Towards a heuristic for assessing adaptation knowledge: impacts, implications, decisions and actions

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Abstract
Climate change poses a significant challenge to primary industries and adaptation will be required to reduce detrimental impacts and realise opportunities. Despite the breadth of information to support adaptation planning however, knowledge is fragmented, obscuring information needs, hampering strategic planning and constraining decision-making capacities. In this letter, we present and apply the Adaptation Knowledge Cycle (AKC), a heuristic for rapidly evaluating and systematising adaptation research by analytical foci: Impacts, Implications, Decisions or Actions. We demonstrate its application through an assessment of ten years’ climate change adaptation research for New Zealand’s primary industries. The letter draws on the results of systematic review, empirical analysis, workshops, interviews, narrative analyses and pathways planning to synthesise information and identify knowledge gaps. Results show the heuristic’s simplicity is valuable for cross- and transdisciplinary communication on adaptation in New Zealand’s primary industries. Results also provide insight into what we know and need to know with respect to undertaking adaptation planning. With the development of tools and processes to inform decision making under conditions of uncertainty—a such as adaptation pathways—it is increasingly important to efficiently and accurately determine knowledge needs. The combination of systematic data collection techniques, and heuristics such as the AKC may provide researchers and stakeholders with an efficient, robust tool to review and synthesise existing knowledge, and identify emerging research priorities. Results can in turn support the design of targeted research and inform adaptation strategies for policy and practice.

1. Introduction
Climate change is inevitable. Changing patterns in annual and seasonal rainfall, increasing likelihood of sudden heatwaves, droughts, storms and floods are well documented; current impacts widely felt; and future projections point towards widening climate variability, extremes and slowly emerging impacts (Arnell and Lloyd-Hughes 2014, Cook et al 2015, Lewis and King 2017). While we are able to predict certain effects, determining future implications relies on probabilistic, largescale models of an interconnected climate-human-ecological system that provide finite insight into future possible conditions (Burke et al 2014, Harrison et al 2016). This implies a need for flexibility in human reactions to climate change (Folke 2006).

This need for flexibility is especially relevant for land-based primary economic activities such as agriculture—including high value horticulture and viticulture, livestock, arable, and pastoral farming (Pretty et al 2010, Bizikova et al 2012). Agriculture is inherently sensitive to changes in mean climatic conditions, changes in the frequency and severity of extremes, increases or decreased temperatures and changes in precipitation patterns that have the capacity to adversely affect producers through changes to productivity and yield, or quality (Howden et al 2007, Meinke et al 2009). Some adaptation therefore will be required. While there is consensus on the degree to
which climate change is happening, its effects, and effective strategies to respond to it, are still being investigated.

To gain insight into the impacts of climate change for agriculture and inform adaptation planning, a considerable body of research has been developed in recent years (Crane et al 2017, Panda 2018, Vermeulen et al 2018, Wiréhn 2018). Studies range from biophysical models to predict changing outcomes for production and yield, to in-depth, bottom-up qualitative explorations of stakeholders’ perceptions of climate risks, capacities for adaptation, and more recently, integrated assessments which seek to combine scenarios of future change, with stakeholders’ experience and insights (Challinor et al 2014, Herrero et al 2014, Cradock-Henry 2017, Ausseil et al 2019). With adaptation knowledge being generated in different contexts, case studies and small comparative studies are providing valuable first steps in building a deep contextual understanding of climate change adaptation (Adler et al 2017). The knowledge base however, remains fragmented (Ford et al 2011, Ford and Berg-rang-Ford 2016, Pearce et al 2018).

Knowledge fragmentation and inherent communication barriers make it difficult to communicate insights across disciplines and working contexts, and collaborate effectively in order to promote adaptation planning and actions. This is especially true for transdisciplinary approaches—i.e. research involving academic, non-academic and community members—increasingly promoted in the adaptation literature as important. There is an urgent need therefore to overcome communication barriers (see Misra and Lotrecchiano 2018), and simplify the ways we pool, track and translate (research) insights to enhance impact and support the development of adaptation solutions.

In this letter, we propose the Adaptation Knowledge Cycle (AKC); a heuristic for evaluating large bodies of knowledge output. Heuristics are widely used in climate change research and can assist with reviewing, synthesising and tracking advances in understanding (Walker et al 2006, Preston et al 2015, Macintyre et al 2018). Our heuristic can be seen as the first step a decision-making process that first clarifies what we know and still need to know, then evaluating it against a pathways process, building on clearly communicated adaptation insights. It is effectively a perspective to sort and interpret existing research, to pair adaptation insights in such a way as to inform future adaptation decisions and planning. While we cannot overcome existing research limitations this way, we can demonstrate a way in which communication on adaptation can be simplified to better equip transdisciplinary collaboration on adaptation planning and action, and provide a potential tool for other interested reviewers. Our initial sorting process uses a systematic review (SR) methodology as well as interviews with primary industry stakeholders, combined with adaptation tracking and pathways planning.

SR methodologies have been promoted in the literature as a way to efficiently and effectively review and summarise the growing body of adaptation knowledge (Berrang-Ford et al 2015). Originating in the health sciences, SR is now increasingly being used for climate change adaptation to systematise knowledge at multiple scales—from local, regional, national—diverse jurisdictions, and contexts (Ford et al 2011, Flood et al 2018, Pearce et al 2018, Vermeulen et al 2018). While such reviews are welcome, there remain significant challenges to systematising and assessing the results of various studies and operationalising findings to enable effective adaptation.

Similarly, adaptation tracking can help establish a baseline to determine the status quo of adaptation planning and action, adaptation effectiveness, support and information needs (Ford et al 2013). What and how we track adaptation is further complicated by the inherent complexity of the field (e.g. Pearce 2018). Adaptation pathways planning has been developed to support decision making under conditions of complexity and uncertainty (Haasnoot et al 2013, Walker et al 2013), and can be seen as a meaningful addition to ‘dig deeper’ after the first process of tracking adaptation knowledge.

The letter is organised in four parts: the adaptation evolution and the need for tracking knowledge development as well as factors that are considered relevant for tracking exercises is next; we then discuss the AKC; and illustrate its application using the case of drought and primary industries in New Zealand. We close with conclusions identifying future avenues for research, application and refinement.

2. Adaptation in primary industries

Adaptation is both a process and a condition of altering system components, behaviour and planning to prepare for and reduce climate change impacts (Smit et al 1999, Nelson 2011). From the adaptation turn in the mid-1990s, to the present, the field has grown in size, scale and coverage to encompass nearly all aspects of human-environment relations in the context of climate change (Ford et al 2011, Agrawal et al 2013, Bierbaum et al 2013, Vink et al 2013). Adaptation research stands alongside mitigation as an essential response to climate change (Field et al 2014), as demonstrated in scientific literature, policy and planning, media and public awareness (Moser and Ekstrom 2010).

Agriculture was one of the first areas in which a focus on adaptation originally began (Smit et al 1999). Concern over the impacts of higher temperatures and declining precipitation on crop yields, for example, were at the centre of pioneering research modelling the vulnerability of agriculture to external stressors (Johnston and Chiotti 2000, Kenny et al 2000). These early studies—later described in terms of ‘outcome
vulnerability’ (O’Brien et al 2007), ‘end-point’ or ‘wounded soldier’ approaches (Kelly and Adger 2000) —began with emissions trends, climate scenarios, and on to biophysical impact studies and the identifying adaptation options (Kelly and Adger 2000).

In a lot of agricultural research vis-à-vis climate change, there continues to be an emphasis on ‘end-point’ approaches (Kelly and Adger 2000), using crop simulation analyses (Howden et al 2007, Tao et al 2011). Downscaled climate models are used to derive target temperature increases to describe the impacts on production using the mechanisms through which climate shapes agricultural production patterns (Howden et al 2007). For instance, water stress (drought or water excess) and thermal stress (heat or cold) might have large impacts on plant production by disrupting the phenology (foliation, flowering, life cycle, etc), growth and yield (size, number and quality of grains) of plants and their spatial distribution (Ebi et al 2009). The effects on animal production are similarly modelled, through examination of the disruption to feedstock production; and the distribution and propagation of emerging diseases that could impact plant and animal production (Junk et al 2012, Escarcha et al 2018).

Such modelling studies do have significant value. Models can demonstrate the potential significance of adaptation in moderating the impacts of climate change in agriculture; however they often neglect the complex dynamics that shape how climate change is experienced and responded to by human systems. Models also tend to over-emphasise future conditions and neglect current stresses. There is also a tendency in such approaches to assume a priori that climate is the most significant stressor faced by producers, and also which climate stimuli are important (Meinke et al 2006, 2009, Wreford and Adger 2010, Gawith and Hodge 2018). Ignoring adaptation however can also lead to a serious overestimation of the damage of climate change (Tol et al 1998). Not only does this assumption lead to overestimations of damage, it also conveys the message that there are no actions available in the face of climate change and the only option is to mitigate emissions or suffer serious consequences (Wreford and Adger 2010).

While there continues to be considerable focus on impacts, the breadth and depth of adaptation research has broadened considerably in recent years. Researchers are now considering for example, more closely decision-making processes and the nature of barriers to adaptation: their source, strategies to circumvent, remove or lower them, and the ways in which they are influenced and constrained by local or far-removed circumstance and influence (Moser and Ekstrom 2010). In studies of farmers, empirical studies show contradictory results on farmers’ adaptation. While some find that farmers do not adapt to climate change (Arbuckle et al 2015, Prokopy et al 2015, Burke and Emerick 2016) others find that farmers are currently adapting to climate change, while the ‘policies supporting higher resilience of farming sector to climate change are either missing or in preparation’ (Olesen et al 2011, p 108).

This behavioural dimension of adaptation is also a focus of close examination, in both comparative-empirical and experimental contexts (Grothmann and Patt 2005, Niles et al 2016, Buelow and Cradock-Henry 2018). Grothmann and Patt (2005) develop a framework for analysing the individual willingness to adapt, which is tested in an experiment by Buelow and Cradock-Henry (2018). Based on Arbuckle et al’s findings (2015), it can be assumed that most farmers do not interpret weather events as consequences of climate change, but instead interpret them as single events that they react to at that point in time, in a specific region, context and sector. The need for long-term adaptation is hence not self-evident, unless farmers experience climatic variability as a reoccurring, limiting factor to agricultural production and planning.

The growing breadth and depth of adaptation research, and the complexities associated with characterising and assessing it, leads Pahl-Wostl (2009) to conclude that ‘only further development and application of shared conceptual frameworks taking into account the real complexity of governance regimes can generate the knowledge base needed to advance current understanding to a state that allows giving meaningful policy advice’. Integrated frameworks for assessing adaptation then require a focus on dynamic interactions between the social, ecological, and economic state of systems. They need to be context aware, paying attention to multi-actor settings, networks, hierarchies and preferences in the social sphere, follow market-trends, preferences, interactions and transactions in the economic sphere and match those to feedback loops, structures and development of the environmental sphere (Berardi et al 2011, Sinclair et al 2014).

This complexity of both climate change as well as the effects of it on all systems makes adaptation tracking appealing as a way of continuously keep an eye on the developments at different scales in different, but interrelated spheres. Adaptation tracking seeks to characterise, monitor, and compare general trends in climate change adaptation over time. It is essential for evaluating current states and monitoring advances however, there have been few attempts to develop systematic tracking approaches (Pearce et al 2018). While it is highly important to know more about the state and development of adaptation, there are no commonly defined, easy to track adaptation metrics, leaving an abundance of insights and an overall fragmented understanding (Ford et al 2013, Ford and Berrang-Ford 2016, Pearce et al 2018). In the absence of agreement on indicators, data, methods of assessment and expertise, the opportunities to realise the benefits of comprehensive assessment, limit the
success of learning and practice for both research and practice (e.g. Moser and Ekstrom 2010).

Notwithstanding, the capacity to track the status quo and progress of adaptation comes with a number of potential benefits: it might spur national, local and regional governments to action to see how their work compares to that of other jurisdictions (Ford et al 2013, Vogel and Henstra 2015, Ford and Berring-Ford 2016, Pearce et al 2018). Furthermore, estimates of effective measures allow us to prioritise some activities over others and thus further reduce negative climate change impacts. All tracking needs to define what adaptation looks like in practice, how we define success and effectiveness and what kind of data sources we can rely on (Ford et al 2013).

To support this broader push for methods and frameworks to enable more effective adaptation tracking, we advance the following heuristic as one way to document in particular, progress towards understanding adaptation knowledge in a particular sector or knowledge domain. The relevance of identifying impacts, implications, decisions and actions in the context of agricultural adaptation is based on our collective experience working with primary industry stakeholders and end users, and empirical and conceptual studies of adaptation in Aotearoa New Zealand (New Zealand). It has been co-developed in a transdisciplinary context as part of the Sustainable Land Management and Climate Change (SLMACC) research programme, administered by New Zealand’s Ministry for Primary Industries (MPI 2018). The SLMACC programme supports research 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).

As part of a review of the programme’s outcomes and impacts since its inception in 2007, we evaluated 32 SLMACC adaptation projects against six criteria (Science capacity and capability enhancement, Influence on science, Engagement and networks, Learning, awareness and knowledge exchange among end users, Usability of research for end users, Influence on stakeholders and impact for NZ) (Cradock-Henry et al 2018). We conducted a systematic literature review and prepared an annotated bibliography of the published peer-reviewed literature related to adaptation in NZ primary industries (Cradock-Henry et al 2019); performed a cost benefit analysis of adaptation research for pastoral farming; developed and applied the Impacts-Implications- Decisions-Actions heuristic, and classified SLMACC projects and the published literature using the heuristic to identify salient characteristics of each. We have also repeatedly discussed findings and methods with primary industry stakeholders and adaptation researchers solicit feedback on our analysis and its relevance. This process is iconic of the complexity of adaptation research: it makes it confusing and complicated to engage in conversations on the ‘bigger picture’, or the status quo of climate adaptation.

To remedy this, we propose the following AKC as a suggestion for evaluating adaptation research, and for simplifying complexity by sorting and categorising through an iterative process. We use it to identify and characterise adaptation knowledge by analytical foci: Impacts, Implications, Decisions and Actions. The AKC provides a tool for identification and review, and can assist with reviewing, synthesising, and assessing adaptation knowledge gaps rather than improvements of limitations in adaptation studies. As such, it is well suited for in-depth analyses of the field, assisting decision-makers and researchers alike in the process of wilding through the unclassified, existing consortium of output on adaptation, and pointing to existing knowledge gaps.

In the following section, we briefly introduce the AKC, before demonstrating its application to a case study example.

3. Adaptation knowledge cycle

Given the significant uncertainties associated with possible climate futures, there is a growing emphasis on the need to incorporate principles of adaptive management into planning processes to reduce risks and vulnerability. Adaptive management is understood as an operationalisation of adaptive governance that can bring about collaborative policy solutions to natural resource use in the agricultural sector (Folke et al 2005), integrating different types of knowledge and learning processes in the progress of management action (Lundmark and Jonsson 2014). In this, management means the process of participatory decision-making, a way of administering agricultural adaptation to climate change as a product of agricultural co-regulation.

A number of frameworks have been proposed to support adaptation planning, including pathways approaches (Haasnoot et al 2013), resilience assessment (Liu 2014), and bespoke tools and processes for different contexts or challenges, such as coastal hazards and sea-level rise (Barnett et al 2014, Lin et al 2017). Many of these frameworks employ a circular logic, proceeding stepwise through a deliberate process of determining and assessing impacts and the ways in which climate stressors will affect a system of concern (Bosomworth et al 2017).

The AKC (figure 1) is used to systematise the knowledge base with respect to impacts, implications, decisions and actions (I–I–D–A). The approach is based in part on previous work by members of the review team (Lawrence et al 2016) and has been further adapted to the context of the primary industries based on our collective experience and expertise (Cradock-Henry 2017, Buelow and Cradock-Henry 2018, Cradock-Henry et al 2018, 2019). The I–I–D–A classification originated as part of
the ‘Climate Change Impacts and Implications’ (CCII 2015) project. The aim of the project was to determine the ‘predicted climatic conditions and assessed/potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100’. In order to widen the scope beyond impacts and implications, the authors undertook research on decision-making within the CCII project to consider the ways in which stakeholders acquired and used climate information, and took action (Lawrence et al 2016). Subsequently, we have continued to develop and apply I–I–D–A as device for engaging with stakeholders on climate change (Lawrence et al 2018, Cradock-Henry et al 2019).

We define the four elements as follows: Impacts–research is focused on the direct impacts of climate change on the natural or linked natural-human environment. For primary industries, this might include research that describes changes in climatic variables that are relevant to primary industries including temperature, precipitation and any changes in climate variability or extremes. Impacts on agroecological systems, e.g. including floods and droughts, are also included (IPCC 2014). Implications–focused research examines the knock-on or cascading effect of specific climate impacts on the primary production system and implications for management (e.g. rising temperatures on pastures and effects on industries involved, regions, economic structures etc). Implications describe the effects for human-environment systems, such as primary industries. For example, the direct impact of higher temperatures will have implications for pasture productivity (Lee et al 2013), pests and invasive species (Kean et al 2015). Studies on decisions provide information to make adaptation decisions by identifying when, where and what decisions need to be made (‘What can we do about the impacts or implications of climate change?’). Finally, adaptation actions–focused research supports changes in behaviour and implementation of on-the-ground actions for adaptation (e.g. rising temperatures on pastures in the context of different varieties introduced, different policies and their effect, sowing dates and tillage practices etc) (‘How do we take action?’), and assists with monitoring the effectiveness of management interventions (‘How do we know we are doing the right thing?’).

This first step of categorising adaptation knowledge is combined with adaptation tracking and a pathways approach. The aim is to track and make sense of the knowledge streams that contribute to publications, findings and communication on impacts, implications, decisions or actions. Using a multi-methods approach, we analysed data sorted according to summaries we developed of relevant outputs (n = 52) (table 1), reviewed commentary and feedback from the researchers’ responses to survey(s), and discussed outputs projects as a team. We then assessed the information provided against the Impacts–Implications–Actions–Decisions heuristic, and recorded all other key characteristics for SLMACC adaptation reports (n = 32).

The review of project reports was supplemented with a SR of the literature on adaptation in New Zealand’s primary industries which identified relevant published literature (n = 20). An identical process was then applied to these outputs as well. In our empirical analysis, we have looked at Impacts, Implications, Decisions and Actions in the context of funding, industry sectors, research organisations involved, geographical location, uptake of research by stakeholders and their awareness of adaptation knowledge, and publications (Cradock-Henry et al 2019). This analyses provided an overview on the effect of research on primary sector industries and continuously fed into transdisciplinary pathways planning processes (see Cradock-Henry et al 2019). A detailed discussion of the review methodology is available elsewhere (Cradock-Henry et al 2019).

The second step was to assess adaptation knowledge against an applied adaptation pathways framework (figure 2). Adaptation pathways planning has been developed to support decision making under conditions of complexity and uncertainty (Haasnoot et al 2013, Walker et al 2013). While originally developed for flood risks, it has been widely applied in diverse settings, including for primary industries (Leith et al 2012, Bosomworth et al 2017). The pathways planning process is intended to identify a suite of adaptation options, rather than limit decision makers to a single strategy. It is open-ended, and a range of future scenarios are incorporated into the analysis to encourage an exploration of adaptation options, how they will be affected over time, and whether any options have a point at which they are no longer viable. Decision-makers determine which combination of options (or pathways) are most suitable. Once options
### Table 1. Research outputs generated through systematic review and SLMACC programme

| Title                                                                                      | Author(s)/Year                          | Journal/Report                      |
|--------------------------------------------------------------------------------------------|-----------------------------------------|-------------------------------------|
| Impacts of climate change on erosion and erosion control methods: a critical review         | Bashor et al (2012)                     | Report (SLMACC)                     |
| Climate change impacts on plant diseases affecting New Zealand horticulture                | Beresford and McKay (2012)              | Report (SLMACC)                     |
| Projected effects of climate change on water supply reliability in Mid-Canterbury          | Bright et al (2008)                     | Report (SLMACC)                     |
| Learning from past adaptation to extreme climatic events: a case study of drought          | Burton and Peoples (2008)               | Report (SLMACC)                     |
| Drought, agricultural production & climate change: a way forward to a better understanding| Clark and Tait (2008)                   | Report (SLMACC)                     |
| Scenarios of regional drought under climate change                                       | Clark et al (2011)                      | Report (SLMACC)                     |
| Impacts of climate change on land-based sectors and adaptation options                    | Clark and Nottage (2012)                | Report (SLMACC)                     |
| Exploring Perceptions of Risks and Vulnerability To Climate Change in New Zealand Agriculture | Craddock-Henry (2008)                 | Political Science                   |
| New Zealand Kiwifruit growers’ vulnerability to climate and other stressors               | Craddock-Henry (2017)                   | Regional Environmental Change       |
| Operationalising resilience in dairy agroecosystems                                       | Craddock-Henry and Mortimer (2013)      | Report (SLMACC)                     |
| Impacts, indicators and thresholds in sheep-and-beef land management systems               | Craddock-Henry and McCusker (2015)      | Report (SLMACC)                     |
| Defining climate adaptive forage traits and genetic resources                             | Crush (2014)                            | Report (SLMACC)                     |
| Tomorrow’s pastures: subtropical grass growth under climate change                       | Dodd et al (2009)                       | Report (SLMACC)                     |
| Innovative and targeted mechanisms for supporting adaptation in the primary sector        | Dunningham et al (2015)                 | Report (SLMACC)                     |
| Vulnerability of New Zealand pastoral farming to the impacts of future climate change on the soil water regime | Fowler et al (2008)                   | Report (SLMACC)                     |
| Vulnerability of pastoral farming in Hawke’s Bay to future climate change: Development of a pre-screening (bottom-up) methodology | Fowler et al (2013)                    | New Zealand Geographer             |
| The management of risk in a dryland environment                                           | Grey et al (2011)                       | Proceedings of the New Zealand Grassland Association |
| Climate change risks to pastoral production systems                                       | Guo and Trotter (2008)                  | Report (SLMACC)                     |
| Climate change and Aotearoa New Zealand                                                   | Hopkins et al (2015)                    | WIREs Climate Change                |
| Impact of climate change on crop pollinator in New Zealand                               | Howlett et al (2013)                    | Report (SLMACC)                     |
| An integrated biophysical and socio-economic framework for analysis of climate change adaptation strategies: The case of a New Zealand dairy farming system | Kalaugher et al (2013)                 | Environmental Modelling and Software |
| Effects of climate change on current and potential biosecurity pests and diseases in New Zealand | Kean et al (2015)                     | Report (SLMACC)                     |
| Grassland production under global change scenarios for New Zealand and pastoral agriculture | Keller et al (2014)                    | Geoscientific Model Development     |
| Adaptation in agriculture: Lessons for Resilience from eastern regions of New Zealand    | Kenny (2011)                            | Climatic Change                     |
| Adapting to climate change in the kiwifruit industry                                      | Kenny and Porteous (2008)              | Report (SLMACC)                     |
| Māori environmental knowledge of local weather and climate change in Aotearoa—New Zealand | King et al (2008)                      | Climatic Change                     |
| Climate-change effects and adaptation options for temperate pasture-based dairy farming systems | Lee et al (2013)                      | Journal of British Grassland Society |
| Improved field facilities to study climate change impacts and adaptations in pasture     | Lieffering and Newton (2008)            | Report (SLMACC)                     |
| Exploring climate change impacts and adaptations of extensive pastoral agricultural systems by combining biophysical simulation and farm systems models | Lieffering et al (2016)                | Agricultural Systems               |
| Climate Smart Intensification options for New Zealand pastoral farmers: a farmer’s guide to intensification options in the context of climate change | McCusker et al (2014)                  | Report (SLMACC)                     |
| Flood risk under climate change: a framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios | McMillan et al (2010)                  | Report (SLMACC)                     |
| Dealing with changing risks: a New Zealand perspective on climate change adaptation       | Manning et al (2015)                    | Regional Environmental Change       |
are identified, they are evaluated and sequenced over time, often using a participatory process (Haasnoot et al 2013).

Incorporating pathways into the knowledge cycle helps to validate the focus on impacts through to actions. Both elements are conceptually and theoretically grounded in adaptive management, and emphasise planning, doing, monitoring and review (Bosomworth et al 2017). Second, given the growing prevalence and interest in pathways planning, it provides an efficient way to determine decision-relevant knowledge gaps, and provides a practical avenue for action. The combination complements tracking and monitoring exercises and forms the basis of an evaluation of effectiveness for improved adaptation support, information for governance as well as communication to the public (Ford et al 2013). Pathways planning and similar adaptation decision-support systems, provide a structured approach for decision-making when dealing with complex systems and uncertainty. Instead of reacting to systems’ surprises on an ad hoc basis such processes provide a decision-oriented framework for considering a full range of adaptation pathways for a particular setting from which the most critical pathways can be determined (Haasnoot et al 2013, Maier et al 2016).

To illustrate the application of our heuristic in combination with pathways planning, the following section presents a case study example focusing on adaptation to drought for pastoral farming. We begin with a brief introduction to climate change and primary industries in New Zealand.

4. Climate change and primary industries in New Zealand

New Zealand is a small, relatively wealthy country in the Pacific. As an exporting, and trade-dependent nation, with low population density, and a history of agricultural

Table 1. (Continued.)

| Title                                                                 | Author(s)/Year | Journal/Report       |
|----------------------------------------------------------------------|----------------|----------------------|
| Scenarios of storminess and regional wind extremes under climate     | Mullan et al (2011) | Report (SLMACC)      |
| change                                                              |                |                      |
| Empowering farmers for increased resilience in uncertain times       | Orwin et al (2015) | Global Change Biology|
| Enhanced modelling capability to conduct climate change impact       | Niles et al (2015) | Agriculture, Ecosystems and Environment |
| assessments                                                          |                |                      |
| Impact of elevated atmospheric carbon dioxide concentration on       | Newton et al (2011) | Report (SLMACC)      |
| pasture, production forestry and weeds                              |                |                      |
| Detection of historical changes in pasture growth and attribution    | Newton et al (2014) | Climate Research    |
| to climate change                                                    |                |                      |
| How limiting factors drive agricultural adaptation to climate change  | Niles et al (2015) | Climatic Change      |
| Farmer’s intended and actual adoption of climate mitigation and       | Niles et al (2016) |                      |
| adaptation strategies                                                |                |                      |
| Effects of climate change on the delivery of soil-mediated ecosystem  | Orwin et al (2015) |                      |
| services within the primary sector in temperate ecosystems: a review  |                |                      |
| and New Zealand case study                                           |                |                      |
| Farmers and Climate Change: A Cross-National Comparison of Beliefs     | Prokopy et al (2015) | Environmental Management |
| and Risk Perceptions in High-Income Countries                        |                |                      |
| Four degrees of global warming: effects on the New Zealand           | Renwick et al (2013) | Report (SLMACC)      |
| primary sector                                                       |                |                      |
| Evaluating intensification trajectories in the context of climate     | Rosin et al (2015) | Report (SLMACC)      |
| change                                                              |                |                      |
| Changes in atmospheric circulation and temperature trends in         | Sturman and Quénol (2012) | International Journal of Climatology |
| major vineyard regions of New Zealand                                |                |                      |
| Development of advanced weather and climate modelling tools to help  | Sturman et al (2015) | Report (SLMACC)      |
| vineyard regions adapt to climate change                             |                |                      |
| Designing resource-efficient ideotypes for new cropping conditions:  | Sylvester-Bradley et al (2012) | Field Crops Research |
| Wheat (Triticum aestivum L.) in the High Rainfall Zone of southern    |                |                      |
| Australia                                                            |                |                      |
| Improving sustainable lifetime performance of pastures: Learning     | Tozer et al (2011) | Report (SLMACC)      |
| from extreme climatic events                                        |                |                      |
| Forage crop opportunitites as a result of climate change             | Trollove et al (2008) | Report (SLMACC)      |
| Retaining Adaptive Capacity in New Zealand’s ecological systems      | Weller et al (2008) | New Zealand Journal of Agricultural Research |
| Framework for assessment of climate impacts on New Zealand’s         | Zemansky et al (2010) | Report (SLMACC)      |
| hydrological systems                                                 |                |                      |
| Spatially explicit modelling of the impact of climate changes on     | Zhang et al (2007) | Climatic Change      |
| pasture production in North Island New Zealand                       |                |                      |
development, primary industries make a significant contribution to GDP (Statistics New Zealand 2018). Land-based primary industries in New Zealand currently operate in an environment of increasing risk and uncertainty. Primary enterprises will contend with more frequent climate crises (e.g. drought and flood), ecosystem services degradation (e.g. eroding soils, water pollution), biosecurity incursions, changing social and market demands (e.g. the demand for sustainable products) (Kenny 2011, Cradock-Henry 2017). Some of these act as persistent pressure on enterprises, while others act as short, sharp shocks. Collectively they can have a significant impact on the sector and New Zealand’s economy (Stroombergen et al 2006, Spector et al 2018).

The increased frequency of such events is extremely relevant to New Zealand. Approximately half the land base is in productive pasture and arable cropping, including 1.8 million hectares of productive forest plantation. Nationally, it is a significant economic driver, employing 350,000 people, and is fundamentally important to many local and regional economies (Patterson et al 2006).

Climate events such as El Niño–Southern Oscillation (ENSO) have demonstrated their impacts on the economy, and there is increasing evidence of human influence on recent climate extremes affecting New Zealand (Harrington et al 2014). Primary sector economic activities such as pastoral farming, horticulture, viticulture and cropping are acutely vulnerable to climate change (Cradock-Henry 2017). The shift towards more intensive production and high-input systems has exposed the sector and there is further potential to create new risks and increase uncertainty for producers. Overall, as much as 79% of New Zealand’s economic activity is considered vulnerable to future climate change (Fitzharris 2007, Hopkins et al 2015, Manning et al 2015).

4.1. Adaptation knowledge and drought
Drought is one of the most significant climate change related impacts for New Zealand’s primary industries (Kenny 2011, Harrington et al 2014, Reisinger et al 2014). There is already evidence to suggest a close correlation between GDP and El Niño–driven drought cycles, and recent persistent dry conditions have had a marked economic impact over the last decade. Climate change is expected to increase the likelihood of dry conditions—particularly in eastern regions—which may be compounded by intensification, water restrictions, and decreased flexibility with respect to management options.

To assess the adaptation knowledge base, we identified a sub-set of reports ($n = 9$) and published peer reviewed papers ($n = 7$) from table 1, that focus explicitly on drought, or that have a significant drought-related component to the research (table 2).

To apply the AKC, and assess adaptation knowledge for drought, each research output was read multiple times by the authors. Thematic content analysis was used to code research outputs according to multiple criteria, including sector (e.g. dairy, livestock), geographic scale and focus (e.g. local, regional, national; Canterbury, Hawke’s Bay); temporal scale (historical analysis; current conditions; future focused) and its contribution to adaptation knowledge (Impacts, Implications, Decisions, Actions) (table 3).

Climatic drought risk is expected to increase during this century for all areas in New Zealand that are currently drought prone (Clark et al 2011) and it is of significant concern for primary industries. Coding research outputs relating to drought shows a body of work on the impacts and implications of drought for primary industries, as well as some work on adaptation decision-making.

Clark and Tait (2008), for example, analysed drought risk in combination with economic analysis to consider the implications for risk management, while Burton and Peoples (2008) extended that even further to examine farmers’ ‘tacit’ knowledge (instrumental, embedded knowledge) and the ways in which they had coped with previous droughts.

To support on-farm decision-making and enable adaptation preparedness, Cradock-Henry and Mortimer (2013) developed a model of a drought-resilient farm, incorporating psycho-social, environmental and economic indicators for monitoring and evaluation. Other practical tools are included in a review of the development and practice of climate-smart agriculture to counter the impacts of drought, high temperatures, and heavy rainfall (McCusker et al 2015).

There is also drought-related research in the published literature (table 3). This includes model-based studies of the impacts for wheat phenology (Sylvester-Bradley et al 2012) and spatial assessment of the effects of climate change on North Island pasture production (Zhang et al 2007). The implications for the dairy industry are considered by Lee and colleagues (Lee et al...
| Title                                                                 | Author(s)/Year | Type        | Contribution to adaptation                                                                                                                                                                                                 |
|----------------------------------------------------------------------|----------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Learning from past adaptation to extreme climatic events: a case study of drought | Burton and Peoples (2008) | Report      | Examines the ‘tacit’ knowledge (instrumental, embedded knowledge) of farmers in NZ. It looks at past extreme weather events to see what the best coping strategies for future droughts. |
| Drought, agricultural production and climate change: a way forward to a better understanding | Clark and Tait (2008) | Report      | Recommends a programme of research that encompasses applied risk analysis with enabling science initiatives. The aim is to maintain high levels of innovation in adapting to climate change. |
| Scenarios of regional drought under climate change                    | Clark et al (2011) | Report      | Uses models (with data from the IPCC) to predict drought frequency and intensity under three major global greenhouse gas emissions scenarios (B1, A1B, and A2). Highlights the need for adaptation in regions, such as the Canterbury Plains, where there is a high likelihood that droughts will increase in frequency and intensity. |
| Impacts of climate change on land-based sectors and adaptation options | Clark and Nottage (2012) | Report      | Summarises existing data on climate change and then offers adaptation options for a range of land-based industries (dairy, sheep and beef, cropping, horticulture, forestry, viticulture). |
| Exploring perceptions of risks and vulnerability to climate change in New Zealand agriculture | Cradock-Henry (2008) | Journal article | Identifies vulnerabilities and adaptive capacities of agricultural producers in the Rangitaiki Plains, Bay of Plenty on the North Island, in order to contribute to the development of effective strategies to assist farmers in adapting to climate change. |
| Impacts, indicators and thresholds in sheep-and-beef land management systems | Cradock-Henry and McCusker (2015) | Report | Uses a stability landscape model to characterise resilience in sheep-and-beef land management systems, and then develops an indicators-based evaluation framework. |
| Operationalising resilience in dairy agroecosystems                  | Cradock-Henry and Mortimer (2013) | Report | Develops a novel framework for assessing resilience in dairy-agro-ecosystems. |
| Innovative and targeted mechanisms for supporting adaptation in the primary sector | Dunningham et al (2015) | Report | Reviews tools and mechanisms used in New Zealand climate change adaptation communication and research, and then identifies the motivating levers of decisive action at different scales across the primary sector activities. The intention was to identify communication mechanisms to support climate change adaptation in the primary sector. |
| The management of risk in a dryland environment                        | Grey et al (2011) | Journal article | Provides an inventory of farmers’ risk management strategies, including analysis using descriptive statistics, through the issue of a questionnaire completed during face to face interviews with 24 farmers in the Hawke’s Bay hill country. |
| Climate change and Aotearoa New Zealand                               | Hopkins et al (2015) | Journal article | A desktop review examining adaptive responses to climate change in New Zealand and with a focus on key industries (agriculture, tourism) and communities (coastal, Māori). The devolved structure of adaptation is also explored. |
| Climate-change effects and adaptation options for temperate pasture-based dairy farming systems | Lee et al (2013) | Journal article | A desktop review that describes projected changes in climate in NZ and southeast Australia, likely effects on the feed base used in the pasture-based dairy industry and the flow-on effect on milk-solids production and profitability. |
2013), who examined drought in relation to feed availability and flow-on effects for productivity and profitability. There is also work from Hawke’s Bay (Grey et al 2011) and the Bay of Plenty (Cradock-Henry 2008) on adaptation, vulnerability and risk management strategies for farming, and a national perspective on climate change risks is provided by Hopkins et al (2015). With respect to climate change and the primary industries, drought is the most-well-studied impact of climate change on the primary sector. There is a very little work on adaptation actions (Dunningham et al 2015), however there may be valuable insights that could be derived from other studies of the industry, which have looked at incentives and barriers to action, particularly for management of freshwater (Bewsell et al 2007, Kaine et al 2017).

Findings show the published literature has enhanced our understanding of drought, climate change and primary industries, particularly, through a ‘whole of cycle’ approach to the topic (which may have been incidental rather than deliberate). For example, the research shows an analytical focus on both impacts and implications and exploring on-farm adaptive strategies and decision-making (figure 3). With respect to planning therefore, we would suggest that there is already sufficient knowledge in the literature to inform the initial development and assessment of adaptation planning strategies, at least at a high level, and for selected industries, e.g. pastoral farming.

This is not surprising. Pasture-based farming (including dairy and livestock) have been among the largest economic drivers of New Zealand’s rural economy for some time. Despite the scepticism of some in the farming community about anthropogenic climate change, the industry as a whole, likely has sufficient information to begin planning for climate change. This will still require in-depth, contextually sensitive studies to gain insight not only into regional climate variations—which are not insignificant, owing to New Zealand’s island-climate and complex topography—but also into economic drivers of pastoral farming in New Zealand. Climate scenarios of increased temperature and increased (or decreased) rainfall were investigated by integrating a regression model for pasture production with a Geographic Information System (GIS).

Table 2. (Continued.)

| Title | Author(s)/Year | Type | Contribution to adaptation |
|-------|----------------|------|---------------------------|
| Climate Smart Intensification options for New Zealand pastoral farmers: a farmer’s guide to intensification options in the context of climate change | McCasker et al (2014) | Report | Collates data on the threats and opportunities of farm intensification in the context of climate change |
| Four degrees of global warming: effects on the New Zealand primary sector | Renwick et al (2013) | Report | The document examines many issues under the assumption of a 4 degree rise in temperature by 2100. The issues include growing days and frosts, extreme rainfall and flooding events, pasture growth, forestry, and animal heat stress |
| Designing resource-efficient ideotypes for new cropping conditions | Sylvester-Bradley et al (2012) | Journal article | Tests modelling procedures to optimise wheat phenology according to risks of abiotic damage (frost, heat and drought) to seedling establishment and grain set. The ultimate aim of the research is to develop a Crop Design Tool that will specify resource-efficient ideotypes for any environment |
| Improving sustainable lifetime performance of pastures: learning from extreme climatic events | Tozer et al (2011) | Report (SLMACC) | Uses on-farm studies in different regions to investigate the relationships between sown functional diversity, pasture age and ingress of unsown species. Case study of Waikato one-in-one-hundred year drought (2007–2008) used to assess impact of climate extremes on between-year shifts in pasture composition |
| Spatially explicit modelling of the impact of climate changes on pasture production in North Island, New Zealand | Zhang et al (2011) | Journal article | Assessment of the potential impact of climate changes on pasture production in the North Island, New Zealand. Climate scenarios of increased temperature and increased (or decreased) rainfall were investigated by integrating a regression model for pasture production with a Geographic Information System (GIS)
| IDA               | Title                                                                 | Author(s)/Year                  | Type       | Sector     | Scale/Location        |
|------------------|----------------------------------------------------------------------|---------------------------------|------------|-------------|-----------------------|
| Impacts          | Scenarios of regional drought under climate change                   | Clark et al (2011)              | Report     | Multi-sector | National              |
|                  | Impacts of climate change on land-based sectors and adaptation options | Clark and Nottage (2012)         | Report     | Multi-sector | National              |
|                  | Climate change and Aotearoa New Zealand                              | Hopkins et al (2015)            | Journal article | Multi-sector | National              |
|                  | Four degrees of global warming: effects on the New Zealand primary sector | Renwick et al (2013)            | Report     | Multi-sector | National              |
|                  | Spatially explicit modelling of the impact of climate changes on pasture production in North Island, New Zealand | Zhang et al (2007)              | Journal article | Pastoral    | National              |
| Implications     | Impacts, indicators and thresholds in sheep-and-beef land management systems | Cradock-Henry and McCusker (2015) | Report     | Livestock   | Regional; Hawke’s Bay, Northland, Canterbury |
|                  | Climate-change effects and adaptation options for temperate pasture-based dairy farming systems | Lee et al (2013)                | Journal article | Dairy       | National              |
|                  | Designing resource-efficient ideotypes for new cropping conditions   | Sylvester-Bradley et al (2012)   | Journal article | Arable      | National              |
|                  | Improving sustainable lifetime performance of pastures: Learning from extreme climatic events | Tozer et al (2011)              | Report     | Pastoral    | National              |
| Decisions        | Learning from past adaptation to extreme climatic events: a case study of drought | Burton and Peoples (2008)       | Report     | Multi-sector | Regional; North Otago, South Canterbury |
|                  | Drought, agricultural production & climate change: a way forward to a better understanding | Clark and Tait (2008)           | Report     | Multi-sector | National              |
|                  | Exploring perceptions of risks and vulnerability to climate change in New Zealand agriculture | Cradock-Henry (2008)           | Journal article | Dairy       | Regional; Bay of Plenty |
|                  | Operationalising resilience in dairy agroecosystems                  | Cradock-Henry and Mortimer (2013) | Report     | Dairy       | Regional; Bay of Plenty |
|                  | The management of risk in a dryland environment                      | Grey et al (2011)               | Report     | Dairy       | Regional; Hawke’s Bay  |
|                  | Climate Smart Intensiﬁcation options for New Zealand pastoral farmers: a farmer’s guide to intensiﬁcation options in the context of climate change | McCusker et al (2014)           | Report     | Multi-sector | National              |
| Actions          | Innovative and targeted mechanisms for supporting adaptation in the primary sector | Dunningham et al (2015)         | Report     | Multi-sector | National              |
incentives have been used, for example, encouraging farmers to fence waterways to prevent stock intrusions and maintain water quality.

5. Summary and conclusions

The development and application of the AKC demonstrates the potential of the heuristic to better characterise the state of knowledge, identify research gaps, and emerging research needs and priorities. By identifying the analytical focus of research outputs and assessing each against its contribution our understanding, a more complete picture of the state of the science can be developed. Insight into direct and indirect impacts of climate change through increased or decreased precipitation, for example is necessary to fully comprehend the potential implications for land management or other agricultural activities; the decisions that stakeholders might need to make in order to adapt to aforementioned changes, and the barriers, enablers and motivations for action on the ground. The application of the heuristic also suggests that there is a need to better balance probabilistic modelling of future climate and its implications, with understanding and motivating adaptation action now. An overemphasis on knowledge production in any one part of the cycle may result in inaction—as stakeholders wait for additional information in order to make a decision. Empirical evidence shows that adaptation to current climate variability and extremes can provide the basis for adaptation to future changes, highlighting the need to explicitly consider the barriers and enablers to taking action now to reduce vulnerability.

Applying the heuristic to drought-related research in New Zealand, we showed that there is a rich and comprehensive body of knowledge for pastoral farming in particular. This research encompasses all aspects of the knowledge cycle, although more work is required for Decisions and Actions. The relative completeness of the existing knowledge base therefore suggests adaptation planning can begin immediately. Resources and efforts can be directed towards practical implementation. Rather than delaying action, existing knowledge can be used now, despite uncertainty. The need for additional information to reduce uncertainty with respect to impacts and implications, is often cited as a rationale for investment in further modelling. However, the results of the analysis suggest adaptation planning can begin immediately. Linking the review of knowledge with an adaptive management cycle, furthermore, can allow for new knowledge to be incorporated quickly and easily, refining strategies as needed.

In closing, the AKC is an initial step towards a more robust heuristic which might be used to systematically characterise the growing body of adaptation literature. The application to a case example from New Zealand does demonstrate its utility, however further conceptual, theoretical and methodological development is warranted.

Three key avenues for further refinement of the AKC and its application for assessing the knowledge base on climate change adaptation have emerged from this preliminary study. First the heuristic has only been applied to primary industries, and to a small \(n = 52\) set of research outputs (Cradock-Henry et al 2019). There is an opportunity therefore to apply the AKC in other contexts and consider its performance, when dealing with larger data sets or subject areas.

Second, the cycle might not only apply to other domains, but at different scales. Kolb (2014) sets out an experiential learning cycle of four stages, in which in which ‘immediate or concrete experiences’ provide a basis for ‘observations and reflections’. These ‘observations
and reflections’ are assimilated and distilled into ‘abstract concepts’ producing new implications for action which can be ‘actively tested’ in turn creating new experiences. Similarly, the AKC might be used as the basis for individualised evaluation of adaptation performance or knowledge needs assessment. Bespoke tools for particular industries or rural professionals could provide a means to assess their own performance, needs and actions, establish priorities and develop strategic plans.

Finally, the results can be used to articulate differences between sectors though the reasons for these differences remain underexplored. There is considerable evidence to suggest that pastoral farmers have a larger coping range than other agricultural activities. Dairy farmers are able to supplement with additional feed, reduce stock numbers or end the season early if conditions become too dry (Craddock-Henry and Mortimer 2013) and there is a well-developed literature to assist with planning. This can be contrasted with New Zealand’s wine sector. Despite viticulture’s economic importance and climate-sensitivity, there is very little research beyond a small number of studies on impacts, to support adaptation efforts (Craddock-Henry et al. 2019). Furthermore, grape growers have limited short-term options at their disposal for dealing with adverse weather conditions, and long-term adaptation strategies require considerable investment and have long lead times. Further research, for example, might examine the correlation between biological limits and coping ranges, with interest in impacts or information demand to better understand adaptation options. Insights gained from pursuing these opportunities into the AKC will enhance the breadth of its applicability and its effectiveness and assist with the development of robust frameworks to track progress towards knowledge synthesis.

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Data availability statement

Any data that support the findings of this study are included within the article.

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