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Climate change adaptation through an integrative lens in Aotearoa New Zealand

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ABSTRACT

Climate change is being felt across all human and natural systems in Aotearoa New Zealand and is projected to worsen this decade as impacts compound and cascade through natural system and sectoral dependencies. The effectiveness of adaptation is constrained by how fast greenhouse gas emissions are reduced globally, the pace of change, the frequency and progression of impacts, and the capacity of our natural, societal and political systems to respond. We explore how these systems and sectors interact with existing and projected climate change stressors by categorising climate change impacts (Trends and Events) and consequential thresholds (Thresholds), and by grouping systems and sectors by types (Typologies). This approach has identified commonalities and differences between the typologies which are illustrated with examples. Critical constraints and opportunities for adaptation have been identified to guide sector adaptation decision-making and for ongoing adaptation progress and effectiveness monitoring. Constraints are found across all sectors, and opportunities exist to address them through modelling and projections, monitoring frameworks, decision tools and measures,

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governance coordination and integration of the Māori worldview of the relationship between humans and nature. However, limits to adaptation exist and will increase over time unless all sectors and all nations urgently reduce their emissions.

Introduction

Climate change is being felt across all human and natural systems in Aotearoa New Zealand and is projected to worsen over this decade as impacts compound, and cascade through dependencies across all aspects of our lives (Lawrence et al. 2022). Ongoing climate change has embedded trends in both average climate and extreme weather in Aotearoa New Zealand. This has played a role in accelerating sea-level rise, more hot days and heatwaves, less snow fall, more rainfall in the south, less rainfall in the north, glacier mass loss, changes to river flows and more extreme fire weather in the east. These trends have combined with exposure and vulnerability to cause impacts in terrestrial, freshwater, and marine ecosystems. In human systems, tidal and extreme coastal flooding in low-lying coastal and estuarine areas, combined with extreme rainfall and heat, have impacted cities and settlements affecting cultural sites, livelihoods, infrastructure, financial, mental and physical health and outdoor workforces. Economic sectors such as agriculture, fisheries, forestry, aquaculture, horticulture, tourism, and the ski industry have been affected by the increasing costs of warming seas, extreme rainfall, drought, and wind, and by poor snow conditions and receding glaciers. The flow-on effects of these trends are emerging to compound such impacts in our natural ecosystems and across sectors.

The choice of where and how we adapt must be informed by an understanding of environmental, cultural, societal and economic factors that are unique to Aotearoa New Zealand. We have a high proportion of endemic species that are already experiencing other stressors, for example the spread of introduced species. The country's cultural context is shaped by the Tiriti o Waitangi, with Māori relationships with the environment defined through the ethic of kaitiakitanga or intergenerational care for species and ecosystems (Awatere et al. 2021). There is an economic dependency on the natural environment through primary production and tourism.

Within communities and sectoral groups, there are varying and potentially conflicting views on what adaptation should look like and when and how it should occur. For some (e.g. some primary sector groups, most tourism sectors), the focus is on maintaining the status quo, and adaptation is considered only as incremental for as long as possible, supported by discourses of delayed climate action (Lamb et al. 2020). Importantly, we lack an inclusive conversation as a nation and in specific contexts to identify what we want to protect, what that could cost and who should pay, how much change we can tolerate, and the implications of these choices. This is important because envisioning collective futures and the co-benefits of climate action can motivate further action (Bain et al. 2016).

This paper builds on the adaptation issues for natural and human systems including economic sectors, their interconnections, and significance for Aotearoa New Zealand drawing from the IPCC Sixth Assessment Report (Lawrence et al. 2022) and published papers since then. We highlight the implications of complex and interacting climate change impacts across these systems and sectors for adaptation.[1] An integrative lens on the multifaceted and dynamic features of adaptation, the limits to adaptation effectiveness, together with their critical enablers, has not hitherto featured in the Aotearoa New Zealand published literature. The following section presents the complex and interconnected impacts of climate change with examples from key systems and sectors of significance for Aotearoa New Zealand. We then use typologies (groupings of natural, cultural, social systems and economic sectors) to explore what complex impacts mean for adaptation, followed by a discussion of the critical enablers for implementing effective adaptation. We conclude with a section on implementing effective adaptation.

Adaptation context: complex and interconnected impacts

The challenges posed by climate change to nearly all systems and sectors include long-term trends such as sea-level rise and warming; shorter term increasingly frequent extreme events such as heatwaves, drought, and flash flooding; increasing variability such as snowstorms in summer or heat waves in winter; and changing climatic cycles, such as the Southern Oscillation or El Nino/La Nina swings. These are summarised in MfE (2018) and Lawrence et al. (2022).

Along with the institutions within which systems and sectors operate, the inter-relationships between them lead to cascading and surprising interactions that confound the adaptation process by decreasing the opportunities for adaptation and the range of viable adaptation choices available (Figure 1). Furthermore, how we collectively (or individually) decide to respond to adaptation challenges can shrink the adaptation space in a context where climate change is ongoing and the risks increasing.

Impacts can propagate as:

(1) Mean climate trends (henceforth referred to simply as Trends) (e.g. ongoing sea-level rise, increases in air, freshwater and ocean temperatures), and/or
(2) Extreme events (e.g. high intensity rainfall events, drought, marine heatwaves).

These two impact types can interact and amplify each other and are therefore not mutually exclusive. Biological and ecological thresholds can be surpassed through changes in mean conditions (e.g. heat, soil moisture, ocean acidification) by exceeding the tolerance range of humans (health, social, economic, and cultural), natural systems and species, and productive systems. Interactions between natural and human systems can lead to cascading impacts that are felt spatially and temporarily distant from the impact source (Lawrence et al. 2020) or cause a shrinking of the physical space and timeframes for coastal (Haasnoot et al. 2021) and forestry adaptation (Wreford et al. 2021). These may bring potentially disruptive surprises and irreversibility in some systems (e.g. low-lying coastal areas, corals, kelp forests, glaciers) and the ability to govern them (Lawrence et al. 2022).

Figure 1 shows the relationships between systems, sectors and institutions and how they interact generating cascading impacts and risks that may confound the adaptation process by decreasing the opportunities for adaptation and the range of viable adaptation choices available.

Here we identify examples of cascading impacts across physical, natural and human systems that represent distinctive adaptation challenges for Aotearoa New Zealand because they are unique, imminent, happening now, are ongoing, are significant singly

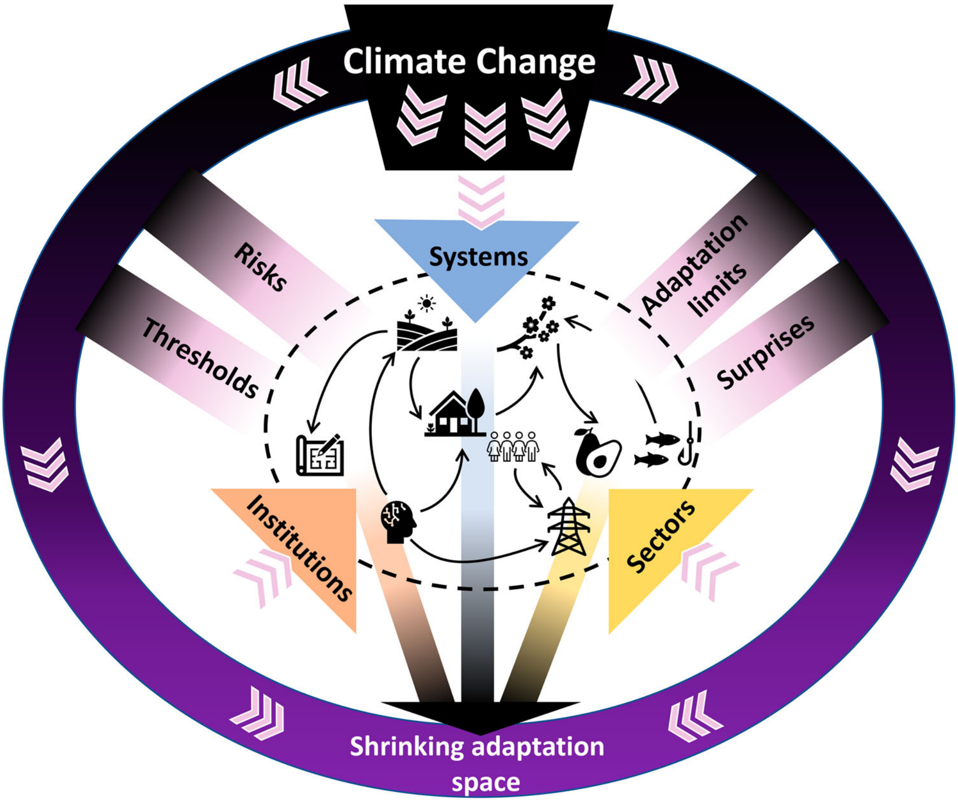

Figure 1. The pervasive impacts of climate change affect systems, sectors, and institutions and generate cascading and unanticipated (surprise) impacts. Impacts then create risks to existing institutions and systems presenting adaptation challenges. How we collectively (or individually) decide to respond to adaptation challenges can shrink the adaptation space. Importantly, ongoing climate change is simultaneously continuing to reduce the range of viable adaptation options.

and in combination, or are critical to adaptation effectiveness through their social, economic and cultural implications:

Challenges associated with accelerated biodiversity loss

Climate change interacts with a range of existing threats to biodiversity, such as habitat fragmentation and invasive species impacts, producing complex indirect impacts that are difficult to predict (Macinnis-Ng et al. 2021). In marine ecosystems, productive waters are being squeezed by three-dimensional changes – from the sea–air interface (e.g. warming and ocean acidification), from changes in weather and climate cycles (e.g. leading to extreme storm and heatwave events), from changing saturation horizons in the deep ocean currently becoming shallower (e.g. resulting in the threat of dissolution of calcareous reefs such as deep-sea corals) (Cummings et al. 2021), and from declining oxygen (Shi et al. 2022). Climate-related changes in the oceans are accelerating and affecting biodiversity, aquaculture, wild-caught fisheries, tourism experiences, and recreational and customary food access. Many effects will be interdependent, for example, interactions between climate and local conditions (e.g. drought followed by fire), while others will be conservation threats getting worse (e.g. habitat fragmentation and invasive species). Many existing invasive species impacts are likely to be accelerated and enhanced (e.g. warmer winters increasing the survival of pests, weeds and diseases). In alpine ecosystems, where thermal squeeze is occurring, invasive predators shift upwards in elevation with warming, reducing the refugia for endangered birds (Walker et al. 2019) and thus cascading and reducing adaptation options.

Adapting to irreversible sea-level rise

Aotearoa New Zealand has the 9th longest coastline of any nation and a high proportion of its population living in low-lying coastal areas. The interaction of sea-level rise and vertical land movement – compounded by some 40% of the country's coastline subsiding at various rates (Levy et al. 2022) is generating cascades of social, economic, cultural and environmental impacts. Observed and ongoing accelerating sea-level rise is compounded by extreme and increasingly frequent climate events, including heavy rainfall. These effects intersect with low-lying land and high-water tables and lead to inundation and salinisation. Increasing exposure of people, their homes and livelihoods, and the things they value in the shrinking spaces at and near the coast, reduce adaptation options and their timely implementation (Haasnoot et al. 2021). In such circumstances there are hard limits to adaptation options due to irreversibility of sea-level rise in human timescales. Pre-emptive managed retreat from the coast can reduce impacts but raises distributional and equity issues that can exacerbate underlying vulnerabilities due to differential adaptive capacity (IPCC 2022b) and echoes of colonisation (Jones et al. 2022). Sea-level rise is thus creating complex, long-term land-use change, and social and cultural issues that are escalating impacts and costs (Lawrence et al. 2022).

Coping with new pressures on human health

Climate change is a health threat multiplier, bearing most heavily on those whose health is compromised, and those at risk due to gaps in health care or adverse social circumstances. Health outcomes are stratified by disadvantage, with Māori experiencing poorer health than non-Māori (Tobias et al. 2008; Masters-Awatere et al. 2022). A health care review of the sector (Health and Disability System Review 2020) identified vulnerabilities, including siloed services and programmes intended to be complementary, isolated decision-making by the former District Health Boards, and weak governance in the quasi-devolved system. The testing of health care by the COVID-19 pandemic highlighted poor workforce planning unprepared for future crises, unreliable information systems and supply chains (Skegg 2021). Climate change occurs at a different scale to the pandemic threat, increasing the likelihood of interactions across systems and sectors and of cascading and compounding threats (Pelling et al. 2022). There is a very real risk of 'state change'[2] leading to unpredictability if progressive climate change crosses physical and social thresholds. As a consequence, we may face novel problems, such as infections not experienced before, or injuries and stresses seldom seen (e.g. large-scale heat-related health problems [Harrington 2020]). Social tolerances may be tested (e.g. resulting from unprecedented population displacement due to flooding and sea-level rise) with impacts on mental health, disease emergence and an increase in the risk of future pandemics (Mora et al. 2022). Land-use change creates synergistic effects with climate change (e.g. forest loss, heat island effects, burning of forest to clear land) and biodiversity loss, which in turn have led to new risks from emerging diseases (IPBES 2020).

Altering agriculture and horticulture as conditions change

Agriculture and horticulture are economically and socially significant in Aotearoa New Zealand. The impact of climate change on these sectors has the potential to cascade through society and the economy, potentially undermining financial stability. The Reserve Bank of New Zealand has begun requiring banks to stress-test their exposure (through their agri-sector lending) to drought risk (Orr 2022). In addition to the direct financial impacts of drought, the incidence of multi-regional drought in agriculture will have an adverse cascading effect on common coping strategies such as the use of supplemental feed or the relocation of stock to neighbouring regions (Timar and Apatov 2020; Cradock-Henry 2021; Paulik et al. 2021). Farmers' responses to drought may involve the increase of supplemental feed and fertiliser application, increasing agricultural emissions and thus becoming maladaptive.[3] Longer-term responses to variable water availability may lead to increased demand for irrigation, creating ecological, health, and social conflict (Lawrence et al. 2022). Other potentially cascading impacts include the implications of changing seasonality and increased temperatures on the agricultural workforce, both in terms of changing labour availability as well as human health concerns. In viticulture, changes in grape phenology and ripening will have flow-on effects for vintage timing. This compression of harvest places additional demands on the seasonal workforce across regions (Ausseil et al. 2021).

Uncertainty and consequences of maladaptation

Across each of these examples of the complexity of interacting and cascading climate impacts, some uncertainty exists regarding the location, pace, timing, and magnitude of impacts. Uncertainties are derived not only from potential future societal behaviours, the influence of non-climatic factors (e.g. population, trade, supply chain, the success or failure of global mitigation actions), but also from the climate models themselves, further complicating adaptation decision-making and potentially contributing to attribution scepticism and potentially, inaction (McClure et al. 2022).

Effective adaptation will depend on how uncertainty is considered, and on the lifetime and lead time of the adaptation options, to avoid maladaptation. Where adaptation is delayed or reaches limits during its lifetime, the costs will be pushed out to future generations. In parallel, there are ongoing maintenance costs that fall across ratepayers and central government agencies that eventually reach effectiveness thresholds, including infrastructure, community and iwi/hapū[4] facilities, and loss of valued habitats and amenity.

An appreciation of complex and interconnected impacts is also essential to enable adaptation to achieve both collective and individual outcomes in the short and long term. When considering climate change adaptation, it is very easy to be challenged by the detail and complexity of impacts and implications in specific locations, or within systems and sectors. Despite distinct system and sectoral differences and specific challenges, we argue that there are some common adaptation challenges across Aotearoa New Zealand. Accordingly, by grouping the systems and sectors into similar clusters (typologies) these commonalities and differences become visible and thus increase the room for collective learning and action within and between researchers and decision-makers. To this end, the following section begins by framing adaptation challenges and then groups systems and sectors into five typologies of similar characteristics to discuss adaptation opportunities, barriers and limits through examples within each grouping.

Framing sector adaptation challenges

How actors (e.g. iwi/hapū, communities, managers within the affected systems and sectors) navigate the adaptation challenge will have implications for social and cultural outcomes. This will also affect the extent to which there is capacity and capability to reduce the risks through adaptation and transformational changes at sectoral, community, and organisational levels.

Understanding how natural and human systems and their interactions affect the choice of adaptations, and the ongoing monitoring of their effectiveness, is critical for adaptation implementation. Key gaps in our understanding in this context are identified in Lawrence et al. (2022) and discussed below with enablers.

In order to advance adaptation in Aotearoa New Zealand we propose two ways to frame the adaptation challenges; first using the impacts type (trends and/or events) and then highlighting the consequential thresholds that enable us to look at common adaptation pathways, and second, adaptation typologies to look for common challenges and differences across diverse systems and sectors.

Impact-based adaptation pathways

Three generalised impact-based adaptation pathways for trends and events, and the consequential thresholds that arise from trends and events, are illustrated in Figure 2.

Although the different types of impacts will likely affect all systems and sectors, it is useful to distinguish between them because the generalised adaptation pathways have different opportunities/needs for both incremental and transformational adaptation:

Adaptation to trends (Figure 2A); Trends may initially appear manageable via incremental adaptation (orange lines), where small changes are made to the existing system as the conditions change. As the changes intensify over time, transformational adaptation will be needed as adaptation thresholds are reached (blue lines). Many of these are foreseeable (e.g. ongoing sea-level rise) and pre-emptive planned transformation may be the viable alternative.

Adaptation to events (Figure 2B); Adaptation to events (e.g. high intensity rainfall) can either be planned systems transformation, or reactive after events that fail to account for cascading effects. Reactive decisions often lead to short-sighted and maladaptive outcomes (e.g. sea-wall end-effects, removal of sediment, height limits, and amenity removal); raising buildings and filling land (e.g. stranded assets as seas rise, floods occur, or water for irrigation diminishes). These outcomes often result from a series of incremental actions until coping capacity is exceeded. Between events, systems largely return to their previous state, but the declining period between events and increasing scale of events should signal that a shift towards more transformational measures is required.

Adaptation to thresholds (Figure 2C); Thresholds are a set of conditions where the tolerance range of humans (health, social, economic, and cultural), natural systems and

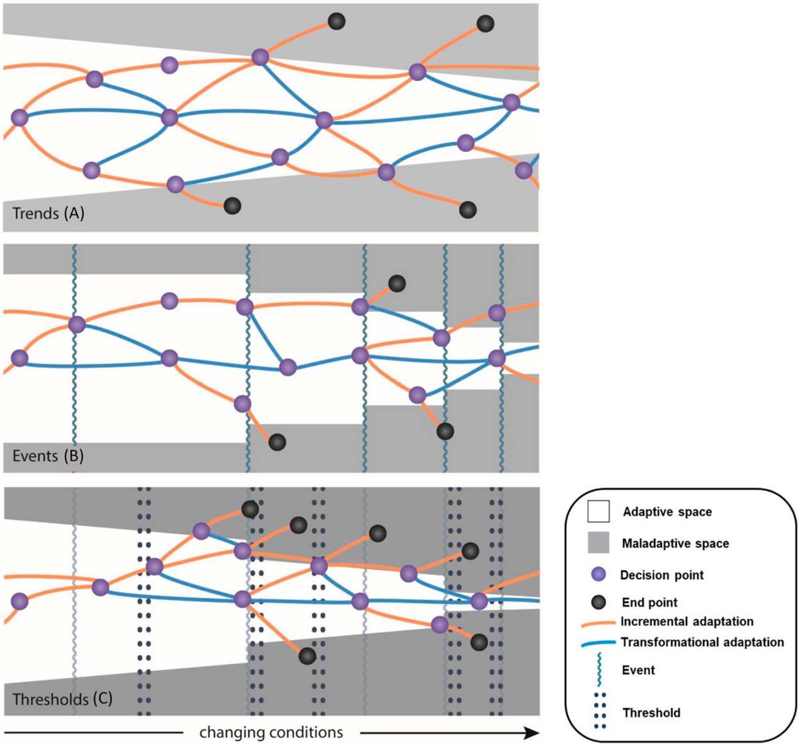

Figure 2. Generalised impact-based adaptation pathways, **A** trends, **B** events, and **C** thresholds that arise from trends and events (i.e. points at which the system or sector transitions into another state that may be irreversible). Each type of impact suggests the type of adaptation response (incremental or transformational) that keeps the sector or system in the adaptive space and ensures social, cultural, environmental and economic objectives are met as conditions change over time. Note that in practice trends and events interact, producing additional complexity, and that thresholds arise from both trends and events.

species and productive systems are exceeded, leading to a fundamental shift in the system. Thresholds arise when the system is fundamentally altered and cannot return to its original state. For example, changes in mean conditions (e.g. heat, soil moisture, ocean acidification) and sea-level rise can be monitored through anticipatory pathways planning for early signals of system change to prepare for or avoid system thresholds.

Adaptation typologies

In this section we explore the nature of possible adaptations across five system and sectoral typologies, including the ability of each system or sector to effect change and meet desired outcomes, the barriers and limits, and examples of the range of adaptation options available. The typologies were derived by the authors using expert judgement as a means of grouping similar and different types of systems and sectors. They are not mutually exclusive but allow for the exploration of common adaptation challenges. Appendix 1 provides a detailed analysis of each typology with respect to adaptation opportunities, barriers and limits to adaptation. What follows here is an overview of each typology using only some examples for illustrative purposes.

Typology 1: Natural ecosystems in Aotearoa New Zealand

Of the 54,000 species known in New Zealand, a remarkable 50% overall, and 30%, 40% and 70% of freshwater, marine and terrestrial biota respectively, are endemic (species occur nowhere else) – perhaps the highest endemicity of any country (Costello et al. 2010; Macinnis-Ng et al. 2021; Costello 2023). These species are affected both by changes in mean trend conditions (Figure 2A) and by pulses of severe events (Figure 2B). In addition, climate change can create indirect effects that make existing threats worse. Some effects will be specific to the ecosystem (e.g. ocean acidification of marine ecosystems; drought in terrestrial ecosystems), while others will be more generally experienced across all ecosystem types such as forests, wetlands, subalpine habitat, kelp forests (e.g. heatwaves). Many terrestrial native ecosystems and species are restricted by human land uses and geographic barriers, and by their own physiological limitations, such as inability to adapt to changing temperature and fire regimes, slow reproduction, and inadequate dispersal mechanisms.

Human retreat from rivers and coastlines could provide opportunities for ‘rewilding’ these areas with flow-on improvements in water quality, carbon sequestration, and communal green spaces. ‘Rewilding’ could be large in scale and cost little per hectare where indigenous seed sources are present, and the environment will support change in the diversity and abundance of species in the community over time towards eventual indigenous dominance (McAlpine et al. 2021). More active nature-based or ecosystem-based adaptation (e.g. wetland restoration for flood protection, native planting for urban and agricultural shade and shelter; McVittie et al. 2018) offer potential for multiple benefits and can increase human wellbeing through enabling and inspiring people to engage with nature. However, such interventions will often be smaller in scale than passive rewilding and have shorter-term benefits that buy time.

Incremental adaptation options are focused on improving ecosystem resilience to current threats because transformational actions are limited for natural ecosystems. Interventions within natural systems are likely to be complex to execute due to limits on the degree of control that human agents have over complex self-ordering natural systems. Nevertheless, recognising that the integrity and biodiversity of ecosystems play a key role in the likely success of natural ecosystems survival is critical in a changing climate and requires support.

Typology 2: Indigenous communities

Māori have a high level of investment in climate sensitive sectors (Awatere et al. 2021) with a worldview that involves caring for the human and non-human community, acting with mana (authority and respect), cherishing the natural environment’s tapu (sacredness) and maintaining its mauri (life force) (Harmsworth and Awatere 2013; Awatere et al. 2021). At the core of Māori relationships with the environment is the ethic of kaitiakitanga, or intergenerational care for species and ecosystems. Kaitiakitanga is inextricably linked to the notion that humans are connected with each other, our ancestors, Papatūānuku – Mother Earth, and the cosmological entities (Harmsworth and Awatere 2013). The implementation of kin-based responsibilities to the environment is through kaitiakitanga – the expression of a two-way relationship that involves obligations to give, receive, and repay (Kawharu 2000), the notion of reciprocity.

These components of a Māori worldview offer opportunities for informing adaptation, in particular, intergenerational and long-term impacts, and working with nature for sustainable outcomes. The social-cultural networks, conventions and practices through collective action and mutual support amongst Māori communities are invaluable for initiating responses to, and facilitating recovery from, climate stresses and extreme events (Lambert and Mark-Shadbolt 2021). Māori tribal organisations have a critical role in defining climate risks and policy responses (Awatere et al. 2021), as well as entering into strategic partnerships with business, science, research and government to address these risks (Beall and Brocklesby 2017).

Typology 3: Location specific productive land-based sectors

Productive land-based sectors such as forestry, horticulture, viticulture, cropping and pastoral farming, have a degree of control over production practices and a portion of the resources (e.g. water) used in the activity. In general, these sectors will experience gradual change as trends (Figure 2A), increased climate variability, and more frequent extreme events that affect the productivity (and profitability) of the land (Figure 2B), as well as cascading and complex impacts resulting from disrupted supply chains, infrastructure, and transport. There may be opportunities resulting from global disruption in food supplies such as diversification of farming activities to better position producers for changing consumer preferences, or higher market prices for producers due to extreme weather events elsewhere (Wreford et al. 2022a).

A reasonable body of evidence exists for understanding future impacts across land-based productive sectors, although it is dominated by research into the pastoral sector (Cradock-Henry et al. 2019). Evidence is summarised in Lawrence et al. (2022) and detailed in sector-specific literature (see, e.g. Mosedale et al. 2015; Bisbis et al. 2018; Tait et al. 2018; Watt et al. 2019; Leisner 2020; Santos et al. 2020).

While overshadowed by the volume of mitigation research in the primary sector, adaptation research is accelerating. The focus remains very much on incremental adaptation, including adapting crop rotations (Teixeira et al. 2018), adjusting the timing of operations such as pruning in viticulture (Ausseil et al. 2021) and kiwifruit (Cradock-Henry 2017) and pasture management (Keller et al. 2021). The main transformation being discussed involves land-use change, a complex area encompassing other pressures and relating very much to farmer identities and values (Griffin et al. 2023). However, as global temperatures continue to rise generating many complex impacts, there will come a time when current adaptations are no longer effective (Wreford et al. 2022b) and land-use transformation will be unavoidable. Planning ahead for this eventuality will be critical for avoiding disruptive transitions.

Typology 4: Economic sectors that rely on natural systems

A defining characteristic of these sectors is that they have limited control over the natural resource on which the activity depends. Two examples of this type of sector are highlighted below: (1) tourist attractions and alpine recreation areas; and (2) wild caught fisheries and aquaculture, including their associated facilities. This type of sector will experience gradual change (Figure 2A), increased climate variability, and more frequent extreme events that affect productivity and profitability (Figure 2B) and reach thresholds (Figure 2C).

New Zealand's tourist experiences are critically reliant on natural heritage (Typology 1), such as outdoor recreation, in isolated regions and coastal and mountain settings that are highly exposed and vulnerable to climate change impacts (Steiger et al. 2022). Climate risks (MfE 2020) to this sector include changes to landscapes and ecosystems, and impacts on lifelines and infrastructure from gradual onset change and more extreme weather events (Christie et al. 2020; Paulik et al. 2020). Glacier tourism and the ski industry are expected to experience receding glaciers, declining snowfall and limits to snowmaking by mid-century (Purdie 2013).

The tourism industry is also impacted by how tourists perceive and adapt to climate change – which in turn affects how the industry adapts – by changing their destinations, their activities, or the timing of their trips (Becken et al. 2020; Gössling et al. 2020; Purdie et al. 2020; PCE 2021). To date, no transformational climate change adaptation has been adopted by the tourism industry that changes the nature of the tourism sector as a whole (Sun and Higham 2021), and there remains a disconnect between science knowledge about impacts and policy needs (Loehr and Becken 2021; Scott and Gössling 2022).

Factors hindering tourism industry adaptation strategies include its fragmented nature dominated by small and medium enterprises lacking the knowledge and resources to focus on long-term strategic adaptation which default to short-term decision-making focused on 'climate coping strategies', rather than future-oriented planning (Hughey and Becken 2014). Tensions and contradictions also exist between proposed adaptation strategies and the needs of the industry to remain financially viable, with most tourism policy to date focused on economic growth (Becken et al. 2020; Scott and Gössling 2022) – for example, attracting 'high yield' tourists to maintain economic returns whilst reducing climate impacts through lower visitor numbers that have an uneven impact on businesses and destinations. In order to maintain memorable tourist experiences, and thus economic sustainability, some adaptation strategies are also maladaptive; for example, West Coast glacier tourism experiences which are increasingly reliant on helicopter flights that increase the carbon footprint of the industry and reduce the amenity for other users of natural heritage.

The seas around New Zealand are undergoing similar changes to those reported elsewhere in the world. While ocean acidification is a great threat to many marine species, shellfish and habitat-forming seabed communities, the greater threat is from rising temperatures (Law et al. 2017; Cummings et al. 2021). In particular, the abundance and geographic distribution of fish populations and other kaimoana on which commercial, non-commercial fishers and iwi depend, are changing and maximum body size is reducing in concert with ocean warming (Cheung and Frölicher 2020; Lavin et al. 2022; Dunn 2022a, 2022b). Managing wild-caught fisheries catch levels under the current Harvest Strategy Standard assumes that environmental conditions show no trend, even though conditions differ annually (MPI 2008). This assumption can no longer hold true under a changing climate. Understanding the point at which the sustainability of fish catches is affected by the changing marine environment is necessary for adaptation (Lavin et al. 2022).

The complexity of the marine ecosystem and the paucity of data for species other than those that are commercially important, necessitate different approaches to adaptation. For example, scenario testing of the impacts of climate change on fish productivity and distribution; asking what economic consequences are likely under different climate scenarios for local fishing communities, for kaimoana abundance, and for commercial fisheries; and what adaptive management options are available to minimise impacts (Pinsky and Mantua 2014). Such a systems-based approach could provide a better understanding of all the factors at play and help inform a more integrated ecosystems-based management than currently exists (Cryer et al. 2016).

Typology 5: The human and built environment

The human and built environment comprises the infrastructure and the social and cultural systems of cities and settlements that are constructed, maintained, and controlled by a range of agents and institutions. This typology includes cities and settlements by the sea, on flood plains and steep unstable slopes, where the impacts compound and cascade. It also includes the governance and institutional arrangements that enable adaptation (participatory processes, decision making tools and measures; regulatory arrangements and funding instruments including compensation). The human and built environment relies on the outputs and outcomes from the other typologies to meet desired outcomes. Local and central government have the ability and responsibility to lead adaptation across human and built systems in preparation for the suite of climate impacts (Figure 2A–C) and in association with mitigation actions that reduce carbon emissions. These systems have inertia and tend to adapt incrementally by perpetuating the status quo until a trigger point is reached. This reduces the amount of lead time for more sustainable responses that can be staged to build climate resilience or for transformational adaptations that remove the risk, such as managed retreat of existing settlements in exposed and vulnerable areas at the coast or on unstable land. Changes to the design of institutions and their governance that can deliver services (e.g. health, water services) in a changing environment, or changes in underlying vulnerabilities that are compounded disproportionately by climate changes, will be essential for building the adaptive capacity to reduce climate risks.

Commonality and difference across the 5 typologies

The five typologies face both similar and distinct adaptation challenges (Box 1) as detailed in this section.

Box 1. Summary of commonalities and differences between the adaptation challenges faced by each typology.

Common challenges across the typologies:

- Navigating uncertainty and knowledge gaps arise from a lack of baseline data, and monitoring and reporting to detect and highlight changing conditions. In particular, for natural systems (Typology1), and economic activities in Typology 4.
- Unknown adaptation limits exist for most sectors except those affected by sea-level rise and some flood events.
- The responsibility for adaptation is distributed among a diverse group of individuals and organisations, which have varying abilities to access resources to adapt. Potential for poor co-ordination and conflict around desired outcomes and rights exist.
- Extent of adaptation needs over time will require considerable resources across all typologies. Contestation between typologies for resources (e.g. funding or land) could occur.
- Short-term decision making competes with a long-term view across all sectors with maladaptive outcomes that will cost more over time.

Differences between typologies:

- Transformational adaptation will be required in all sectors in the long term but land-based productive sectors (Typology 3) and the human and built environment (Typology 5) are likely to generate maladaptive outcomes if incremental actions alone are relied upon.
- Typology 3 may be able to take advantage of some opportunities arising from climate change, such as CO_2 fertilisation (Watt et al. 2019) changing crop suitability within Aotearoa New Zealand and changes in international production and trade patterns arising from global climate change (Wreford et al. 2022b).
- The ability to implement adaptation options varies between typologies but adaptation in natural systems (Typology 1 and Typology 4) will likely be more challenging than for systems where humans have a higher degree of control of the change process.

Navigating information gaps and uncertainty

All typologies have gaps in information, knowledge, baseline data, and monitoring and reporting to detect and share changing conditions. In particular, natural systems (Typology 1), and economic activities in Typology 4 have uncertainties that could be reduced with further research (Lawrence et al. 2022). Inherent long-term uncertainty presents specific requirements for adaptation (see Cross-Chapter Box DEEP in New et al. 2022). However, gaps in knowledge, and a lack of knowledge, does not imply a lack of risk nor justify delayed adaptation action (Lawrence et al. 2022).

This highlights the need for robust monitoring systems that can track changes in system conditions ahead of thresholds being reached. Greater investment in such monitoring systems is critical for all typologies outlined in this paper. Decision-making tools are already available for navigating uncertainties. These are centred on stress testing adaptation options under a range of plausible future scenarios, to build dynamic adaptive pathways that retain flexibility to adapt and avoid lock-in of adaptation actions that will create greater costs of adjustment later (Haasnoot et al. 2013). Assessing the pace of change, identifying critical triggers and thresholds, and integrating feedback loops are crucial for effective adaptation.

Unknown adaptation limits exist

Across the typologies adaptation limits appear to be acknowledged, but poorly described.

Adaptation comprises a suite of Avoid, Protect, Accommodate and Retreat measures which may vary in kind and degree and can be temporary, permanent or transformational (IPCC 2022b). Many adaptations will reach limits to their effectiveness. The IPCC (2022a, p. 2898) defines limits to adaptation as 'The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions'. For example, ecological and human systems are both likely to reach thresholds and limits to adaptation, although these limits depend in part on how the goals of adaptation are defined (Adger et al. 2009).

The unique characteristics of Aotearoa New Zealand's natural ecosystems, including invasive species impacts and high levels of endemism, are likely to limit potential for adaptation that can protect current ecosystems. While there may be some scope to manage habitat squeeze due to invasives with sufficient research and operational investment, other impacts on ecosystems and species will present challenges to adaptation. The ability of ecosystems and nature-based adaptation to support other sectors' adaptation will also reach limits to its effectiveness (IPCC 2022b).

For many populated regions of Aotearoa New Zealand, the hottest days of the year have warmed by more than 0.5 °C over the last 20 years, a rate that exceeds average annual changes across the country, signalling larger risks with further warming over the twenty-first century (Harrington and Frame 2022). Direct public health effects arise as temperatures increase beyond the current coping range, and secondary effects from disease and pathogens increase for humans. Stable social-economic arrangements are fundamental for ensuring vulnerable people, including the elderly, disabled, and Māori, can cope with these health effects. The pace and range of the changes will determine such effects. Higher temperatures will affect economic sectors through primary sector impacts, where adaptation will reach limits to its effectiveness as impacts intensify (Wreford et al. 2022a) and require shifts in animal breeding and food production within primary sectors on land and in the oceans. Outdoor workforces will increasingly be constrained as heat increases (Kjellstrom et al. 2016), requiring adaptations to workplace management in the farming, horticulture, roading, and construction sectors particularly. Additionally, the integrity of mātauranga Māori, Te Reo Māori, and hapū/iwi identity will be fundamentally altered by anthropogenic-induced climate changes because identity and language are intimately intertwined with landscapes (Awatere et al. 2021). Narratives and proverbs resonate within cultural landscapes and often signify the importance of keystone species and other landscape features to different hapū/iwi. Climate change poses risks for the maintenance and transfer of mātauranga Māori associated with mahinga kai (wild food, gathering of wild kai) and has implications for language retention, tribal identity, and well-being (Awatere et al. 2021).

Distributed responsibility for governance

Adaptation in each typology falls to a range of individuals, communities, iwi, hapū, organisations, businesses, investors and central and local government (Appendix 1). The fragmentation of responsibilities across different scales presents both a co-ordination problem and a challenge around the ability of different groups to effect adaptation that leads to desired outcomes. It also inhibits the ability to collectively imagine new possible futures and system transformation.

Without attention to coordination, adaptation may be ad hoc and increase the risk of fragmented and disconnected responses that result in adverse or inequitable adaptation burdens or outcomes. The IPCC (2022b) stresses that inappropriate responses to climate change create long-term lock-in of vulnerability, exposure, and risks that are difficult and costly to change and exacerbate existing inequalities. Careful evaluation of the wider impacts of adaptation on other goals and over time is critical, and ideally adaptations that have overall long-term benefits should be prioritised (Boston and Lawrence 2018; Productivity Commission 2019). Government has a role to provide this type of guidance (which is accepted in the National Adaptation Plan). In addition, the independent Climate Change Commission is mandated to monitor adaptation progress for its effectiveness and draw attention to the barriers and how these can be addressed.

Our ability to adapt and the size of the adaptation burden will be determined by institutional changes in Aotearoa New Zealand that focus on coordinated and aligned processes and policies, removal of barriers to adaptation and a focus on the rate and sustainability of global emissions reductions.

High resource needs and the potential for conflicts

The magnitude of the suite of adaptations across each of the typologies is likely to be considerable, requiring significant investment over time and addressing compensation issues (Tombs and France Hudson 2018; Productivity Commission 2019). However, the ability to access the necessary funding and financing to adapt is likely to be variable with challenges noted for natural systems (Typology 1) and Indigenous communities (Typology 2). Tailored and equitable funding and financing arrangements for adaptation are essential to fill the gap between adaptation needs and available resourcing, especially for natural systems (Typology 1), Indigenous communities (Typology 2) and the human and built environment (Typology 5).

There is a shortfall in infrastructure funding in Aotearoa New Zealand, as well as a lack of dedicated funds for climate risk reduction, post-disaster betterment, compensation, and community resilience (MfE 2020). Public funding is constrained, however (Boston and Lawrence 2018). Local government has debt limits and few revenue options. Central government has greater fiscal capacity but faces political-economy constraints to keep debt and expenditure low (MfE 2020). Greater diversification of the sources and instruments of funding and financing, including engagement with private capital markets, can minimise shortcomings and allocate the duties to pay more fairly (Hall 2022).

The issue of equity is especially important given that the poor are disproportionately harmed by disasters (Hallegatte et al. 2020), because a lack of financial resources heightens vulnerability to shocks, limits access to risk transfer opportunities like insurance, and exacerbates existing socioeconomic inequalities. For example, only 33% of Māori have general insurance compared with the average of 54% of non-Māori; 21% have life insurance and/or income protection policy compared with 27%; and 21% have health insurance compared with 27% (Retirement Commission 2021). Consequently, climate-related risks can amplify inequalities produced by colonisation and, ultimately, degrade the social cohesion that is critical for the societal resilience that underpins effective adaptation.

Favourable adaptation pathways may lead different sectors into competition for land, water or other resources. For example, a particular location may be suitable for a variety of productive uses, but also have important natural ecosystems. Inattention to how adaptation is funded or supported will lead to delays in implementation and ongoing resource contestation.

Different pathways are available but all roads lead to transformation

Short-term decision making competes with long-term pathways but all roads lead to transformation eventually. For example, as conditions continue to change over time and thresholds are reached in human and natural system tolerance of the impacts or in the feasibility and affordability of adaptation actions, fundamental transformation will be required across all of the impact pathways for each of the typologies.

Often, adaptation seeks to build climate resilient development pathways (IPCC 2022b). Resilience is both a value and an outcome.[5] In the context of outcomes, resilience is 'a positive attribute when it maintains capacity for adaptation, learning and/or transformation' (Matthews et al. 2021, p. 2245). Yet, in the context of transitioning from one system to another, resilience can also be a negative attribute, blocking change (Unruh 2000). Systems have feedback loops that stabilise the status quo, and reduce the impetus for change, impeding preparations for future shocks and putting far greater stress on existing institutions.

The need for anticipatory governance and pre-emptive risk reduction is clear, but the current governance systems resist acting on this knowledge because of the intertemporal trade-offs between visible upfront costs compared with less visible and uncertain future costs that generate powerful political and electoral asymmetries (Boston 2017). But as the frequency and magnitude of extremes increase, seas continue to rise and climate trends continue, transformational adaptation will be unavoidable to lessen or remove the proximate risk. Changes to the mean conditions will also necessitate system change as thresholds are breached (e.g. ongoing heat and soil moisture changes).

Sector opportunities

There are opportunities to leverage change in adaptation responses. Some examples follow, noting that no single opportunity will set us on a more proactive adaptation path.

Modelling of climate change biophysical impacts can provide useful insights into adaptation strategies for the agricultural and forestry sectors. For example, knowing the scale of temperature warming across a range of Representative Concentration Pathway scenarios and the likely impacts can help farmers make decisions on cultivar choices, sowing timing and feed stock management to reduce risks due to drought prevalence (Ausseil et al. 2019a). CO_2 fertilisation[6] could also be beneficial for the forestry sector (Watt et al. 2019) and pastoral sector (Keller et al. 2021), however the magnitude of its effect is still unclear. Maps of changes in crop suitability can also support farmers in choosing new land use options that may be profitable and adapted to climate change (Lilburne et al. 2022).

Projections of both average and maximum temperatures, including likelihood of heatwaves can be used to identify the suitability of locations for aquaculture. This would enable the industry to plan to vacate some locations and obtain permits for new locations. Similarly, fisheries management could take a precautionary approach where fish stocks may decline due to climate change while seeking new opportunities where stocks may be boosted by warming.

Extreme events, especially when they occur at scale or in quick succession, create opportunities for positive transitions within communities (Cradock-Henry et al. 2019). Pre-emptive and precautionary planning using a suite of complementary options and pathways can build the necessary adaptive capacity that is essential for responses that can be activated before and after events that surpass community coping levels (Lawrence et al. 2022).

Institutional arrangements that support pre-planning across sectors, such as risk and vulnerability assessments, 'fit for purpose' decision tools and national planning instruments (e.g. National Policy Statements, National Environmental Standards, national guidance) play a critical role in enabling opportunities to be realised. Opportunities also exist for integrated adaptation and mitigation planning at a regional level of government that can support sector adaptation by providing policy stability in addition to national climate change policy responses (Dickie 2020).

Māori institutions, knowledge and values supported by central and local government can enable self-determination which creates opportunities to develop adaptation responses to climate change that are effective by promoting collective action and mutual support. These are based on human-nature relationships and ecological integrity that incorporate practices to detect and anticipate changes taking place in the environment. Such social-cultural networks and conventions are critical to responding to, and recovering from, adverse environmental conditions across sectors (Lawrence et al. 2022).

Variable ability to effect adaptation outcomes

Adaptation in natural systems (Typology 1 and Typology 4) will likely be more challenging than for systems where humans have a higher degree of control of the change process and a range of suitable options over time (Typology 2, Typology 3 and Typology 5). Where there is limited ability to implement successful options, the system may quickly shift towards transformation.

Finding leverage points with the greatest effect will be critical to address the self-stabilising tendencies of current systems. However, one of the greatest obstacles to adaptation is attitudinal, and an endemic ‘it’s too hard’ and ‘let’s wait and see what happens’ mentality impedes foresight, anticipation, and pre-emptive action (Lawrence 2019). Changing mindsets and paradigms have the greatest transformative potential (Abson et al. 2017; O’Brien 2018) which can be given effect by reframing the climate change problem and its consequences through experiential learning, such as using serious games based on dynamic adaptive pathways planning (Lawrence and Haasnoot 2017). These open up the opportunity for activating other leverage points through regulatory, financial, and institutional innovations, as already illustrated in Aotearoa New Zealand (Ryan et al. 2022).

In many low-lying coastal areas, retreat of buildings and assets as a response to rising seas will be likely, due to hard adaptation limits to nature or human settlements, but this requires planning and staging, and facilitating buyouts and identification of new areas for development. However, it is critical that the retreat process is planned and conducted alongside communities and in partnership with iwi/Māori to achieve outcomes that enhance the mana of local communities.

By framing adaptation challenges through impacts, adaptation pathways and typologies, common adaptation challenges emerge across diverse systems and sectors. Following similar logic, adaptation can be implemented and accelerated by a common set of enablers as detailed in the following section.

Enablers for accelerating effective adaptation and supporting adaptation decision-making

The IPCC Sixth Assessment Report found an increase in adaptation planning but little evidence of effective implementation for Aotearoa New Zealand (Lawrence et al. 2022). There were gaps in knowledge and missing adaptation enablers, both of which are critical for effective implementation of adaptation.

Critical gaps in knowledge and decision tools for enabling effective adaptation and its implementation include the following (Lawrence et al. 2022): new knowledge on system complexity, managing uncertainty and how to shift from reactive to pre-emptive adaptation to accelerate adaptation, the value of Indigenous ethics and mātauranga Māori indicators for adaptation across sectors (Awatere et al. 2021), economic methodologies for risk assessment of complex natural and human systems (Warner et al. 2020), improved decision-making tools for changing risk situations and for investment appraisal (Dittrich et al. 2016; Haasnoot et al. 2021; Lawrence et al. 2021; Stroombergen and Lawrence 2022), better understanding of decision behaviours to inform robust decision making (McClure et al. 2022) and priming adaptation processes to build adaptive capacity (Flood et al. 2018), understanding the impact of climate change knowledge on decision-making processes across sectors, and public understanding of how sea-level rise is propagating to enable a shift in mindsets in adaptation decision processes (Priestley et al. 2021).

Data and scenarios for modelling futures and sensitivity of adaptation options are essential for designing adaptation options in highly dynamic climate change environments where changing trends and extreme events dominate and have compounding and cascading consequences across sectors (Cradock-Henry 2021). Integrated climate, biophysical and economic models that can address the social and human dimension to fully understand the magnitude of adaptation required (Giupponi et al. 2021) are essential tools for implementing effective adaptation. Mixing quantitative modelling outputs and narratives including Indigenous knowledge to inform conversations and futures thinking, provide leverage to adaptation decision making (Frame et al. 2018; Ausseil et al. 2019b).

Monitoring environmental change and societal impacts is an integral part of our science endeavour in complex systems affected by climate change (Mullan and Ranger 2022) for making progress and to inform adaptation of the changes ahead. Such monitoring is critical for informing high quality climate change decision making both under the Climate Change Response Act for mitigation and adaptation and under resource management legislation. The pivotal role that monitoring plays in measuring change in the environment and societal impacts is not well supported in Aotearoa New Zealand (OECD 2010; PCE 2019). Systematic monitoring of key domains remains unresolved, especially in the marine environment, and for understanding the societal distributional impacts of climate-related change in terms of current and future inequality, and monitoring of the distributional impacts of adaptation decisions.

In the natural environment, adaptation depends on understanding complex interactions, and how they affect environmental tolerance at key life stages. For example, in the fisheries sector this requires long-term investment in collection of data on marine catch levels, catch distribution and productivity or refugia to be able to monitor change and adapt sector behaviour in time. With inadequate baseline data, risk assessment modelling (Simpson et al. 2021), taking a broader systems approach (Inácio and Umgiesser 2019), or the implementation of adaptation action plans (e.g. the seafood sector; The Aotearoa Circle 2021), will likely fail. For example, fisheries as a wildlife harvest are entirely dependent on natural foods webs, and thus on the dynamics of other species in the ecosystem. This means that monitoring needs to be representative of the species dominating ecological interactions from primary producers to top predators. Similarly, monitoring in terrestrial and freshwater environments needs to be stratified spatially, temporally, and ecologically. That is, it needs to be geographically representative, frequent enough to detect change, and include keystone species that form habitats and dominate food webs.

Not only do changes in the environment require ongoing monitoring and evaluation, but the adaptive capacity of those implementing adaptation measures and their communities also need evaluation based on a systematic framework. Moderated citizen science engagement via global communities of practice such as the Group on Earth Observations Biodiversity Network (https://geobon.org/) can inform adaptation efforts (Pearce-Higgins et al. 2022). Similarly, new technologies make monitoring cost effective. Aotearoa New Zealand has not yet invested in the collection of sufficient data to detect annual climate-driven changes in biodiversity.

The power of kaitiakitanga

One of the greatest opportunities for a paradigm shift is the growing influence of a Māori worldview in assessing values affecting the adaptation process (Ruru 2018). Through timeless concepts such as whakapapa, the principle of connectivity between people and the natural environment (Roberts 2013), adaptation compels hapū and iwi responsibilities to both past and future generations. Innovative concepts such as manahau (Mika et al. 2022) might also provide alternatives for general society that is eager to embrace 'reciprocal exchange for shared well-being', rather than economic activity that produces damages and maladaptive outcomes. In this regard, the Crown's efforts to give effect to te Tiriti o Waitangi and to enable the exercise of locally based adaptation approaches by hapū/iwi, can provide guidance to those yearning for a shift to less destructive, more resilient socioeconomic practices in Aotearoa New Zealand (Awatere et al. 2021).

Kaitiakitanga is a powerful enabler of adaptation due to its objective of intergenerational care for the environment. Kaitiaki, guardians of natural resources, have rights and responsibilities that regulate the behaviour of humans for collective and multi-generational benefit (Kawharu 2000; Harmsworth and Awatere 2013). This links strongly with adaptation as an ongoing set of obligations to people and responsibilities for nature, concepts now embedded in IPCC assessment reporting (IPCC 2022b). Furthermore, long-term aspirations for collective well-being and the natural environment that inform natural resource management policy (e.g. the Ministry for the Environment's long-term insights briefing, The Treasury's 2021 Living Standards Framework and first Wellbeing Report 2022) have commonalities with Māori conceptualisations of place and belonging in the natural environment.

To enable all sectors to undertake effective adaptation, the aforementioned gaps and enablers will need to be filled and in place to address avoidable and unavoidable risks, and to restore those systems that support resilient ecosystems and sustainable human activities.

Conclusions

Adaptation to the impacts of climate change has been deconstructed by system and sector types (Typologies) and classified according to two categories of climate change impacts (Trends and Events), and the consequential thresholds that arise from these impacts (Thresholds). This approach has identified commonalities and differences between the typologies. The critical constraints and opportunities for adaptation have been identified to guide sector adaptation decision-making and for ongoing adaptation progress and effectiveness monitoring. Whether adaptation is delayed, or choices are made now, are decisions that will affect the ability to adapt as climate change impacts worsen and opportunities for adaptation are squeezed. Filling the knowledge gaps and monitoring the changes are necessary for understanding decision-relevant impacts and the consequences of those decisions; these are urgently needed in a coherent package that informs effective adaptation.

The implications of failing to adapt effectively are immense globally and for a small nation like Aotearoa New Zealand, the opportunity costs are large. While New Zealand can learn from other countries about adaptive systems and approaches, only we can develop and implement our own National Adaptation Plan that is tuned to the unique challenges we face here. It requires capacity and a willingness to respond effectively and in a timely manner, which in turn will take courage and leadership of a kind never before witnessed at a scope and scale commensurate with the consequences for us.

Critical decision-relevant factors for adaptation that need to be integrated within and across sectors include: that adaptation is an ongoing process that addresses continual and abrupt climate changes, and that there are limits to adaptation. Our information will change as we learn more about the climate system and improve our monitoring systems, but decisions cannot wait for full understanding. We must work from what we know now, and can project into the future, using the tools that we have available such as scenario testing, modelling, and decision tools appropriate for a dynamic and changing risk landscape.

The limits on many adaptation actions will become greater as time goes on. Nature may provide a buffer in some situations for ameliorating the worst extremes if we manage our responses proactively to avoid maladaptation; however, only urgent emission reductions across all sectors by all nations can ultimately reduce the worst impacts and the adaptation burden for future generations. Building adaptive capacity, avoiding unnecessary risks, and heeding climate signals are fundamental to meeting the adaptation challenges. Building sustainable ecosystems and human systems, funding and financing adaptation investments and compensating losses are essential ingredients for effective adaptation. Such enablers must be included in the proposed Climate Change Adaptation Act to ensure alignment and coordination by the responsible agencies and sectors.

Notes

1. When using ‘systems and sectors’ in this paper the authors are distinguishing between natural and human systems and the economic sectors dependent on the natural and human systems within which they operate.
2. ‘State change’ in this context means crossing a physical or social threshold to another state where the consequences are unknown and unpredictable and require different approaches and institutions.
3. Maladaptation is defined as ‘actions or inactions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future’ (Noble et al. 2014, p. 857).
4. Māori terms used in this paper. Hapū/iwi: an iwi is a Māori kinship group or tribe, generally comprising several hapū descended from a common ancestor. Mahinga kai: to work the food. Marae: a Māori meeting house and surrounding area. Te Ohu Kaimoana: the Māori Fisheries Trust a representative organization for protecting iwi and Māori customary and commercial interests in fisheries and the marine environment. Wāhi tapu: a sacred place to Māori. Te Reo Māori me ōna tikanga: the Māori language and its cultural practices. Tikanga: Māori custom and traditional values. Rangatiratanga: self determination.
5. Resilience is defined as ‘the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure’ (Matthews et al. 2021, p. 2246).
6. CO_2 fertilisation is the potential increase in photosynthesis rate and leaf transpiration decrease in plants due to increase in CO_2 in the atmosphere.

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Appendix 1. Adaptation opportunities, barriers, and limits for different sector types

TYPOLOGY 1 Natural Ecosystems		
Incremental adaptation	**Barriers and limits**	**Responsibility**
Management of existing weeds, pests, and diseases Prepare for managing new pests and diseases (e.g. seed banking vulnerable species) Enable ecosystems to move naturally with changes (e.g. remove stop banks, retreat from development on rivers, coasts, and other marginal land, enable and incentivise regeneration of indigenous ecosystems on marginal land and wetlands) Change harvest regimes (e.g. fishing quotas, mahinga kai) Place marine-protected areas and sanctuaries to allow for future environmental changes associated with climate change	Inadequate baseline and monitoring especially of marine populations Funding and technological limitations for the research, development and deployment of weed, pest, and disease management Difficulties in predicting new arrivals, focusing research effort, and communicating to decision-makers Funding to limit current spread of pests and weeds having limited effect Contestation for land and other property rights	Department of Conservation (DOC) Regional councils District councils Ministry for Primary Industries (MPI) Ministry for the Environment (MfE) Hapū/iwi[6] Private landowners Industry Pan-Māori organisations
Transformational adaptation	**Barriers and limits**	**Responsibility**
Advances around in situ pest management (e.g. new and more efficient toxins and tools for controlling major pests and weeds) Human retreat from coastal and riparian zones,-allowing systems freedom to move in the wider landscape and seascape Geographic relocation of existing species	As for incremental adaptation but focused on lack of financial or other incentives Inadequate monitoring of marine species to detect population movement Many Aotearoa New Zealand ecosystems are long-lived and difficult to move and re-establish	MPI DOC Regional councils Industry (e.g. farming, fisheries) Hapū/iwi Pan-Māori organisations
TYPOLOGY 2 Indigenous Communities		
Incremental adaptation	**Barriers and limits**	**Responsibility**
Adaptive management of keystone species, and mahinga kai (similar to Typology 1) Protect or adaptive management of cultural infrastructure including marae, wāhi tapu, urupā, and wāhi taonga (similar to Typology 5) Adaptive management of business interest/investments (primary sector, fishing, and tourism Typology 1 and Typology 4) Invest in strategies that assist the maintenance, revitalisation, and intergenerational transfer of Te Reo Maori me ōna tikanga Hapū/iwi are consulted on for adaptation responses and recovery from extreme weather events	Access to resources including finance and land Changing land management rules that fail to consider the rights of hapū/iwi to practice tikanga Centralised and inflexible top-down processes Spiritual and wellbeing impacts of displacement and dislocation from whenua and identity associated with cultural landscapes Māori property rights not adequately considered by Crown agencies	Kaitiaki Hapū/iwi Māori businesses Crown agencies Government departments Pan-Māori organisations
Transformational adaptation	**Barriers and limits**	**Responsibility**
Hapū/iwi-led adaptation approaches fully supported by local and central government agencies and hapū/iwi led recovery from extreme weather events	Lack of access to alternative land (sea-level rise) Availability of finance	Hapū/Iwi Central government Local government

(*Continued*)

Continued.

TYPOLOGY 2 Indigenous Communities		
Māori ethical approaches to interacting with the natural environment inform societal behaviours and perspectives on managing natural resources Co-governance processes informed by Te Tīriti shape adaptation approaches	Inequities due to unequal impacts of climate change Crown willingness to support rangatiratanga	
TYPOLOGY 3 Location-specific, Productive Land-based Sectors		
Incremental adaptation	Barriers and limits	Responsibility
Management changes examples: Livestock: changes to stocking rates, dates and timing of practices, adjusting feed types and regimes Forestry: changes to timing and method of planting, adjust management regimes (e.g. thin to lower stand density), increased use of firebreaks Horticulture: changes in canopy management; leaf removal, introducing shade nets or sunscreen protection against sunburn and extreme heat Comprehensive biosecurity approach and continued research to reduce risks Identification of resilient species and genotypes and optimal allocation throughout the landscape *Technological advances:* Improved monitoring systems to identify impacts earlier Investment in new pest management treatments *Infrastructure:* Stop banks, irrigation systems, water harvesting and storage, firebreaks	Coping capacity of species and system can be exceeded High demand and long waiting lists for new vines/cultivars Conflicting regulations Limits to water storage and harvesting in drier areas Low uptake by forestry companies (e.g. less than 10% of smallholder forest owners have adopted adaptation strategies [Villamor et al. 2022]).	Council Plan Changes Landowner and industry-led research. Consortiums (i.e. irrigation schemes) MPI/biosecurity
Transformational adaptation	Barriers and limits	Responsibility
Geographic relocation of existing species (e.g. changing locations of vineyards to cooler regions or higher altitudes) Long-term farm and forestry planning around cultivar choice and diversification of species and activities Focused tree breeding programmes on key climate risks (e.g. drought resistance) – develop genotypes with optimal phenotypes for these traits and deploy in vulnerable areas	Monitoring systems not robust across many sectors Uncertainty around the magnitude of climate change impacts on plants (e.g. on CO_2 fertilisation; and the extent of increased water use efficiency from increasing CO_2 during droughts) Availability of climate resilient species and research investment Guidance on cultivar suitability Long lead times in forestry	Industry-led research MPI Māori incorporations and trusts Pan-Māori Regional/district councils Landowner adjustments Regional Council

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TYPOLOGY 3 Location-specific, Productive Land-based Sectors		
Landscape level fire planning for forests including changes in plantation distribution and age classes Land use change Transformation from an oil-based economy to a cross-sectoral, plant-based circular bioeconomy where industrial systems are designed to minimise waste and make the most of biological resources (or biomass)	Understanding of species suitability and how this will shift Capability and cost constraints Competition for land and resources Combined effects of trends and extreme events Legislative constraints for land use change	Central government policy and funding support with local government (drought relief for adverse events has a limit)
TYPOLOGY 4 Economic Sectors that Rely on Natural Systems		
Incremental adaptation	Barriers and limits	Responsibility
Set more precautionary limits on fish catches and tourism exposure Adaptive management for ecosystems and species persistence Development of an ecosystems approach to fisheries and socio-ecological systems approach to tourism management to factor environmental change into decision making Adapt tourism services and experiences to align with changing conditions (e.g. means of access to retreating glaciers, artificial snowmaking noting potential maladaptation, 'last chance' tourism, voluntourism for habitat restoration) Shift tourist activities geographically or temporally Room for the ecosystem to move (e.g. coastal squeeze, alpine habitats, fish communities)	Tolerance range of species and ecosystem exceeded Contestation for land and sea space Property rights issues / existing users Insufficient monitoring of marine and land-based resources to understand fish movement, changes in ecosystem functionality, changing patterns of tourist behaviour and environmental impacts Existing investments and structures/stranded assets (e.g. fishing fleets or tourist infrastructure, ski fields) Reduction in economic return Focus on economic sustainability and short-term profit focus The fragmented nature of the sectors Tensions between adaptation strategies (e.g. attracting 'high-value tourists', to achieve a drop in total numbers of tourists whilst maintaining economic returns, may lead to shorter stays; or maladaptive adaptations such as snow-making and increased use of helicopters)	DOC Regional councils District councils Hapū/iwi (e.g. Ngai Tahu Tourism) Te Ohu Kaimoana/Federation of Māori Authorities/NZ Māori Tourism Tourism Industry Aotearoa MBIE (Tourism) Individual investors
Transformational adaptation	Barriers and limits	Responsibility
Geographic relocation of existing species (limited) and associated infra-structure (e.g., relocate fishing fleet and aquaculture facilities, tourism infrastructure and attractions) Freedom to move in the wider landscape/seascape Shift to another species to harvest (e.g. blue cod to snapper) Spatial relocation of fishing quotas, and sedentary species such as shellfish and aquaculture facilities to ocean ranching Innovative tourism/recreational experiences utilising existing	Competition for land and resources Cost of relocation of assets – establishing new supply chains Shifting the location of tourist demand	MPI DOC Regional councils Seafood industry Tourism industry Hapū/iwi Te Ohu Kaimoana/Federation of Māori Authorities/NZ Māori Tourism

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TYPOLOGY 4 Economic Sectors that Rely on Natural Systems		
infrastructure (e.g. from ski field to mountain bike park) Virtual tourism 'Voluntourists' to give back to the environment and information sharing and interpretation by the tourism service providers		Federation of Māori Authorities NZ Māori Tourism

TYPOLOGY 5 The Human and Built Environment		
Incremental adaptation	Barriers and limits	Responsibility
Physical protection of current assets (e.g. roads, properties, water, cultural infrastructure, and wastewater infrastructure) Reduction of existing social inequities in health and wellbeing Improved service delivery and resilience of current system (e.g. health, mobility) Planning rules and policies (to reduce exposure) Improved emergency preparedness and response Creation of heat refuges Greening urban areas Hydraulic neutrality and stormwater storage for attenuation of extremes	Opportunity cost of temporary investments Competition for resources (time, money and space) between locations and issues Political processes and influence of power Governance capacity and capability Existing vulnerabilities, e.g. higher rates of illness add to the disadvantage experienced by Māori under climate change (the 'threat multiplier' principle)	City, district, and regional councils Hapū/iwi Government departments Communities Non-Government organisations Private sector developers and investors (e.g. insurance companies and banks)
Transformational adaptation	Barriers and limits	Responsibility
Reconfiguration of cities and infrastructure including cultural infrastructure to respond to climate hazards, changing mean conditions and gradual onset change Reconfigure health and social support systems to work much more effectively with other sectors, e.g. environment, primary industry	High degree of interagency coordination required Management of stranded assets and realignment of river and coastal systems Funding windows unavailable for long-term planning of essential services and facilities, e.g. hospitals	City, district and regional councils Government ministries and departments Communities Non-Government organisations Hapū/iwi Pan-Māori organisations Private sector, investors, and insurers Health sector