture species changing simultaneously (Kenny, 2011).

Given the above, there is a need for industry-specific, regionally based options and pathways to support adaptation (Barnett et al., 2014; Dannevig et al., 2012; Lee et al., 2014). It is unlikely that many universal solutions can be identified as farming and growing practices, social norms and values, aspirations, access to resources, and infrastructure vary. The results of the analysis shows however, the majority of primary industries adaptation research takes a broad, national scale focus ($n = 22$). The remaining 10 studies are unevenly distributed between selected regions. This closely corresponds to trends in the published literature as well, with one-third of research papers focusing on either the national level ($n = 7$), or a single region (Hawke's Bay, $n = 9$).

Similarly, the research is unevenly distributed across different primary industries and industry issues such as biosecurity. Pastoral farming accounts for nearly one-third of all studies ($n = 15$) (Table 2).

As shown in the data above: there is an urgent need to extend adaptation knowledge for local contexts, under-represented issues and industries including biosecurity, wine and grape growing, arable farming and horticulture. For each of these industries and issues, knowledge does not appear to extend beyond a few studies on the impacts of climate change, with research on implications, decisions and actions largely absent.

This empirical gap is best illustrated by the example of the New Zealand wine industry. Viticulture is extremely sensitive to climate change due to grape phenology (Fleming et al., 2015; Holland and Smit, 2010; Metzger and Rounsevell, 2011). At a regional scale, sensitivity is strongly influenced by characteristics of terroir: soils, topography, microclimate and varietal. Unlike arable crops however, which can be changed relatively quickly in response to changing growing conditions, vines take years to be established and have productive lifespans lasting decades, with planting decisions having long-term industry implications and the long lead times required to establish vines and build market share. Understanding the degree to which the industry is exposed and sensitive to climate change therefore, is essential to designing and implementing successful adaptation strategies.

Despite its economic significance the sector remains under-researched. Regional climate modelling for selected regions provides some insight into future climate however, there is very little understood about the potential for changes in management practices to adequately cope with future changes, including the development and adoption of new varieties, changing location for vineyards, or upgrading infrastructure to cope with compressed harvests. Thus, there is an urgent need to understand decision-making processes and adaptation intention around climate and weather-related risk, and how these are weighed up against risks from other natural hazards or economic and market forces.

Furthermore, farms, orchards, vineyards; the supporting industries that harvest, process, and distribute agricultural products nationally and internationally, are part of an interconnected system of production, processing, marketing and distribution. Nearly all the adaptation research we reviewed takes a narrow view, focusing on a single aspect of the value chain (Clark and Nottage, 2012;

Table 2

Research outputs: primary industry, issues and adaptation knowledge.

		Impacts	Implications	Decisions	Actions
Sector	Cross-sector	2	4	1	1
	Pastoral	12	1	2	
	Dairy		1	4	
	Kiwifruit			2	
	Viticulture	4			
	Horticulture	3			
Theme	Biosecurity	1			
	Extremes	3	1		
	Indigenous knowledge ¹	1			
	Ecosystem services ¹	1			
	Farmer behaviour ¹			4	

¹ Research outputs for this theme only in the published literature. There is no published literature on adaptation 'action' for primary industries in New Zealand.

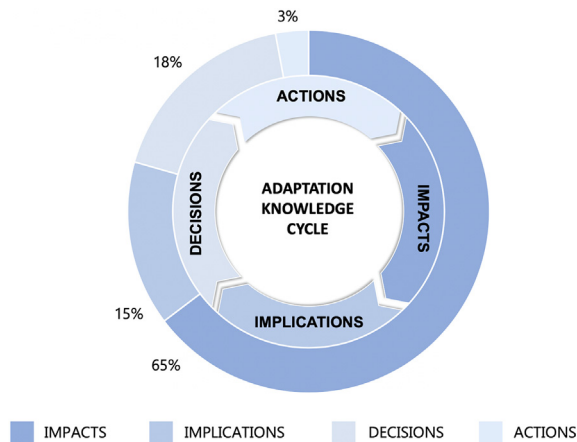


Fig. 3. Adaptation Knowledge Cycle shows distribution of current research.

Cradock-Henry, 2017; Kenny, 2011). There is increasing evidence however to suggest that climate risks are interconnected (Moser and Hart, 2015). Impacts have the potential to catalyse a cascade of implications between connected systems and sub-systems (Koks, 2018; Rocha et al., 2018). Kiwifruit for example are harvested in early autumn but may remain in the orchard for several days before being moved to a packing facility. With higher temperatures, fruit ripens and is harvested earlier – April instead of May. This requires cool stores to activate in late-March and requires excess heat to be removed from concrete pads prior to packing. The net result is energy costs for lowering the cool store temperature, plus the energy cost for lowering the temperature of a warm fruit in the cool store, are significantly higher (Cradock-Henry, 2017; Lawrence et al., 2016). Focusing only on the direct impacts therefore may fail to adequately account for interconnected climate risks; non-climatic stressors – such as changes in policy or legislation governing the production of commodities – or cascading implications triggered by impacts elsewhere. Interactions with other goals, particularly emissions reduction in the agricultural sector, but also water or soil quality, as well as productivity, should also be examined.

3.2.2. Methodological gaps

Adaptation research for New Zealand primary industries has focused primarily on understanding climate change impacts and implications. Consequently, we have limited understanding about potential adaptation options, decision making and the effectiveness of adaptation action. As shown in Fig. 3, eighty-percent of the literature we reviewed is concerned with impacts and implications (65% and 15% respectively). There is little information about decision-making (e.g., Can we do anything about the impacts? What opportunities might be realized? When do decisions need to be made?) or how best to enable adaptation action. To address this imbalance new insight from a range of methodological perspectives is required.

The majority of this research is ‘top-down’, synonymous with outcome vulnerability (O’Brien et al., 2007). Assessment begins with scenarios of future climate and then uses coupled biophysical or crop models to determine the likely effects on a sector or activity (e.g. Clark and Tait, 2008; Newton et al., 2011). Fewer studies begin from the perspective of stakeholders and end users who identify the most relevant impacts of climate change (e.g. Burton and Peoples, 2008; Cradock-Henry and McKusker, 2015; Kenny and Porteous, 2008).

Climate change however, adds an additional level of complexity that may not be captured in top-down or bottom-up (‘contextual vulnerability’) studies on their own (Berkes et al., 2008; de Boer et al., 2010; O’Brien et al., 2007; Preston et al., 2015). In this context, new methodologies are required to identify, assess and implement adaptation options. Model-based scenarios in combination with knowledge gained through social science and applied research methods together might advance our understanding of all aspects of climate change adaptation (Ausseil et al., 2019).

A number of tools are readily available to support adaptation planning and decision-making. For example, adaptation pathways have been applied to coastal hazards in New Zealand (Lawrence and Haasnoot, 2017) and may also be used for natural resource management (Bosomworth et al., 2017). Integrated socio-economic, policy and climate change scenarios can be used to engage diverse audiences in exploring and considering the outcomes of multiple futures (Cradock-Henry et al., 2018b; Frame et al., 2017). Resilience assessment and systems approaches have been used for assessing the impacts of and responses to, natural hazard events and lend themselves to climate adaptation research by accounting for potential interactions across scales and between systems (Cradock-Henry and Fountain, 2019).

Successful adaptation will require in-depth understanding not only of the impacts of climate change, but also the risk management implications, decisions that need to be made to reduce exposure to those risks and effective ways to motivate action across the primary industries. Failing to advance the research beyond a narrow focus on impacts may result in maladaptation (Barnett and O’Neill, 2010). Overall a more complex take on adaptation research for the sector might yield positive results for the sustainability of primary industries. Multiple perspectives, interdisciplinary research and applied social science can contribute knowledge on how to advance, monitor and evaluate adaptive capacity in New Zealand, and can play a critical role in developing solutions.

3.3. What is needed?

Climate change is impacting New Zealand now, affecting droughts and rainfall extremes (Harrington et al., 2014). These are having a disruptive effect on current production, and without adaptation, will have an even greater impact on primary industries (Ausseil et al., 2019; Cradock-Henry, 2017; Kenny, 2011). In closing we briefly discuss the need to address barriers to decision-making and the capacity for transformation, two priorities identified by primary industry stakeholders in a plenary workshop for the review.

First, results of the review show that the frequently cited barriers to adaptation action relate to changes in knowledge, beliefs, norms and behaviours including prioritisation of short term, or tactical management of existing climate variability, at the expense of longer-term planning; and scepticism regarding projected impacts (Reisinger et al., 2011). Both are compounded by significant uncertainty and the need to plan for multiple possible futures (Haasnoot et al., 2013). In decision-focused adaptation projects, for example, while climate change was identified as a risk, land managers often referred to other, more pressing concerns relating to farm performance, production and yield and profitability (Cradock-Henry and Mortimer, 2013; Cradock-Henry and McKusker, 2015; Dunningham et al., 2015). Climate variability was often identified as more significant than the long-term prospect of climate change (Cradock-Henry and Mortimer, 2013). The net result is that management practices are focused on addressing immediate and short-term issues, rather than on adaptation.

Furthermore, adaptation planning is also associated with a high degree of uncertainty. Future climatic conditions in New Zealand will be a function of emissions pathways, social and economic changes and policy responses – domestic and international (Challinor et al., 2018; Cradock-Henry et al., 2018b). Different responses might also be preferred depending on how the climate (and other non-climate parameters such as population or social values) change through time. Adaptation planning therefore must allow for a range of possible futures.

Given this complexity, working out what to do now to adapt to climate change can be overwhelming. Where stakeholders and end users perceive there is uncertainty and complexity it makes decision making more difficult, and some may postpone adaptation decisions and actions altogether (Burnham and Ma, 2015; Star et al., 2016). We suggest there is an urgent need to better understand decision-making processes that enable change in management practices to improve environmental, social and economic outcomes. In this context, this could include better understanding of the psychological components of (mal)adaptation and the ways in which values might motivate action. Regulatory incentives for example aimed at promoting adaptation need to act on beliefs, values and preferences that farmers hold (Buelow and Cradock-Henry, 2018). Gaining insight into measurable and alterable psychosocial factors that contribute to complex decision-making under uncertainty may help overcome barriers to inaction.

Second, small scale and ‘tactical’ responses to existing climate variability are likely to be insufficient but continue to be the basis for much of the response to climate change within the primary industries (Clark and Nottage, 2012). As discussed earlier, most adaptation research to date has been national-level efforts at focused on understanding impacts. This type of research is reactive and often fails to address region-specific planning requirements. There is scope therefore, to explore the feasibility of transformational change (Alexandra, 2012; Cradock-Henry et al., 2018a; Fleming et al., 2015; Rickards and Howden, 2012; Walker et al., 2004). Transformation involves widespread change to existing decision-making processes and patterns (Rickards and Howden, 2012). One aspect of this can include involving affected stakeholders in designing and deciding on future options (Brown et al., 2015; Leith et al., 2018). This in turn can empower them to develop inclusive solutions and enhance economic outcomes. Communities of practice comprised of diverse interests and perspectives can develop location-specific, group-specific and time-specific planning pathways (Pahl-Wostl, 2009; Ross et al., 2015). Evidence from work in New Zealand on collaborative processes for freshwater management, for example, demonstrates the positive learning outcomes associated with developing community experience with dealing with complex problems (Cradock-Henry et al., 2017). Embracing such opportunities—for example an exchange on regional and local best-practice examples of adaptation—can in turn lead to a transformation of habits.

The results of the review do demonstrate valuable successes. SLMACC-funded projects in particular have been highly effective in building adaptation research capability and capacity (MPI, 2018). The programme has funded early-career researchers, supported experimentation and fostered networking with international partners (e.g. Cradock-Henry and Mortimer, 2013; Dunningham et al., 2015).

Interdisciplinary research on climate change adaptation in the primary industries is growing and was a trend strongly supported by stakeholders. This is encouraged through a funding system that emphasises best teams and seeks closer alignment between the needs of stakeholders and science delivery. Collaboration between social and physical sciences has the potential to advance adaptation research (Adler et al., 2017; Bremer and Meisch, 2017; Reisinger, 2011), bringing together disciplinary and stakeholder knowledge on climate change adaptation.

4. Conclusions

The results of our research – commissioned as part of a larger review of climate change research in New Zealand (MPI, 2018) – demonstrates the value of combining systematic review with a detailed analysis of project outputs to determine the state of knowledge for a given adaptation domain. We reviewed 54 research outputs, which collectively address a diverse set of issues relating to adaptation, the impacts of climate change, and implications for management systems, geographic areas, and farming practices. The review systematises a diverse body of research and identifies key research gaps.

The key finding of the review is that adaptation research to date has been empirically and methodologically limited. The majority of studies we reviewed have been focused on better understanding the broad, national-scale impacts and implications of climate

change for pastoral farming. This work has primarily used top-down, biophysical and climate impacts modelling to assess the ways in which climate change will affect productivity and yield. It has been geographically focused on small number of selected regions, but many other NZ regions have had little or no context-specific or focused study.

Assessing research against the Adaptation Knowledge Cycle also shows that there has been considerably less work done on adaptation decisions and only one study on adaptation actions. These gaps therefore suggest a need for more social science and interdisciplinary research to complete the Adaptation Knowledge Cycle and support proactive adaptation as a more effective and sustainable strategy. Gaining insight into the barriers and enablers of adaptation action, expanding the focus of future research to explicitly include new conceptual and methodological approaches and analysis of decision-making could enhance the impact of research on stakeholders, provide better value for money and build resilience.

A key step in adapting to climate change is understanding what vulnerable and at-risk regions and sectors are, knowing how climate change will interact with other socio-economic and environmental stressors, and identifying options to build near- and long-term resilience to current and projected changes (Challinor et al., 2018; Walker et al., 2009). Further studies using integrated, cross-sectoral approaches to adaptation, and targeted research to meet urgent empirical and methodological gaps including under-represented industries and regions and adaptation knowledge are also needed. This is based on our assessment that narrowly focused actions may not create an adaptive sector (if it does not account for opportunities, challenges, and preferred adaptations in other sectors). Research that incorporates such horizontal integration, can help decision makers to prioritize specific adaptation actions that could contribute to the provision of multiple ecosystem services.

Findings from the research outputs included in this study demonstrate the need to adapt primary industries to manage seasonal variability and long-term climate change.

To face these challenges, there is a need for greater flexibility and ability to change and recover from short-term climate events. The primary sector will also need to be adaptive over the long term considering the possibility reduced production in times of climatic events. Addressing these challenges will require new and novel solutions to be able to increase adaptive capacity. This will require greater collaboration with stakeholders and end-users, to ensure the creation of salient, relevant and credible knowledge; and linked-up and systems thinking to bring social- and physical- sciences together. Such research is particularly important in New Zealand given the economic, and socio-cultural significance of primary industries, and its sensitivity to current and future change.

Finally, there is an opportunity to grow the small community of adaptation researchers in New Zealand. New Zealand-based researchers have made significant contributions to mitigation research over the last decade and have an international reputation for science excellence. A companion review found nearly ten times the number of papers on mitigation for New Zealand primary industries ($n = 224$) compared to adaptation research over the same 10-year period (van der Weerden et al., 2018). While the New Zealand Government is committed to a low-emissions economy, climate change already poses significant risks. The results of the review provide a robust empirical basis to build on the legacy of successful research to date, extending the impacts modelling to meet the growing urgency for practical and applied adaptation solutions. Moving the research agenda forward – from impacts research to implications and applications – can enable timely delivery of actionable information for climate-adapted primary industries, equipping the sector to face future challenges.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.crm.2019.100190>.

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