Predicted impacts of climate change on New Zealand's biodiversity

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In New Zealand, climate change impacts have already been observed, and will increase in future decades. Average air temperature is predicted to warm by 2.1°C by 2090 for a mid-range IPCC scenario (A1B), with larger increases possible for some IPCC scenarios with higher rates of future emissions. Sea-level rise projections range between 0.18 – 0.59 m by 2100, based on six IPCC future emission scenarios excluding future rapid dynamical changes in polar ice-sheet flow. Global surface ocean pH is predicted to decrease by an additional 0.14 – 0.35 units by 2100, with a similar decrease expected in New Zealand waters. Rainfall is predicted to change significantly, with increased precipitation in the west, and reduced precipitation in the east, and more intense rainfall events. Increasing temperature is likely to result in species' range shifts southward and upward, and mortality during extreme heat events. Ocean acidification is expected to cause declines in carbonate communities, with cold water communities predicted to decline first due to a lower aragonite saturation horizon in cold waters. Sea-level rise is likely to impact on coastal biota, reducing coastal habitats, changing inundation patterns, and increasing vulnerability to storm surges and tides. Changes in storm and rainfall intensity are predicted to increase disturbance to terrestrial and aquatic communities. Areas with increased precipitation will amplify rates of disturbance, erosion and sedimentation into aquatic, estuarine and coastal ecosystems, while areas with low precipitation will experience increased fire risk. In New Zealand, climate change projections are being integrated into management, including increasing protection and improving management of coastal habitats. Contributing to a global reduction in greenhouse gas emissions, New Zealand is the first country to include forestry in their Emissions Trading Scheme, already positively affecting biodiversity by reducing deforestation.

Key words: review, coastal adaptation, mangrove, Emissions Trading Scheme

INTRODUCTION

THE scientific evidence for human–induced climate change is robust. In New Zealand, and globally, impacts of climate change are already observable and will increase (Ministry for the Environment 2008a). Even with immediate global action to curtail greenhouse gas emissions, the legacy of historical emissions will continue to change climate for centuries, with predicted impacts through rising temperatures, sea-level rise, ocean acidification, and potential changes to patterns of storms, precipitation and global ocean circulation.

New Zealand's emissions are unusual for a developed nation, with agriculture contributing almost 50% of total emissions based on 100-year global warming potentials, primarily as methane (CH_4) from ruminant animals and nitrous oxide (N_2O) from animal excretions and nitrogenous fertilizer use (Ministry for the Environment 2009). The 100-year global warming potentials of methane and nitrous oxide are 25 and 298 times greater, respectively, than carbon dioxide based on how much heat each unit mass of greenhouse gas traps in the lower atmosphere integrated over 100 years, though both have shorter atmospheric lifetimes (IPCC 2007). New Zealand's agricultural component (48.2%) is larger than the contribution of the energy sector (including transport) of 43.2% (Ministry for the Environment 2009). In contrast, agricultural emissions are small for most other industrialized nations, relative to the transport and energy sector. For example, mean agricultural emissions for the European Union were 3.2% of total emissions in 2000 (Clark 2006). As such, New Zealand prioritizes research into reducing agricultural emissions, for example reducing methane emissions from ruminant animals by improving production efficiency (decreasing emissions per quantity of product) (Clark 2006). Irrespective of this rather unique emissions profile, New Zealand will still be largely affected by globally-driven changes in climate, with secondary variations and trends arising from regional or local effects.

We review evidence of changes to New Zealand's climate, and projections of future changes in climate and their predicted impacts on New Zealand's terrestrial and marine habitats. We then discuss case studies of key strategies taken in New Zealand to adapt to and mitigate climate change impacts. We conclude with a review of New Zealand's Emissions Trading Scheme which includes a forestry component, and how this scheme is designed to reduce emissions and conserve biodiversity, through reduced rates of deforestation.

New Zealand's biodiversity

New Zealand was isolated from Gondwanan continents at least 80 million years ago (Thornton 1997). It lies at the convergence of two oceanic plates, resulting in frequent volcanic

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and seismic activity and high topographic complexity, offset by high erosion potential due to regular strong rainfall. Geographic isolation, physiographic complexity, and latitude ranging from 29° to 53°S have resulted in high endemism of fauna and flora. New Zealand's marine territory is about 15 times its land area (over 3.5 million km^2, not including offshore territories) and has complex circulation, resulting from the interaction of sub-tropical and sub-Antarctic fronts, water masses and deep-water and surface currents (de Lange *et al.* 2003; Carter *et al.* 1998).

New Zealand is one of the global hotspots for biodiversity due to its high endemism, and potential threats to fauna and flora (Myers *et al.* 2000; Mittermeier *et al.* 2004). Species richness is relatively low due to geographic isolation and a period of approximately 30 million years (60 –30 million years ago) when up to four-fifths of the island sank below sea-level (Cooper and Milliner 1993). New Zealand's indigenous flowering plants and vertebrate animals species have extremely high levels of endemism: 80% of all vascular plants, 70% of terrestrial and freshwater birds, all bats, all native amphibians, all reptiles and 90% of freshwater fish are endemic (Bishop 1992; Parsons *et al.* 2006). New Zealand's fauna is unique, evolving without mammals (except bats); birds filled many ecological roles occupied by large mammals on other continents. The extensive seascape is a global hotspot of marine diversity, supporting 17,135 known species (over 50% endemism), and at least 17,000 additional undescribed species (Gordon *et al.* 2010).

Compared to most land masses, New Zealand was only recently colonized by humans. Polynesians arrived about the 13th century (Wilmshurst *et al.* 2008), contributing to the extinction of at least 34 native land birds including moas (Holdaway and Jacomb 2000). European arrival from the 16th century produced further extinctions: 16 land birds, one native bat, one fish, at least a dozen invertebrates and possibly as many plants (Holdaway 2009). About 78% of terrestrial habitats have been extensively modified through conversion to agricultural, pastoral or urban landscapes (Myers *et al.* 2000). About 8% of New Zealand's indigenous vascular plants (or 38% "at risk" species, defined as declining and naturally uncommon taxa) are threatened with extinction (de Lange *et al.* 2009). In addition, 37% of New Zealand's resident native bird species (or 82% 'at risk' species) are threatened with extinction (Miskelly *et al.* 2009).

Even though a third of New Zealand's terrestrial biome is currently protected in reserves (the highest in the OECD), native biodiversity continues to decline (Green and Clarkson 2005). Habitat loss and degradation, invasive species, climate change, pollution, over-exploitation and disease threaten biodiversity in New Zealand (Kingsford *et al.* 2009). There have been few documented effects on the indigenous biota from changes in average temperature, but many ecological reactions to extreme climatic events have been observed (McGlone *et al.* 2010). While other threats are responsible for historical impacts on biodiversity, future climate change is predicted to act synergistically with existing threats. As such, minimizing other impacts may allow ecosystems to be more resilient, in the face of an uncertain future due to changes in climate.

Projected impacts of climate change

Temperature

New Zealand warming trends are consistent with the global pattern, with multiple lines of direct and indirect evidence showing that New Zealand has warmed during the past century. The longest dataset archived by NIWA includes surface air temperature measurements from seven climate stations, with reliable records dating back to the early 1900s (Mullan *et al.* 2010). These seven stations show a warming trend over the past 100 years (1910-2010) of 0.96 ± 0.29ºC (Fig. 1). These temperature trends have been calculated after merging different temperature records from a number of local sites, accounting for changes in local temperature due to physical movement of a site, changes in exposure, and changing instrumentation (Mullan *et al.* 2010).

Warming is predicted to be fairly uniform across the country, with some regional variation indicating greatest warming in the north of New Zealand, and lesser but still significant warming in the southeast, and additional variability in warming between seasons and regions (Ministry for the Environment 2008a).

These observed terrestrial temperature trends are consistent with independent regional sea surface temperature measurements (ERSSTv3 - Extended Reconstruction Sea Surface Temperature v3b) from NOAA averaged over a geographical box (160–190°E, 30–50°S) around New Zealand (http://www.ncdc.noaa.gov/ersst). The correlation between variation in land and sea surface temperatures demonstrates the influence of the oceanic environment on New Zealand's island climate. Land temperature variability is 50% more extreme on average than sea surface temperature variability in the sub-tropics, as expected from the heat capacity of the oceans (Sutton *et al.* 2007).

Long term projections for New Zealand suggests warming (mid-range projections relative

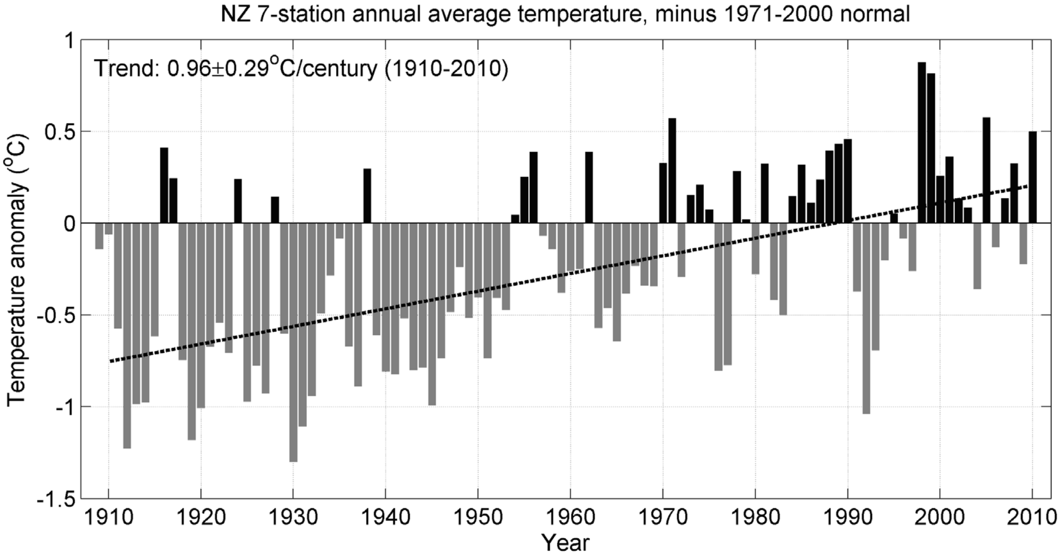

Fig. 1. Temperature anomalies for 1910-2010, based on annual average temperature from seven New Zealand climate stations (Auckland, Masterton, Wellington, Hokitika, Nelson, Lincoln, and Dunedin), with homogeneity adjustments to account for site and other changes as described in the text (http:/www.niwa.co.nz/climate/nz-temperature-record).

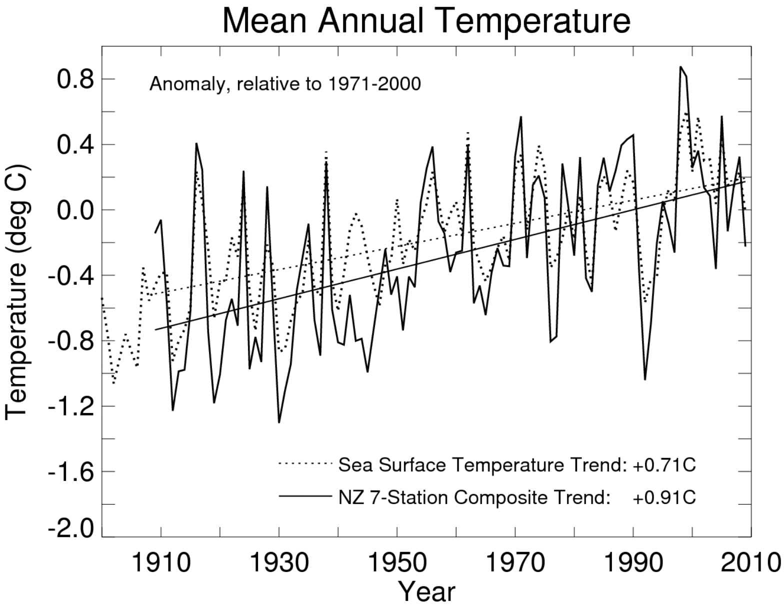

Fig. 2. Annual time series of ERSSTv3 (Extended Reconstruction Sea Surface Temperature v3b) sea surface temperatures (dotted line) and the NIWA (National Institute of Water & Atmosphere Ltd.) seven-station composite series (solid line) based on stations at Auckland, Masterton, Wellington, Hokitika, Nelson, Lincoln, and Dunedin. Temperature is expressed as anomalies relative to the 1971-2000 average temperature. Linear trends over the period 1909-2009, in °C/century, are noted under the graph (based on Mullan *et al.* (2011).

to 1990 based on IPCC global climate scenario A1B) of 0.9°C by 2040 and 2.1°C by 2090 (Table 1; IPCC 2007). The number of hot days is predicted to increase and the number of cold days and frosts to decrease (Ministry for the Environment 2008a). The increased temperatures are associated with projections of shortened duration of snow fall, rise in snowline, decrease in snowfall events, and continuing long-term reduction in glacier volume and length (Ministry for the Environment 2008a).

Rainfall

Generally, regional predictions suggest a wetter west and drier east of New Zealand than in the past, with increased rainfall intensity during severe rain events (Table 1, Wratt *et al.* 2006). Projected annual mean precipitation changes suggest up to a 5% increase in the west by 2040, and 10% by 2090, and decreases in the east and north, sometimes exceeding 5% by 2090, driven by increased westerly winds in

Table 1. Summary of climate changes and projections in key climate change stressors for New Zealand, based on local studies and the 2007 IPCC assessment (IPCC 2007).

Climate stressor	Changes and potential projections	Certainty of impact
Temperature	■ Surface temperatures in New Zealand have increased by about 0.9ºC since pre-industrial times. ■ Projections of average surface temperature warming of 2.1°C by 2090 relative to 1980-99 (mid-range IPCC A1B scenario).	High, already observed
Sea-level rise	■ Mean sea-levels have risen at an average rate of 1.7 ± 0.1 mm y^{-1} since 1900. Including a small glacial isostatic adjustment gives absolute sea-level rise of 2.0 mm y^{-1}, which is within the range of the global average. ■ Plausible increase likely to be between 0.5 – 1.0 m by 2100, but higher rises cannot be ruled out.	High, already observed; rate will accelerate over this century as polar ice sheet discharges increase
Atmospheric carbon dioxide	■ Record since 1970 at Baring Head demonstrates rise of > 2 ppm y^{-1}.	High, already observed. Rate has accelerated in recent decades
Ocean acidification	■ Average global pH of surface waters has dropped by 0.1 since the mid-nineteenth century to a current value of approximately 8.1. ■ Global prediction of further decrease in pH of 0.14 – 0.35 units by 2100. ■ Data from bi-monthly cruises off the Otago Coast since 1998 indicate a slight trend to decreasing pH in the transect's subantarctic waters, but high variability in coastal waters.	High, already observed
Precipitation	■ Variable across New Zealand, with predicted increase in the west (Tasman, West Coast, Otago, Southland, and the Chatham Islands), and decrease in the east (Northland, Auckland, Gisborne, and Hawke's Bay). Intensity of rainfall predicted to increase, with larger frequency of severe rain events. ■ Predicted decreased duration of seasonal snow lying, rise in snowline, and decrease in snowfall events.	Moderate for increase and decrease by region; high for intensity
Storm events	■ Predicted changes in frequency and magnitude of storm surges and storm tides. ■ Westerly winds predicted to increase in frequency.	Low for location and frequency

winter and spring (Ministry for the Environment 2008a). Rainfall is predicted to be more spatially and seasonally variable than in the past. Areas predicted to have increased rainfall (Tasman, West Coast, Otago, Southland and the Chatham Islands) may have increased soil erosion and landslips, impacting terrestrial, aquatic, estuarine and coastal habitats. The frequency of extreme rainfall events is expected to increase 7–20%, based on a temperature increase of 1–3°C (Wratt *et al.* 2006). However, high natural variability in rainfall and sediment yield is linked to climate and New Zealand's geological history, making predictions of the relative impact of climate change-driven variation difficult.

Decreased annual-average rainfall is predicted in many northern and eastern regions already susceptible to drought (Northland, Auckland, Gisborne, Hawke's Bay) (Wratt *et al.* 2006). For eastern areas of the North and South Islands, drought frequency is predicted to increase from 1-in-20 year return frequency to a 5-to-10 year return frequency (Mullan *et al.* 2005). Drought-associated increases in fire frequency are predicted for the east coast of both islands, particularly the Bay of Plenty, and for the central (Wellington/Nelson) region (Pearce *et al.* 2005).

Cyclone/storm events

Climate change is expected to change storm conditions, altering frequency and magnitude of storm tides and wave and swell conditions (Mullan *et al.* 2011). Westerly winds are predicted to increase in frequency by 2040 and beyond, particularly in the South Island (IPCC 2007). Severe storm projections are less clear, since both ex-tropical cyclones (originating from the southwest Pacific) and extra-tropical cyclones (generated in the middle and high latitude westerlies) can impact New Zealand. The IPCC 4th assessment (IPCC 2007) suggests a likely increase in intensity of tropical cyclones, but

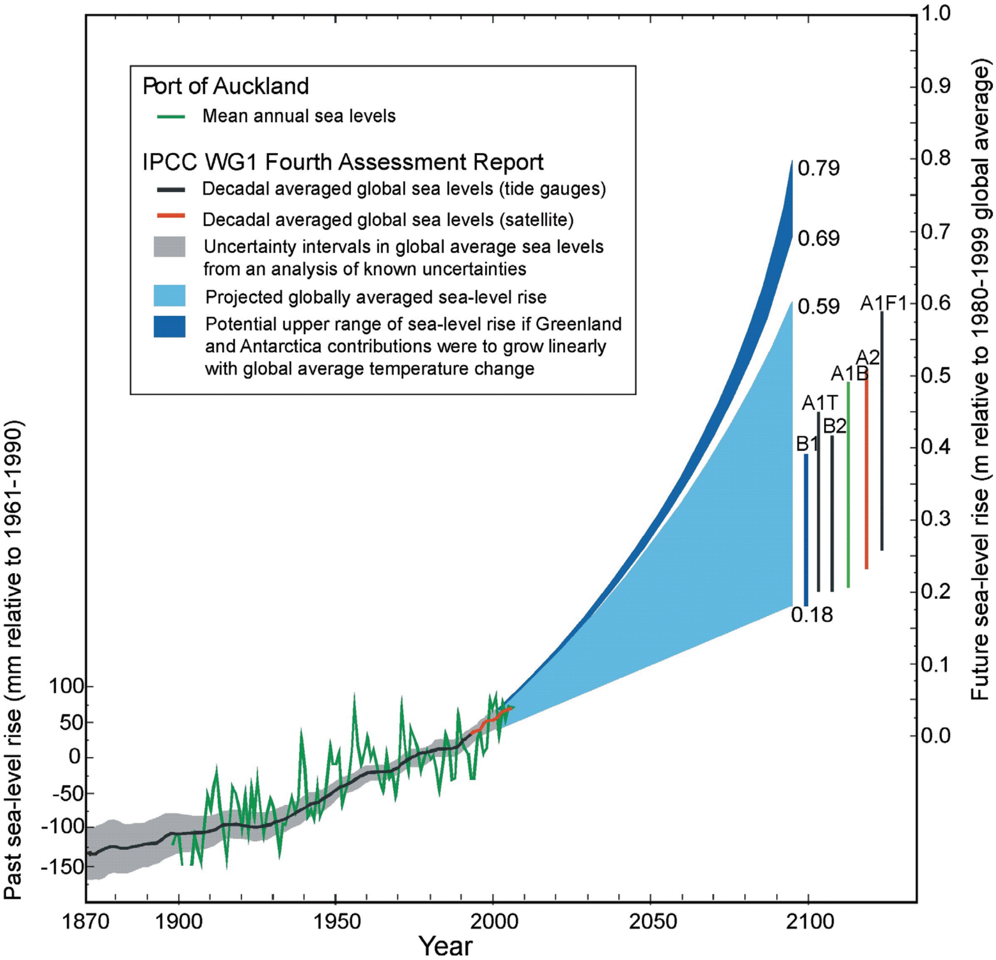

Fig. 3. Historical sea-level rise (mm relative to 1961-1990) for tide gauge and satellite measurements, and projections of sea-level rise (mm relative to 1980-1999 global average) for six IPCC global emissions scenarios, and further projections of sea-level rise considering contributions of Greenland and Antarctica (based on Ministry for the Environment 2008b).

there is low confidence about how cyclones exiting the tropics might affect New Zealand. IPCC (2007) suggests a likely decrease in the total number of extra-tropical cyclones, with a poleward shift of the storm track. This is consistent with the results of Mullan *et al.* (2011), who found a reduction in future cyclone numbers (from global model projections) over the North Island in winter, and a decrease in intensity over New Zealand in both summer and winter. However, an increased cyclone intensity south of New Zealand was likely in winter and spring, with a stronger pressure gradient and associated westerly winds over the South Island (Table 2).

Sea-level rise

Historical rates of relative sea-level rise recorded at the main ports of Auckland (Waitemata Harbour), Wellington, Lyttleton (Christchurch) and Dunedin are the longest available time series on sea level in New Zealand, with records back to 1900. Sea-level rise has averaged 1.6 ± 0.2 mm y^{-1}, or 0.16 m in the last century, based on relative mean sea-level rise records for these four sites (Hannah 2004), slightly increasing up to 2009 to 1.7 ± 0.1 mm y^{-1} (Hannah *et al.* 2010). Allowing for an average landmass uplift of 0.3 mm y^{-1} (due to the glacial isostatic adjustment), absolute sea-level rise around New Zealand of 1.9–2.0 mm y^{-1} is within the range for the global average sea-level rise of 1.7 ± 0.3 mm y^{-1} (IPCC 2007). This means that mean global sea-level rise projections can be reasonably confidently applied directly to New Zealand's coastline. Thirty-five additional New Zealand sea-level datasets exist for shorter time series (generally less than a decade), which precludes them from an analysis of long–term trends (usually performed on records of >50 years). However, an assessment of sea-level trends at a further six New Zealand stations (where local mean sea-level datums were set earlier last century and good historical records remain) have yielded the same long-term average rate of 1.7 ± 0.1 mm y^{-1} as the four main ports (J. Hannah, University of Otago, pers. comm.).

The IPCC 4th Assessment projections suggest a rise in sea level by the 2090s of 0.18 to 0.59 m (mainly thermal and glacier contributions), plus a further 0.1–0.2 m for limited ice-sheet

Table 2. Predicted changes in tropical and extra-tropical cyclones in New Zealand (based on Ministry for the Environment 2008b, adapted from IPCC 2007, and Mullan *et al.*, 2011).

Cyclones	Description	Projected change and certainty
Ex-tropical cyclones generated in the tropical Pacific	Peak wind intensities increase	Over most tropical cyclone areas; likely
	Mean and peak rainfall intensities increase	Over most tropical cyclone areas; likely
	Frequency of occurrence	Fewer weak storms and more strong storms (medium confidence). Fewer storms relative to global average. Specific regional changes will depend on change in sea surface temperature (medium confidence) and on changes in El Niño-Southern Oscillation (low confidence)
Extra-tropical cyclones generated in the middle and high latitudes	Frequency and position change	Fewer extra-tropical cyclones likely. Poleward shift of storm tracks likely, resulting in fewer cyclones over North Island in winter. Increased cyclone activity in Tasman Sea in summer (medium confidence)
	Storm intensity and winds change	Decreased cyclone intensity over New Zealand winter and summer, but intensification in winter south of New Zealand resulting in increased extreme winds and more rainfall in the west South Island (medium confidence)

dynamics across several emission scenarios with the highest value at nearly 0.8 m, relative to a 1980-1999 baseline (Table 1; IPCC 2007 and associated IPCC Summary for Policymakers). Importantly, due to uncertainties in how polar ice sheets may respond to rising temperatures, IPCC did not provide an upper bound or a best estimate on sea-level rise (so larger values cannot be excluded). The current New Zealand guidance recommends risk-based assessments covering a range of possible sea-level rises by the 2090s, starting assessments at 0.5 m and considering at least 0.8 m above the 1980-1999 mean sea-level (Ministry for the Environment 2008b). A review of more recent publications (Royal Society of New Zealand 2010) indicates that sea-level rises above 1 m or more by 2100 cannot be ruled out.

Increasing atmospheric CO_2 and ocean acidification

Rising atmospheric levels of CO_2, representing the southern hemisphere atmospheric concentrations, have been documented at Baring Head in New Zealand since 1970 (Lowe 2006). These measurements show similar increasing trends to the long-term northern hemisphere CO_2 record at Mauna Loa, with the same rate of increase, though Baring Head displays a smaller seasonal variability, due to the larger oceanic influence on southern hemisphere measurements relative to the northern hemisphere (Lowe 2006). The current increase per annum is >2 ppm.

Increasing atmospheric CO_2 increases CO_2 concentration in the oceans. As CO_2 is absorbed by seawater, it reacts with water to form carbonic acid, dissociating to release hydrogen ions, and decreasing seawater pH. As solubility of carbon dioxide increases with reductions in temperature, the changes in acidity due to increased atmospheric concentrations of CO_2 will be more acute in cold waters (Guinotte *et al.* 2006). IPCC emissions scenarios project reductions in average global surface ocean pH of 0.14 – 0.35 units by 2100, adding to the current decrease of 0.1 units since pre-industrial times (IPCC 2007). Bi-monthly cruises off the Otago coast since 1998 have collected data on surface water CO_2 concentration from a transect extending 60 km from 45.770°S, 170.720°E to 45.833°S, 171.500°E (Currie *et al.* 2011; Ohline *et al.* 2007). This short dataset demonstrates seasonal trends, with higher concentration of CO_2 in the surface water in winter than in summer, and a slight overall increasing trend in CO_2 concentration in the transect's subantarctic waters, but high variability in CO_2 concentration in coastal and mid-transect waters (K. Currie, pers. comm.).

Predicted effects of climate change on biodiversity

Temperature

Range shifts are predicted for terrestrial and aquatic species, with alteration of latitudinal and altitudinal ranges southwards and upwards (McGlone *et al.* 2010). Native forests in New Zealand are expected to change in distribution and composition, associated with increased temperature, changes in rainfall and increasing westerly winds (Hennessy *et al.* 2007). Northern species are predicted to expand their ranges southward and to higher altitudes; upland forests are likely to be invaded by broad-leafed species; and species adaptation to new climates may be limited by dispersal in already fragmented landscapes (Whitehead *et al.* 1992). Native mangroves, already increasing in abundance, are expected to expand southward, challenging coastal management (Morrisey *et al.*

2010). Rocky intertidal species respond to broad climate drivers such as ENSO events, resulting in heat stress, desiccation, and increased wave forces that resulted in loss of three-dimensional structure (Schiel 2011). Simple relationships between sea surface temperature increase and range shifts have not yet been observed for New Zealand rocky intertidal communities, unlike the northern hemisphere (Mieszkowska *et al.* 2005, Schiel *et al.* 2004), most likely due to short timescales of study that incorporated multiple ENSO events.

Some habitats are predicted to experience significant declines under most climate change scenarios, for example alpine areas (McGlone *et al.* 2010). Marine habitats such as coastal kelp forest habitats formed by large macroalgae are of particular concern, as these species are predicted to decline due to rising sea surface temperature, as observed in the United States and Australia (Dayton *et al.* 1999, Edgar *et al.* 2005).

Increasing temperatures are also predicted to immediately negatively impact aquatic fauna and flora. Projections include increased eutrophication and algal blooms in inland lakes, decreases in wetland habitats, decreases in range of native fish species with reduced thermal tolerance, and increases in invasive species like carp and invasive aquatic macrophytes (Hennessy *et al.* 2007). Mass mortalities of marine fauna have already been observed in intertidal and shallow subtidal areas when heat waves coincide with daytime low tides (Wethey *et al.* 2011). While most freshwater fish and invertebrates show broad distributions across New Zealand, some are adapted to cold water temperatures and will be negatively affected by increasing temperature (McGlone *et al.* 2010). Temperature increases may also negatively impact reptiles such as the tuatara that have temperature-dependent sex determination during the embryonic stages (Mitchell *et al.* 2010). Positive impacts are also likely, with warmer than normal summers linked to increased mast-seeding behaviours in many common New Zealand plants (Webb and Kelly 1993). Indigenous fish and invertebrates in freshwater ecosystems in the north may be positively impacted if warm temperatures cause southward shifts in the distribution of introduced competitors such as rainbow and brown trout (Glova 1990).

Rainfall and storm events

Increasing frequency and severity of extreme weather events is predicted to have strong negative impacts on some ecosystems (McGlone *et al.* 2010). Increased rainfall, including intense events in the west, may increasingly disturb stream and river systems. Intense rainfall events will increase soil erosion, increasing sedimentation and turbidity in some rivers, estuaries and coastal waters (Thrush *et al.* 2004). For eastern regions that are likely to experience decreased rainfall, disruption of aquatic ecosystems through low flows or drying of stream and rivers is predicted (McGlone *et al.* 2010). Reduced annual frequencies of occurrence of flood-related patterns have been observed in eight east coast South Island catchments over the 50-year period 1958-2007, resulting in decreased stream flows (McKerchar *et al.* 2010). Increased fire frequency is also predicted for some eastern regions, associated with decreased precipitation and increased westerly winds (IPCC 2007).

Sea-level rise

Predicted changes in tidal inundation and increases in depth due to sea-level rise will reduce light availability, negatively impacting species such as seagrass (Short and Neckles 1999). For species that must migrate inshore as sea level rises (e.g., mangroves, saltmarsh and brackish wetlands), retreat and reduction in these habitats will occur where topography or human alterations limit the landward extent of coastal expansion (Swales *et al.* 2009). In similarly constrained areas, reductions in abundance of intertidal habitats will decrease abundance of dependent species such as migratory wading birds, including those at the six internationally significant Ramsar wetland sites (Farewell Spit, Firth of Thames, Kopuatai Peat Dome on the Hauraki Plains, Manawatu estuary, Awarua Waituna Lagoon, and Whangamarino wetland). These intertidal areas also provide habitat for commercial, recreational and customary fisheries (e.g., cockles *Austrovenus stutchburyi* and pipis *Paphies australis*) that also provide valuable roles in their filtering capacity for estuarine ecosystems. Sea-level rise is also likely to result in erosion and decreased habitat availability on New Zealand's offshore island sanctuaries for endangered species.

Increasing atmospheric CO_2 and ocean acidification

Ocean acidification will affect marine species that use calcium carbonate in their shells and skeletons (Turley 2006). It will decrease carbonate availability, reducing the creation of carbonate structures, their structural stability, and larval survival and growth of carbonate species (Smith 2009). Many important carbonate-producing species are found in New Zealand's estuarine, coastal and offshore habitats (e.g., shellfish such as cockles, lobsters *Jasus edwardsi*, paua *Haliotis* spp., kina *Evechinus chloroticus*; key habitat-structuring species such as deep-water corals, oysters and bryozoans; and zooplankton that underpin coastal and oceanic food webs). Such impacts will increase uncertainty as to changes in marine communities, and the consequent impacts on ecosystem function if key species are affected (Hofmann *et al.* 2010). There is much uncertainty about the effects of ocean acidification due to inherent spatial and seasonal variability in pH, and variation in response between taxa and between life stages, which make predictions of impacts on marine biodiversity challenging (V. Cummings, pers. comm.). Cold-water corals are predicted to be particularly vulnerable to ocean acidification, with a clear relationship demonstrated between deep-water coral distribution and depth of the aragonite saturation horizon (the thermodynamic potential for the aragonite form of calcium carbonate to form or to dissolve) (Guinotte *et al.* 2006). Predictions of increased ocean acidification indicate that significant declines will occur for deep-water corals, along with their diverse communities across over 800 seamounts in New Zealand's exclusive economic zone (Guinotte *et al.* 2006, Poloczanska *et al.* 2007, Rowden *et al.* 2005).

Increasing atmospheric CO_2 is likely to change productivity and nutrient cycling in terrestrial and aquatic ecosystems (McGlone *et al.* 2010). For primary producers, CO_2 is expected to increase productivity of phytoplankton, algae and coastal and terrestrial vegetation, with unknown impacts on higher trophic levels. Increased plant productivity is predicted due to high concentrations of CO_2, accelerating rates of photosynthesis for most plants (Lovelock and Ellison 2007). Most experimental research has been inconclusive with respect to changes in photosynthesis and growth over the long-term e.g., seagrass (Short and Neckles 1999); mangroves (Ball *et al.* 1997)), with further interactions of climate change on humidity, temperature and nutrient availability that make it difficult to predict long-term changes in plant productivity.

Synergistic impacts of multiple stressors

The most serious threats to New Zealand's biodiversity involve interactions between climate change and pre-existing threats such as habitat loss and fragmentation, and invasive species. More invasive species are predicted to establish with climate change, along with expansion southward of invasives that have already colonized New Zealand (McGlone *et al.* 2010). Invasive pampas grass *Cortaderia selloana* have increased southward distribution (Field and Forde 1990). Climate fluctuations are likely to affect masting (interannual cycles of fruiting in plants that can lead to outbreaks of rodents), further increasing exotic mammalian predators that negatively impacts New Zealand's biodiversity (Choquenot and Ruscoe 2000). Fragmented and isolated populations are presumed to be less resilient to climate change impact.

Adaptation case studies

We discuss two New Zealand case studies regarding active management of ecosystems, based on predicted impacts of climate change. These case studies illustrate management actions that integrate changes in sea-level, storm frequency, and rainfall intensity, and how management may increase protection of coastal habitats and their associated biodiversity.

Impacts of sea-level rise on mangroves

The New Zealand mangrove *Avicennia marina* subsp. *australasica* presently occupies North Island estuaries north of 38°S. Southern limits are determined primarily by physiological stress due to low overnight air temperatures and the frequency and severity of frosts (Morrissey *et al.* 2010). The vertical distribution of mangroves on intertidal estuarine flats is down to mean tide level where the seabed is submerged for less than six hours per tidal cycle. Frequency and severity of wave exposure also influences distribution of mangroves. Mangrove habitat expansion has occurred in many of New Zealand's North Island estuaries (Morrisey *et al.* 2010). These increases are associated with estuary infilling due to accumulation of sediments eroded from land, increasing with catchment deforestation since European colonization, and conversion to pasture and urban land use (Morrisey *et al.* 2010).

Mangroves, currently occupying 58% of potential mangrove habitat in the eastern Auckland area, have increased by 0.8 to 8.4% per annum since the 1940s–1960s. Further changes in mangrove distribution due to climate change are likely, due to impacts of sea-level rise, combined with changing climatic patterns influencing sediment runoff and consequent estuary infilling. Distributional changes due to increasing temperature are uncertain, but likely less important drivers than changes in sea-level and increased rates of sedimentation and storm frequency.

Models have predicted changes in the extent of mangrove habitats in Auckland east coast estuaries for the 2050s to 2090s, based on current distributions, numerical modelling of sediment transport, projections of sea-level rise, estuary infilling rates, influence of local tides, and natural or human alterations to shorelines (Swales *et al.* 2009). Three modelled scenarios predicted potential long-term consequences of current land-use practices and climate change on these estuarine systems, and respective sea-level rise for two future periods (2050s and 2090s): 1) using historical trends in sea-level rise since 1950 in Auckland; 2) using 2007 IPCC mid-range projection for sea-level rise; and 3) using the upper-range 2007 IPCC projection for sea-level rise (Swales *et al.* 2009). Tidal flat elevation profiles were measured and mapped, and used to derive potential habitat above mean tide level in 2050s and 2090s for each scenario, offset by sedimentation of 3.8 mm y^{-1}.

The scenario based on an unchanged historical sea-level rise predicts an increase of 8% (range 0–26%) in potential mangrove habitat by 2050s and 14% (range 0.2–46%) by 2090s, increasing total area of mangrove habitat by 5.8 km^2 by 2090s (Swales *et al.* 2009). The mid-range sea-level rise scenario predicts a reduction of 3.7% in mangrove habitat by 2050s and of 10.2% by 2090s with a total loss of 4.5 km^2 of mangrove distribution by 2090s. IPCC upper-range projections predict a 10.6% reduction in mangrove habitat by 2050s and 27% reduction by 2090s, with total loss of 11 km^2 of mangrove habitat by 2090s (Swales *et al.* 2009). These models assumed no change in sedimentation rate, but increases could occur due to increased intensity and frequency of rainstorms. Mangrove forests with such large sediment supply could keep pace with sea-level rise. In scenarios 2 and 3, reductions are mainly due to barriers preventing landward retreat, such as embankments, motorway reclamations, and seawalls. Increases in mangrove habitat are predicted in small estuaries (<5 km^2 high tide area) with limited exposure to wind-waves and more rapid sediment infilling (i.e., estuaries with small receiving environments relative to catchment area), compared to large estuaries (e.g., Waitemata Harbour). Mangroves are predicted to be displaced from intertidal flats over the long-term, in the main body of estuaries, but remain in tidal creek refuges, assuming continued high sedimentation rates in tidal creeks (about 20 mm y^{-1}). Such predictions provide objective information for decision-making in estuary and coastal ecosystems and their associated land catchments in relation to climate change.

Coastal shoreline adaptation to climate change

New Zealand has over 15 000 km of coastline (Gordon *et al.* 2010). Coastal and estuarine habitats (and human developments) are affected by tides, sea-level rise, long-term fluctuations in sea-level (e.g., El Niño/La Niña cycle), frequency and magnitude of storm surges, tidal range, storms, waves and swell conditions, river flows and rainfall patterns and intensity. These physical attributes affect catchment erosion, subsequent sedimentation in estuarine systems and sand nourishment to the coast. Climate change is likely to increase coastal erosion and inundation, air and sea temperatures, frequency of storm-tide flooding, drainage of low-lying areas adjacent to the coast, seawater influence up lowland rivers and creeks, and alter surface water and groundwater quality (Ministry for the Environment 2008b).

Historically, coastal hazards were combated by coastal defences and shoreline modifications, a problem exacerbated by coastal human development which has greatly modified natural coastal defences such as beaches, dunes, gravel barriers, and coastal vegetation. Historical coastline management usually protected private property by construction of seawalls, groynes and dykes. The 2010 New Zealand Coastal Policy Statement (Department of Conservation 2010), under the umbrella of the Resource Management Act (1991), provides a clear mandate to manage coastal hazards and development through adaptation to climate change over at least 100 years ahead. For example, Policy 18 recognizes the need for public open space, which includes setting aside esplanade reserves for all new developments. These undeveloped coastal buffers should be protected or enhanced (Policy 26) to provide natural defences to coastal erosion from climate change. This new coastal policy should better protect and mitigate threats from coastal development that would impact on native coastal habitats and their associated biodiversity.

There is also guidance in evaluation and management of future coastal inundation and erosion risks (Ministry for the Environment 2008b). Further, sea-level rise projections are incorporated into a risk-based decision-making framework to guide local government in adapting to coastal climate change (Ministry for the Environment 2008b). This manual recommends risk or vulnerability assessments for possible sea-level rises by the 2090s, starting assessments at 0.5 m and considering at least 0.8 m above the 1980–1999 baseline sea-level, with a potential increase of 10 mm y^{-1} in sea-level rise after 2100 (Ministry for the Environment 2008b). The flexible risk-based approach of these guidelines encourages assessment of sea-level rises greater than 0.8 m.

New Zealand's Emissions Trading Scheme

New Zealand is the only country outside of Europe to implement an Emissions Trading Scheme, and the only country to incorporate a forestry component in the scheme (Ministry of Agriculture and Forestry 2010a). This Emissions Trading Scheme aims to contribute to mitigating global climate change, and is compliant with the Kyoto Protocol. New Zealand relies heavily on forest carbon sequestration to comply with the Kyoto Protocol, with a quarter of New Zealand's gross emissions in 2009 offset by forestry (Karpas and Kerr 2011). *Pinus radiata* is the dominant (90%) exotic forest.

In the scheme, carbon units earned under the Kyoto Protocol through reforestation or afforestation are passed to land-owners in the form of New Zealand Units (NZUs) equal to one tonne of CO_2. Similarly, land-owners that deforest exotic forest must surrender carbon credits, making deforestation less cost-effective (Karpas and Kerr 2011). Protections exist for indigenous forest, with only 2% of native forest available for timber harvest (Raison et al. 2001). Further complexity is included in the scheme based on the age of the forest (pre-1990 or post-1989), and a minimum of nine years required from replanting to harvest (Karpas and Kerr 2011). Rotation times are approximately 25-32 years for most exotic species (Ministry of Agriculture and Forestry 2010b); landowners who have received credits are liable for any emissions on harvest. Credits can be earned from 2008, and entry into the system is voluntary.

A preliminary evaluation of the effectiveness of New Zealand's Emissions Trading Scheme suggests that it has already reduced rates of deforestation (Karpas and Kerr 2011). Reducing the rate of deforestation in New Zealand has direct positive impacts on biodiversity by reducing habitat loss and fragmentation (McGlone *et al.* 2010). Deforestation is also linked to soil erosion, decreased water quality, and sedimentation impacts downstream in freshwater, estuarine and marine systems (Thrush *et al.* 2004). New planting of both exotic and indigenous forest is still low due to uncertainties relating to national and international policies that will determine the value of future carbon credits (Karpas and Kerr 2011). Although indigenous forest can also receive carbon credits, there is still some concern that high carbon-sequestering exotic forests will out compete slow growing indigenous forest that would otherwise have regenerated in some areas.

CONCLUSIONS

Climate change resulting from continuing emissions of greenhouse gases could profoundly affect the structure and function of New Zealand ecosystems. Warming from ongoing greenhouse gas emissions and legacy emissions will continue to impact for decades, even if strong global action to reduce global emissions is taken. There remains uncertainty about the rate of change of the physical impacts of climate change by the end of this century and beyond, particularly for sea-level rise where polar ice sheets are expected to play a critical role. We do not understand enough about most species to predict changes in species abundances and distributions; the timing of species life cycles; interactions among species; extinction rates; the structure and composition of communities; and ecosystem function. Further research is needed to develop general principles to predict changes to New Zealand's terrestrial and aquatic biodiversity to guide decision-making.

Climate change policies should address emissions reductions, as well as adaptation to predicted change. New Zealand's Emissions Trading Scheme is contributing to the reduction of emissions, while also reducing biodiversity loss by making deforestation less cost-effective (Karpas and Kerr 2011). Reduction of other human impacts (Kingsford *et al.* 2009) will be a good strategy, as pristine systems are more resilient to climate change impacts (Watson *et al.*, in press). New Zealand has changed its coastal policy to adapt to both climate change and coastal hazard impacts, with emphasis on leaving intact coastal habitats to provide roles in coastal protection. Other adaptation plans need to be advanced to ensure our communities and ecosystems are as resilient as possible in the face of uncertain changes to New Zealand's climate.

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