UNIVERSITY OF GENEVA

BIOLOGY BACHELOR MONOGRAPH

Climate change impacts on New Zealand's endemic terrestrial fauna

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By
Charlotte Grometto

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MONOGRAPH DIRECTOR
Professor Anthony Lehmann
Institute for Environmental Sciences
Science Faculty

MONOGRAPH RESPONSIBLE
Professor Lionel Monod
Chargé de Recherche
Muséum d'Histoire Naturelle de Genève

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SUMMARY

This monograph is a review of the current studies on climate change responses from biodiversity, with a focus on New Zealand's endemic terrestrial fauna. In the introduction, the context of current climate change impacts in New Zealand is reviewed. The first part goes into more detail about New Zealand, its precious biodiversity, climate, and existing pressures on endemic fauna, and presents the issue of climate change as a threat to this category of biodiversity. Then, the second part reviews the different observed, predicted and/or expected impacts of global warming, based on many national and global studies addressing the question of climate change and biodiversity responses. The last part takes more distance from the question and treats the uncertainties and interrogations surrounding both the modeling aspect and the conservation aspect of climate change and its relation to biodiversity.

INTRODUCTION

In 2020, the Living Planet Report published by the *World Wide Fund for Nature* (WWF) announced a decline of 68% in the monitored populations of vertebrates (1). This alarming number translates into a reduction in the abundance of the 21'000 vertebrates' populations that have been monitored since 1970 and is the result of very well-known pressures. To be more precise, modern human activities such as forestry, tourism, agriculture, and fishery are strongly harming biodiversity through different threats causing this decline in population abundance and distribution (1). For instance, the main driver of biodiversity loss is land or sea-use change, causing habitat loss or degradation and being responsible for approximately 75% of the extinctions of plants and vertebrates since 1500 through either overexploitation or agriculture (1). Nonetheless, other pressures like overexploitation, pollution, invasive species, and the diseases they carry are contributing to this biodiversity crisis as well (1). Nowadays, international organizations such as the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem* Services (IPBES) or the *Convention on Biological Diversity* (CBD) which is helping to protect the biodiversity via the publication of reports on the current state or by setting different goals to achieve as the Aichi Biodiversity Target for example. While many countries, including New Zealand, are signatories of the CBD, those targets can be hard to achieve (2). In their 6th report for the CBD, most measures are qualified as "partially effective" but the overall protection of biodiversity, despite showing progress in some areas, is still not deemed sufficient and further measures need to be taken to achieve those goals (2). In addition to these current pressures, anthropological global warming is becoming more and more present in discussions and conventions regarding biodiversity and conservation and represents an additional driver of the biodiversity crisis (1, 3). It is currently challenging to show that this factor alone is causing extinction (4), but it does possess the potential to become one of the most severe pressures on biodiversity in the near future (1). Global warming and more generally climate change has been shown to make extinction risk vary the most in models, illustrating that its consequences could potentially impact flora and fauna in tremendous proportions (3) in the case it is not halted or slowed down in the coming years. The WWF estimated that 1/5 of wild species could already be at risk of extinction during this century due to climate change alone (1) and has been predicted in another study to potentially cause the extinction of 7.9% of species (3) and negatively affect an even greater proportion.

Regarding our future climate, some of its characteristics can be predicted with adequate accuracy, especially temperatures, allowing scientists to model biodiversity's adaptation to their new climate. However, one important factor to keep in mind is that global warming is not going to affect every ecosystem of the planet in the same way (e.g 5, 6, 7, 8) with biodiversity hotspots being in the more vulnerable category. Although climate conditions and critically vulnerable locations can be identified, the responses from species to global warming is a different question that has interested scientists over the past few decades (e.g 4, 9, 10, 11) and it is crucial to gain this knowledge. How can the best protection be offered to all endangered and threatened species without knowing what they will need once the repercussion of greenhouse gases are felt?

In this monograph, we will focus on New Zealand and more precisely on its endemic terrestrial fauna. What responses to climate change have already been reported? What other impacts can be expected, and hopefully anticipated before it is too late? In the first part, we will present the country, its current and projected climate, and its terrestrial fauna. In the second part, we will look at some typical ways climate change has been shown to affect species, directly or indirectly, and then review some examples of expected ecological modifications. Finally, we will discuss the issues that come with modeling such responses, and how the national conservation bodies are currently acting to both manage the current pressures and mitigate the forthcoming ones that global warming will very likely bring in the foreseeable future.

I. AOTEAROA NEW-ZEALAND

New Zealand and climate change

What has been observed

In the austral summer between the years 2017 and 2018, New Zealand faced an unusually harsh heatwave resulting in average air temperature being 2.2°C warmer than the expected average, and sea surface temperature surpassing the average by 3.7°C (12). Other consequences of this singular event have been major species disruption in marine ecosystems, the biggest loss of glacier ice recorded in the Southern Alps, as well as a greater number of tropical cyclones during the summer (12). In general, extreme events result from complex interactions of both anthropological drivers and natural variability and can be hard to predict, however, it has been shown that global warming could lead to an increase in both their frequency and intensity (12). In addition to these kinds of events, which are extreme in their climate conditions but also in the damage they can cause, more subtle signs of anthropogenic climate change have been reported since the 20th century. For instance, the sea level has risen by 17 centimeters since then while temperatures have increased by approximately 1.0°C in the past century (13), as shown in **Figure 1**, and have not been this elevated in the past 10'000 years (14). As seen on this graph, temperatures have been fluctuating all along the measurement period, but the range of fluctuation has shifted toward hotter values, especially since the years 1970-1980.

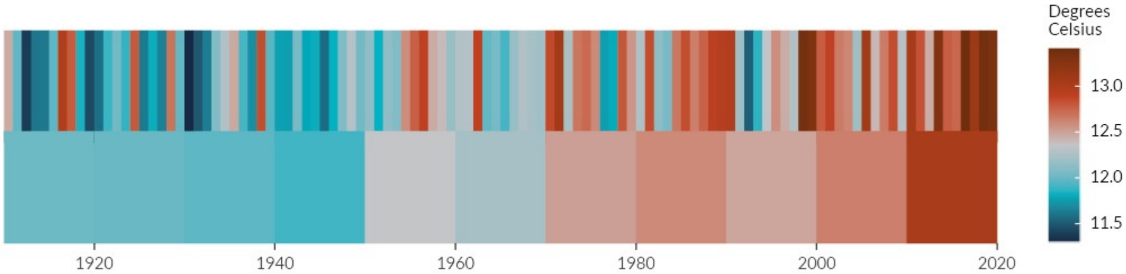

Figure 1 : Average temperatures in New Zealand from 1910 to 2019.
(Royal Society of New Zealand, 2016)

Precipitations have also been affected with a decrease in rainfall totals in the North Island and an increase in the South Island affecting both agriculture and horticulture and increasing the likelihood of floods which also have severe consequences on both ecosystems and human well-being (14). Regarding extreme events, a greater number of heatwaves, coastal flooding, droughts, or change in seasonality have also been reported by the Ministry for the Environment in the past decades, usually greater in their frequencies and intensities. Contrary to temperatures, rainfall patterns tend to vary more and affect parts of the country very differently as they depend greatly on the topography (15). In addition, the ice component of the country is severely affected; indeed, the glaciers are melting more and more rapidly and acutely with a loss of 28% or 15.5 km^3 in 2016 compared to the 1977 reference (14).

What can be expected

As time goes by and anthropological emissions keep on increasing, many more environmental repercussions can be expected in the future. Based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (16), different global climate outcome can be expected, depending on the number of emissions anthropological activities continue to release into the atmosphere, making up different scenarios for 2100. Those scenarios or "RCP", standing for *Representative Concentration Pathway* (17), represent different trajectories of emissions released by human activities, hence their different outcomes on physical conditions such as temperature. For example, keeping our present habits would lead us to follow the RCP6.0 or RCP8.5, while a reduction of our emissions would lead us to the RCP4.5 or RCP2.6 which represents the only curve allowing us to keep global warming under 2°C by 2100 (18). It is important to note that under each of those projections, from the lesser emission scenario to the greater, changes are going to be felt by any living individual on earth in the decades to come (19), as the projected annual temperature and precipitations changes from **Figure 2** illustrates it. Following these scenarios, some projections can be made about the future conditions and climate characteristics.

Temperatures, for instance, are expected to rise from 1°C to 5°C by 2100 compared to the baseline of 1986-2005, depending on the RCP followed (13). However, the left panel from **Figure 2** shows how, even in an intermediate scenario, the warming is going to be uniform over the country and might exceed 2°C. Moreover, frost days are predicted to diminish in proportion, whilst the heat days are likely to increase significantly (13). Following this idea, hot extremes are projected to be much more frequent, in opposition to cold extremes which will likely decline with time. While the increase in temperature is a little under the global average expected for 2100 because of the geographic location of New Zealand, the sea-level rise is expected to be 10% more important than the global value, with a rise between 0.3 centimeters to 1.1 meters depending on the RCP (13). For the precipitations, the projections seem to differ more depending on the region and the data used, making accurate predictions harder to achieve. However, general trends similar to the observed changes are expected to continue, equivalent to an increase in precipitation in the South Island and a decrease in the North Island (20), as visible in **Figure 2**, however big uncertainties remain in the prediction of rainfall pattern and even under RCP8.5 it is hard to determine whether precipitation will change at all (20), but it is still very likely that 99th percentile event regarding precipitation amount will increase in the future (20). Those uncertainties can be shown in the way that precipitations have the potential of being altered on a more local scale than temperature and are shown in **Figure 2** to vary between more than ±10%. Additionally, extreme events such as the 2017 heatwave precedingly cited are expected to be more frequent and intense. Under the RCP4.5 or RCP6.0, the heatwave forementioned would correspond to a typical summer in 2100 (12).

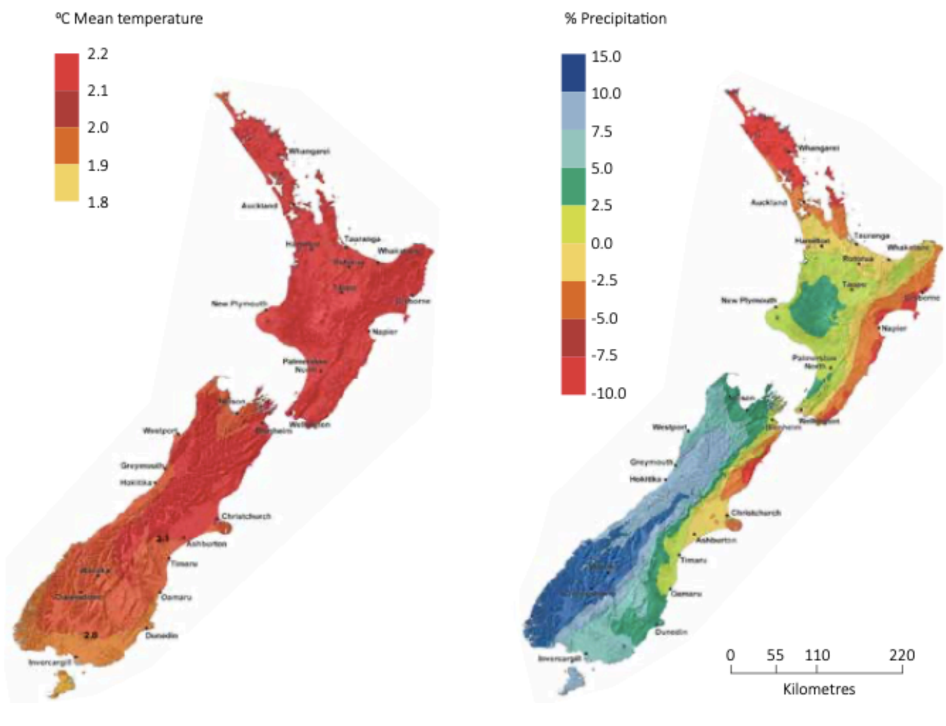

Figure 2 : Projected annual mean temperature on the left and precipitation on the right between the period 1980-1999 and 2080-2099. Projection based on an intermediate scenario of emissions. (Ministry for the Environment, 2008)

New Zealand's terrestrial fauna

Particularities

From flightless birds, birth-giving lizards, a relic genus of reptiles, and a quasi-absence of endemic mammals, New Zealand's fauna is truly one of a kind. This unique composition of species is the result of the geographic history of the Islands composing the country. Being separated from its nearest landmass, Australia, 80 million years ago (21) by the opening of the Tasman Sea and then staying isolated from any other continent has caused the species found on these islands to evolve with very little to no exchanges with another biota for the biggest part of those millions of years. This assembly of islands, now located 2000 km east of Australia (21), possesses as a result a very high rate of endemism (22). Indeed, in some taxa, the part of endemism species is simply enormous, with for instance 81% of the insects, 84% of the vascular plants, and 100% of the reptiles, frogs, and bats not being found anywhere else on Earth (22), occurring at the genus, family, or order level (22).

Land of the flightless birds

Another particularity of the fauna, which also results from its isolation is the absence of endemic mammals, except for a few species of bats (22). Indeed, until recently, the greatest part of the fauna's history has been taking place in the absence of predatory mammals, which is a very rare condition found almost nowhere else on earth. Consequently, birds have taken up the niche which would have been colonized by mammals if those were present, making them free to roam on the ground, sometimes losing the ability to fly, and not having to leave the ground in the absence of predators (22). Some iconic flightless birds from New Zealand, such as the kiwis (*Apteryx*) or the extinct moa (*Dinornithiformes*) are part of the ratites birds lineage and seemingly have independently lost their ability to fly following the colonization from their flighted ancestor approximately 50 to 65 million years ago (23). Moreover, it seems that the ancestor of the moa species colonized New Zealand earlier, allowing them to get huge, whereas the kiwis ancestor arrived later, while also losing the ability to fly, they could not get as tall as moas, due to competition (23). Other birds became flightless after their arrival in New Zealand, for example, the kakapo, which is the only flightless parrot in the world, certainly being able to become so in the absence of mammals (24). Another notable factor that participated in the formation of such a diverse fauna over the country is the multitude of extremely different ecosystems which can be found on the islands. Indeed, despite being a relatively small landmass, New Zealand is composed of many different landscapes and ecosystems, ranging from glaciers to wetlands to temperate forests, with a wide range of microclimates, coming from the latitude extending from 29°C to 53°S (25). These factors, an old separation, coupled with a range of diverse habitats and ecosystems gave New Zealand the potential to become a biodiversity hotspot (26). A hotspot is defined by Myers as a region with "*exceptional concentrations of endemic species and experiencing exceptional loss of habitat*"[1] and New Zealand does fill all these criteria.

[1] Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. Nature. 2000 Feb;403(6772):853–8.

Ongoing pressures on biodiversity

Threat classification

Since the arrival of men back in the 12th century, this exceptional fauna has been threatened and impacted by their activities, which resulted in the extinction of at least 79 species (22), with vertebrates contributing to two-thirds of this entire loss (28). These losses were the result of different pressures, directly or indirectly caused by humans such as the introduction of invasive species, pollution, diseases, and degradation or fragmentation of habitat (29). As of today, according to the New Zealand Threat Classification System (*NZTCS*), 7% of the 11'000 monitored terrestrial species are ranked as "Threatened", meaning that they face imminent extinction should the current trends continue, and 22% as "At Risk", meaning they are likely to become "Threatened" if the pressures on these populations keep on worsening (22). Those numbers are illustrated in **Figure 3**, in which the proportion of Data Deficient species is more visible. Responsible for those threats are human activities such as habitat modification and hunting (22), but the current most impactful pressure on the terrestrial fauna is predation by introduced mammals such as mustelids and feral cats, possums or even hedgehogs (22, 28) and the clearance of indigenous vegetation, which causes substantial reduction of the indigenous species habitat (22).

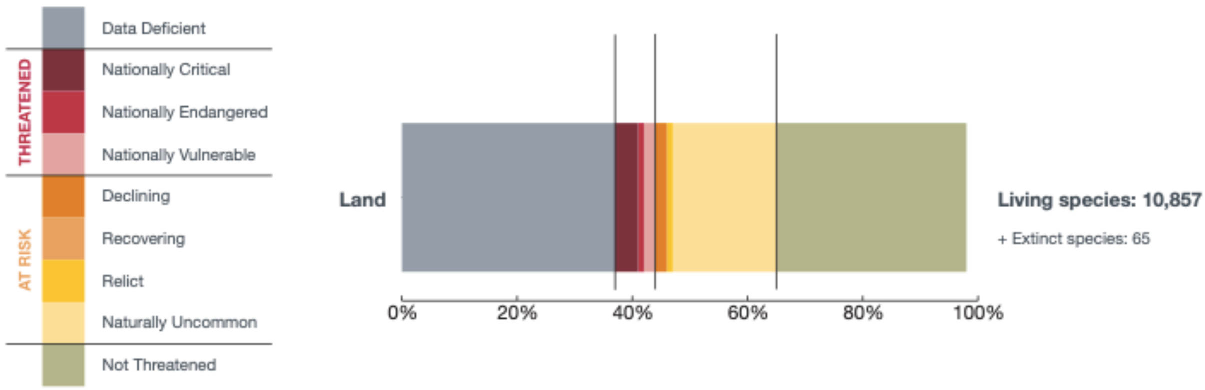

Figure 3 : NZTCS status of conservation for terrestrial native species.
(DOC - Department of Conservation - , 2020a)

Future threats, and vulnerabilities

In addition to these already harmful threats, New Zealand's biodiversity might be more vulnerable to climate change (e.g 5, 8, 30). Manes et al. (2021) showed that endemic and/or native species could be 6% more vulnerable to climate change than introduced species (8) that intrinsically possess more potential in dispersion, migration and are usually more generalist than endemics (8). Additionally, biodiversity hotspots might generally be more affected than other places (5) and the same principle goes for Island biota (8). The vulnerability of those species comes from restricted areas and the fewer possibilities of migration-related to this factor (8).

Moreover, the presence of many "Naturally Uncommon" (31) ecosystems or areas found in New Zealand which are rare covering less than 0.5% of land area and have been since before the arrival of the First Men on the Island (32). Additionally, those ecosystems are often home to high proportion of specialized and/or endemic species both in the flora and the fauna (31). Amongst the 72 different types, 45 have been deemed vulnerable, endangered, or critically endangered (32) by following the same principle as the IUCN Red List for animals. Being under pressure from current human activities and pests (22), the consequently rare biodiversity and communities found in those ecosystems are also declining and could suffer even more pressure in the future (31).

II. OBSERVED AND PROJECTED IMPACTS ON BIODIVERSITY

Typically observed responses

As we have seen, New Zealand's fauna is already under pressure but could even become more at risk in the following decade. Considering that 1 in 5 wildlife species are currently at risk of extinction because of climate change alone (1), the importance of being able to anticipate biodiversity's reactions becomes evident. As it happens, it is challenging to have a good idea of how a single species or population will react in the face of future climate conditions. Some typical responses have been listed, mostly based on ecological observations (33), which offer some basic ideas of what to expect from species adapting to a new climate. Starting from these expected reactions and adding a good knowledge of the ecosystems and the ecological characteristics of species, conservation effort can then be focused on what truly has the potential to make a difference to limit exposure to extreme events, unsuitable conditions, or unwanted interspecific interactions. Accordingly, the long-term monitoring of some species in New Zealand has permitted us to see some shifts in the ecology of the fauna (e.g 28). Those modifications can either be subtle and only be noticed on long-term records or can be more obvious when caused by extreme climate events. Overall, climate change seems to affect all levels of biodiversity, from the genes, the individuals, the populations and even reaching communities (10). Those changes can be summarized in the following categories: *Distribution, physiological properties, interspecific/trophic interactions, and invasive species advantages*. These different categories are inspired by New Zealand's specific issues but also represent a fusion of many categories cited in more global studies identifying basic responses to climate change (e.g; 4, 9, 10, 11,). In the following part, we'll review each category in more detail and see some examples that, although often anecdotical, are illustrating that some species already seem to be suffering from climate change pressure.

Range and distribution alterations

Global trends

The actual distribution of a single species, depends on many factors, but the climate is one of them, through characteristics such as temperature or precipitation tolerance which will affect the area in which a species can survive (34). In a changing climate, it would be expected for species to modify their distribution to stay within their climate niche. Correspondingly, monitored species of several taxa have been reported to follow their optimal climate niche by moving upward in elevation or poleward in latitude (30), searching for colder conditions in a warming world. One direct implication of this general principle is the fact that range-restricted, polar, or mountaintop species might have a hard time finding new suitable habitats in their climate niche (9) as is illustrated in **Figure 4**. The previous top species, represented in white on the right panel, living at the summit might be pushed to rise higher, either by competition or lack of resources but could disappear should one of those factors be deleterious to them. By being pressured to move upward on a mountain, some species might reach the summit and still be outside of their temperature tolerance while not being able to continue their search for suitable habitats (30). Furthermore, such shifts might alter biotic interactions, favoring some competitors or making impossible some essential cooperation (30). In the end, altered biotic interactions, fewer resources, and intolerable temperatures might cause some extinctions in those more restricted environments (30). Although it has been determined that noticeable shifts mostly occur during shorter and extreme events (11), these are expected to become much more frequent (20), as well as more intense, which could lead to recurring range shifts episodes.

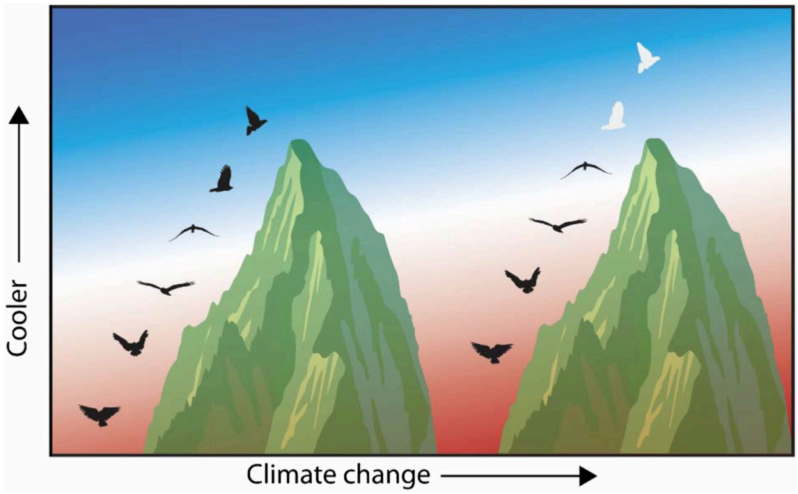

Figure 4 : Representation of the upward movement of species following warming.
(Urban MC, 2018)

In New Zealand, this issue might not affect the Northland biota too harshly (33). Many warm-adapted species are currently not expending toward the south, partly because of the colder climate, but would have the space to find new habitats by shifting their range poleward, should the conditions of their current locations change and not suit them anymore (33). The avifauna being endotherms, warmer temperatures will most likely not impact them directly, some other threats such as predation or the degradation and fragmentation of their habitat are much more impactful on their survival (33).

Climate-restricted invasive species

One of the most threatening pressures on New Zealand's endemic fauna is the presence of invasive species. Brought with the humans which populated the Island, those were introduced in ecosystems they were well-adapted to and which they have been able to dominate in a few centuries, leading to huge declines, especially in avifauna, and in many conservation-motivated attempts to reduce their presence (33). While they seem to be present in most of the territory, it has been suggested that some of those bird predators such as the ship rat (*Rattus rattus*) or the Australian brushtail possum (*Trichosurus vulpecula*) could be climate-restricted in their distribution (35), usually being more prevalent in warmer forest sites and less abundant in cooler forests (35). Therefore, with a temperature increase, these climate-restricted species' distributions could expand. With their intrinsically better capacities of adaptation than those of native species, they could expand, colonize new habitats, and exacerbate declines in their prey populations (35). In other words, the increased extinction risk due to range contraction would be coming from the range expansion of the invasive species and not from a direct climatic condition impact (35).

One example, illustrating both the abilities of range expansion for an invasive species and the speed at which those can colonize those environments after extreme events is the occurrence of rabbits at particularly high altitudes. Right after a volcanic eruption, the invasive rabbits' (*Oryctolagus cuniculus*) populations were seen at altitudes they seemed to have never reached before (36), hinting at the fact that their initial distribution was climate limited. In another reported case, the invasive species of ship rats (*Rattus rattus*), which is present in forests, seem to be affected by the cold weather to some extent, being less present during periods of prolonged cold, and able to breed more during milder months (37). Indeed, recent records show increased presence in areas where they used to be absent only a few decades ago (37). Regarding introduced invertebrates, the main pressure comes from common wasps (*Vespula vulgaris*), which compete with native birds for nectar or even attack juveniles (33). Moreover, being ectotherms, they react to climate quickly and despite currently not being able to survive winters in New Zealand, they could persist all year long under milder conditions (22).

Nonetheless, species that are not invasive can also very well impact another species' distribution. One observed example is one of two species of wētā (*Hemideina crassidens and Hemideina thoracica*), which are endemic insects. While having different preferences in their habitats, those still restrict each other's distribution range through competition (38). Although not surprising and quite a common phenomenon, the principle of biotic restriction of the area could add to the future pressure from global warming. In this example, the species considered are arthropods, which lack thermoregulation abilities (4), making them more vulnerable to suffering from changing climatic conditions. Short-term and short-range shifts in elevation and been observed in both of those species, corresponding to a typical distribution shift following warmer conditions (38). Nonetheless, while theoretically able to search for more suitable habitats, the interaction between those two species could very well lead to the inability of one, or both, to effectively settle in a new area (38), it is predicted that under a warming climate, *H.crassidens* could progressively lose territory while *H.thoracica* extends its range (38). This illustrates how even native and endemic species might interact negatively with each other and cause shifts in communities. Furthermore, the biotic interaction between all species, native or invasive, should be considered when predicting a species future distribution, since solely climate factors cannot fully explain a species distribution, but biotic interactions are necessary to anticipate a population's future distribution (38).

Physiology, phenology, and extreme events

As mentioned, climate change does have the potential to cause population decline, or even lead to extinction (1). However, the dynamics in which these terrible losses occur can be very diverse. Here are some examples of ways global warming could affect species, which have either been observed already or are very likely to occur.

Extreme climate events

Due to the warming of the atmosphere, the occurrence of extreme warm events will increase while the colder counterpart should statistically decrease (12). As shown in **Figure 5,** a shift in average temperature toward a warmer value simply means that current extremely hot weather will become more frequent. However, hot extremes are not the only kind of unusual situation that are projected to become more frequent since floods, fires, heatwaves, extreme rainfall, and droughts have the potential of becoming more intense in the coming decades (33) but are overall hard to predict. In New Zealand, fire severity for instance might increase dramatically locally, especially in the South Island as is depicted in **Figure 6** due to hotter and drier summers and longer periods of suitable conditions leading to forest fires (13). While those typically short-lived events can displace populations and cause range shifts, they can also provoke an abrupt decline in the population in some cases.

For instance, the scree skink (*Oligosoma waimatense*), which is a "*Threatened*" (39) endemic lizard, suffered an 84% decline in population following unseasonal flooding in 2009 (40). Scree skinks are particularly vulnerable with specialized habitats restricting them in their search for new habitats and being under pressure from mammal predation (40). Furthermore, the studied population is found near the braided river ecosystem of the South Island, which while already prone to floods, might become even more susceptible to those in the future, putting in danger entire communities (40). One interesting fact is that, although this population can show tremendous resilience to seasonal floods, they tend to be extremely sensitive and vulnerable to unexpected ones (40).

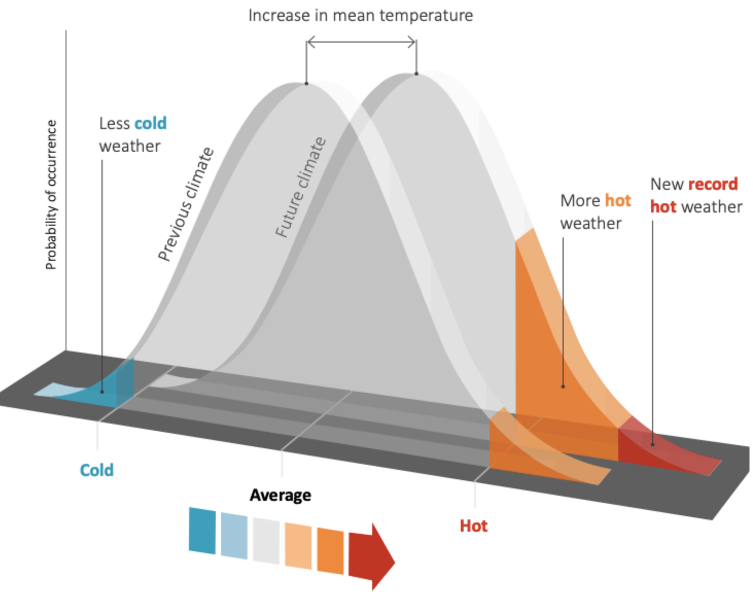

Figure 5 : How new extreme temperature occurrences are shifting under a warming climate.
(Ministry for the Environment, 2008)

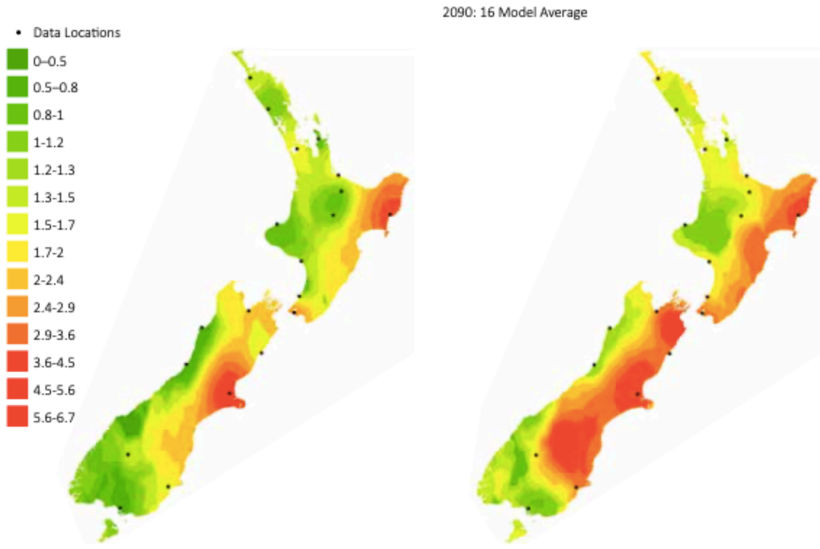

Figure 6 : Current and Projected severity of seasonal fire in an intermediate emissions scenario.
(Pearce et al., 2011)

Through sex-ratio shifts

In addition to its already threatened status, caused by habitat destruction and predation, the tuataras could suffer from an additional issue caused by global warming (41). This last representative of the genus *Sphenodon* is an endemic lizard considered "At-Risk" (42) by the NZTCS and which sex is determined through environmental conditions (*temperature-dependent sex determination or TSD*) or more specifically through soil temperatures (41). The critical temperature is found around 21°C, meaning that lower temperatures favor female development while warmer favor male development (41). Therefore, with increasing temperature, the sex ratio could shift toward the male side, resulting in the population dynamic being altered, complications in breeding, and population decline (44). Although this ancient genus has been able to adjust to changing climates in the past (43), their current distribution has been reduced a lot by more modern pressures such as predation and competition with invasive species, leading conservators to move the remaining populations to remote islands (43). While being protected from mammalian predators, these new habitats offer restricted migration possibilities and fewer alternative nesting sites. Furthermore, the tuatara breeding rate is very low, with a unique egg-laying event every four years after females reach their sexual maturity at 15 years old (43). The combination of all those factors is worrying and could lead to the extinction of this unique genus.

Phenology

Another impacted element is the phenology or the timing of essential life events as it seems that phenology could also be affected by global warming (9). The range of affected events is quite important, for example modification in the timing of breeding, migration, the hatching of eggs, and hibernation which are all seasonal and induced by environmental cues (10). The alteration of such an event could in the end affect "*population dynamics, species interactions, animal movement and the evolution of life histories […] and contribute to shifts in species distributions, population viability and reproductive successes*"[2]. Globally, long-term records on species such as birds or butterflies have shown a significant shift in phenology, which is certainly linked to recent anthropological global warming (11). In a 2013 study by Chambers et al., an advance in phenology was observed in 82% of the terrestrial datasets assessed for the Southern Hemisphere, illustrating the extent of this response (45). In New

[2] (39). Chambers LE, Altwegg R, Barbraud C, Barnard P, Beaumont LJ, Crawford RJM, et al. Phenological Changes in the Southern Hemisphere. PLOS ONE. 2013 Oct 1;8(10):e75514.

Zealand, as temperature increases, some changes in phenology are expected and have already been observed. For instance, earlier egg-laying has been observed in the Welcome Swallow (*Hirundo tahitica*) species (46). Indeed, this species' egg-laying timing is almost 30 days earlier than it was in 1950, which coincides with the period where the warming was the fastest, suggesting a relation between increased temperature and earlier phenology (46). Another example is one of the long-tailed bats (*Chalinolobus tuberculatus*) and its torpor or hibernation period being shortened because of milder cold-season temperatures (47). This endemic mammal, already under pressure from predation, also shows lower survival rates in warmer winter, which can be explained by a shift in phenology (47). Those bats are usually inactive during the winter season but tend to become more active in milder conditions, but while temperatures are higher, resources are not necessarily more abundant, leading to higher mortality, especially in juveniles (47). While these alterations in the timing of such important events are currently related to few population decline, they have the potential of affecting species in a much greater proportion and could very well cause several extinctions. The main issue with shifts in phenology is for tightly dependent species, which might not be synchronous in their interaction anymore, should their phenology be affected differently. Through disruption of essential biotic interaction, communities could become weaker and eventually lose a part of the species composing them.

Alterations in interspecific and trophic interactions

While the direct abiotic effects of climate change can be harmful to species sensitive to temperature or in exposed areas, indirect biotic impacts might be even worse on biodiversity. Indeed, the collateral impacts on interspecific and trophic interactions caused by global warming have the potential of affecting a much larger proportion of species and can lead to extinction through the perturbation of essential interactions, especially regarding food availability (4, 9) or other kinds of interspecific interactions such as predator and prey, host, and parasites or even pollinators and plants (9). Because of different phenologies caused by global warming, some species could lose the ability to realize an essential interaction with another species (10). Additionally, range shifts caused by climate change might lead to the same result (9). By looking at ways climate change causes extinction, Cahill et al. (2013), found that interspecific interaction disruption leading to lack of food availability was the "*single most common proximate factor*"[3] (4). In the following examples, we will see how reduced food availability has already affected several sea-bird species, and how a mast-seeding phenomenon might lead to the increased presence of mammalian predators, which are very harmful to terrestrial biodiversity.

Food availability

In several native sea-bird species of New Zealand, a recent decline has been observed in the past decades (48, 50). For instance, the Yellow-eyed penguin (*Megadyptes antipodes*) is already "*Nationally Vulnerable"* (49) and has suffered a substantial decrease in the past 20 years, which can in part be explained by sea-surface temperature (SST) (48) as can be seen on **Figure 7**. As can be seen on the graph, all the major losses of adult penguins shown by a sharp drop of the black line occurred in years with higher-than-average sea surface temperature, and better survival seems to occur whenever the temperature gets lower (48). While some other non-climate factors are essential to take into consideration for this observation, such as habitat destruction, pollution, or resource competition (48), the correlation between climate warming and this species of bird's survival does exist. Moreover, long-term warming is responsible for this decline, rather than cyclic climate events such as El-Niño Southern Oscillation (ENSO) (50). What happens during these warmer years is

[3] Cahill AE, Aiello-Lammens ME, Fisher-Reid MC, Hua X, Karanewsky CJ, Ryu HY, et al. How does climate change cause extinction? Proc Biol Sci. 2013 Jan 7;280(1750):20121890.

that increased SST are affecting fish distribution, making it more difficult for the penguins to access food or to get good quality regimes but also has extended impacts on breeding success (50). Sadly, with the projected warming of the ocean, the decline is also projected to continue for years to come (48).

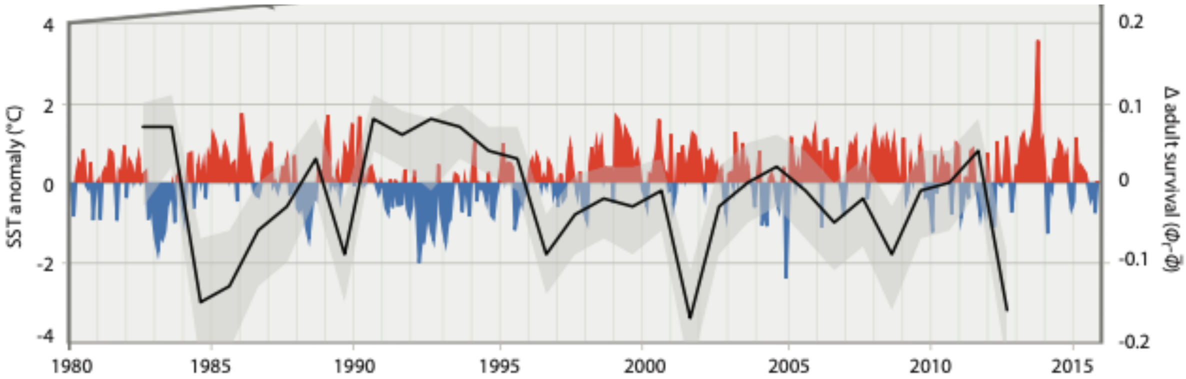

Figure 7 : Adult survival over Sea Surface Temperature anomalies from 1960 to 2015. (Mattern et al., 2017)

Another example is the one of the red-billed gulls (*Larus novaehollandiae scopulinus*), which are "*Declining*" (51) and have undergone a drop of 51% abundance in the last 20 years (52). This quite dramatic decline, which is mainly the consequence of predation, has also been shown to be affected by harsh fluctuations in food availability (52). Additionally, breeding successes were directly correlated with euphausiids abundance, which have an optimal temperature range that might not be found near New Zealand coasts in the future (52). In both of those cases, the indirect effect of climate has been identified in lower survival rates and an overall reduction in population sizes, but they are even more at risk because of sea-level rise, or the consequences of human-made infrastructure to counter this rise that could harm the habitat of these kinds of species (53). Overall, the combination of those factors makes these species more vulnerable and susceptible to decline or even extinction.

Vegetation cycle alteration, mammalian predators, and invasive invertebrates

Invasive species are ravaging New Zealand's endemic biodiversity (22). Through competition for resources between wasps and bird populations or direct predation by mammalian predators, their presence is highly threatening for the avifauna as well as reptiles, causing population decline, extinctions, and restriction of their ranges (53) which makes them the main driver of extinction for these groups (22). In the past decades, some successes have been attained in surrounding islands where no more mammalian predators can be found, allowing the native fauna to thrive (22), but overall, the fight against those species is very hard, and as we have seen, milder condition might lead to increased distributions (33, 35). Furthermore, due to close interaction with the interannual seed cycle in mast-seeding forests, their abundance might even increase in the future (37, 48). While many studies have been conducted to get a better understanding of this phenomenon (e.g; 54, 55, 56), the actual reaction to global warming is still hard to project. However, it is generally accepted that it possesses the potential of giving an advantage to invasive species and increasing their pressure on native fauna (54, 55) through what can be called the "*Predator Plague Cycle*" which is illustrated in **Figure 8.** Mast-seeding species are trees that, occasionally, undergo a process where the flowering can be as much as 10 times greater (54) than average, resulting in a tremendous production of seeds (28). As this process happens, food becomes more available to different groups like mammalian predators, native birds, and reptiles. Consequently, predator abundance has been shown to dramatically increase following a masting season (37, 48). As can be seen in **Figure 8**, as rats get more present due to resource increases, top predators like stoats can follow, and their number increases as well, leading to stronger prey consumption (33).

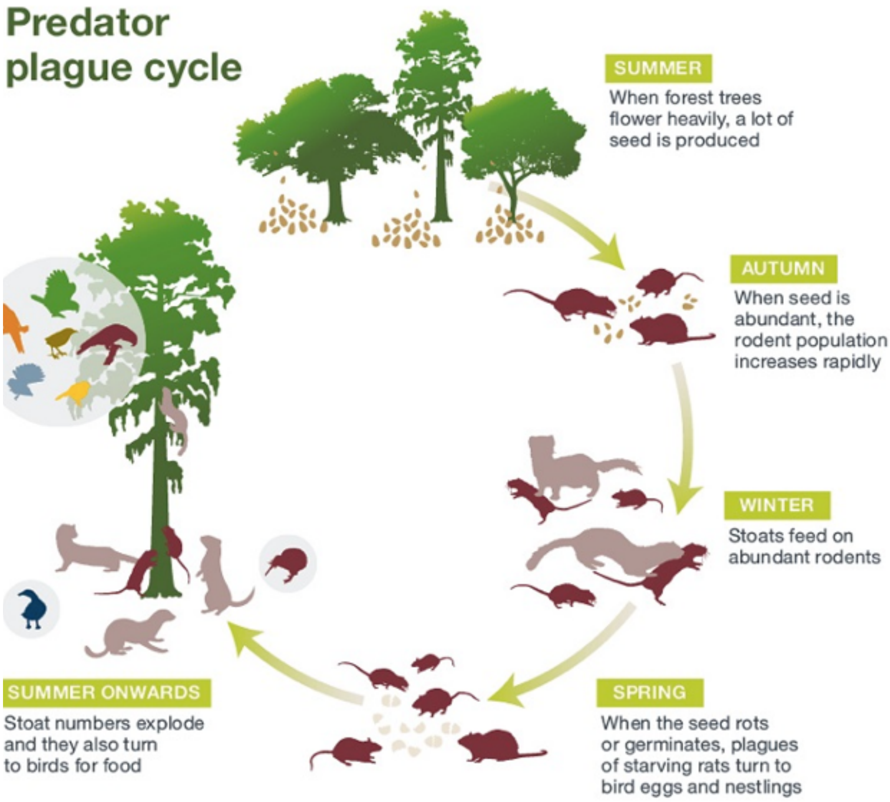

Figure 8 : One year cycle following a mast seeding summer.
(Department of Conservation website)

The preoccupying aspect of this cycle is the fact that these events seem triggered by warmer temperatures, and the frequency of mast years could very well increase in the future, leading to severe predator outbreaks and viability of mammal predators (28, 55). More precisely, mast-seeding seems to happen in the year following exceptionally hot summers (54, 55). Nonetheless, this cycle is not entirely negative, since native animals can also profit from these resources' availability, but also complicates the ability to predict the net effect on endemic fauna (28). Nonetheless, seeing the proportion in which mammal predators currently negatively impact endemic fauna, solutions must be proposed to prevent further extinction and further understanding of these interactions might be the key to better conservation efforts and results.

Regarding invasive wasps, social wasps like *Vespula germanica and Vespula vulgaris* seem highly reactive to climate and global warming will most likely increase their range, because similarly to invasive mammals, those invasive insects appear to be largely climate restricted for the moment (28, 33). Under warmer conditions, the proportion of wasps surviving winter would become greater, leading to increasing abundance over the years (56). Consequently, this increased range would also exacerbate the threat and pressure they represent for native invertebrates through direct predation but also to vertebrates such as birds, with which they can compete for resources like honeydew which is produced by a native scale insect *Coelostomidia wairoensis* (28, 33). Through predation, they reduce invertebrates' abundance but can also harm juvenile birds (33). During the years of higher population density in *Nothofagus* beech forest, they immensely reduce the honeydew quantities available for native species feeding on it (57, 58) leading to observable behavioral alteration in native avifauna (57). The *Vespula* wasps have even been shown to partially be the cause of the decline in native birds' abundance over several years, with a higher decline for insectivorous birds during peak wasps abundance seasons, most likely due to competition for insect consumption (59). Overall, should these invasive invertebrates really benefit from warmer temperatures, their range would most likely increase, worsening their current pressure on native fauna through the direct effect of climate change (28, 60).

III. MODELS AND CONSERVATION

Modeling

Predicting the future

In the face of such an elusive threat as a changing climate, anticipation is crucial to protect biodiversity from its potential impacts. For instance, being able to accurately predict changes in species distribution (61). Being able to get the closest predictions to actual responses can give an enormous advantage and allow conservation efforts to be the most efficient (62). As mentioned in previous examples, long-time monitoring of a population can reveal subtle alterations potentially correlated to climate, but those types of data are hard to collect and require a huge temporal and spatial scale to be truly informative (61). Thus, modeling has naturally become a useful, if not necessary, tool to predict future species' distribution in a changing climate and, since temperature and precipitation can be predicted adequately (62, 63), this information can be used to try and project future species and/or population's distribution (62, 63). However, the sole use of climate envelope models to predict distributions has been criticized (64) and does not seem to give out accurate enough results (61, 64). But concretely, what is currently lacking from our predictive tools, and what additional information could be added to obtain better outcomes?

Biotic contribution

Currently, the most used models try to predict the effects of the recent warming on a single species or a single population's distribution and are using data from what is called a Simple Climate Envelope Model which "*uses statistical relationships between current climate variables and geographic patterns of species distribution and abundance to define environmental space*" [4] and thus gives out a distribution range uniquely determined by abiotic conditions (63). However, it is now evident that a given population's or species' distribution is not solely determined by its temperature tolerance but by a combination of many factors, both biotic and abiotic (65, 66). Unfortunately, by being limited to that information, the whole contribution of biotic factors in a species distribution will be missing from the projection, potentially altering the results. This gap in models can be illustrated by the sometimes huge variability occurring in the "*magnitude and/or direction of range shifts in response to recent warming*" [5] (65, 66), as an example, competition is often responsible for limited range for the weaker species (38, 67) and could also lead to lower abilities to alter its distribution in non-optimal conditions (67).

For species whose ranges are mainly determined by their biotic interspecific interaction, complexity is added through the possibility that the range shift might not match the climate change velocity which is the "*direction and speed of climate displacement across a landscape*" [6] depending on the type of interaction (65). This concept is illustrated in **Figure 9** with positive or negative interactions resulting in range shifts, but which do not always suit the direction of climate change and might result in higher extinction risks caused by the restriction in a non-tolerable habitat caused by an interaction (65). All those conclusions can even be further complicated by the potential apparition of novel communities formed by the arrival of previously non-interacting species in the same habitat or location (66).

[4] Dawson TP, Jackson ST, House JI, Prentice IC, Mace GM. Beyond Predictions: Biodiversity Conservation in a Changing Climate. Science. 2011 Apr 1;332(6025):53–8.

[5] HilleRisLambers J, Harsch MA, Ettinger AK, Ford KR, Theobald EJ. How will biotic interactions influence climate change-induced range shifts?: Biotic interactions and range shifts. Ann NY Acad Sci. 2013 Jul;n/a-n/a.

[6] Idem.

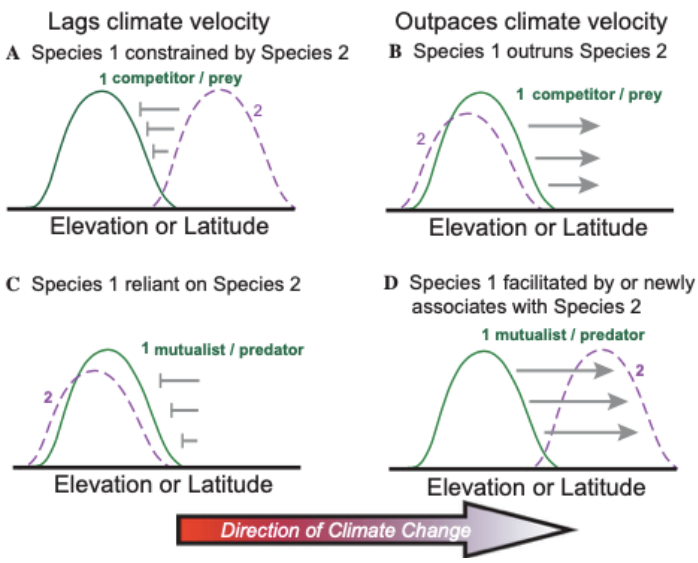

Figure 9 : Different scenarios of mismatch between the direction and/or velocity of climate change and the distribution shift of species.
(HilleRisLambers et al., 2013)

Understanding vulnerability to improve conservation

Criticized for their use in species distribution prediction despite lacking the inclusion of biotic data, they also have been questioned; Dawson et al. (2011) consider that the current climate envelope models are useful to assess the exposure to climate change since they show how conditions will change in the habitats of species, but exposure is only one part of what constitutes vulnerability (63) and being able to take every component into account could be valuable for conservation effort (68). Indeed, vulnerability which has been defined as "*susceptibility of a system to a negative impact*" [7] is composed of different factors such as exposure and sensitivity (68). As we have seen, climate envelope models can help determine the amplitude of the exposure factor but the sensitivity one is related to intrinsic species resilience and adaptive capacity (68). To limit or reduce the exposure factor, global warming would need to be halted or slowed, by a drastic reduction of greenhouse gas emissions (68). On the contrary, the part of vulnerability that is harder to know is the sensitivity factor that is also being affected by pressures other than climate change (68). Interestingly, it is the part that can be improved by conservation effort, for example by implementing regulations that protect species from land-use change or predation by mammals. By understanding what factors determine a species' vulnerability, we could prioritize the species whose adaptative capacities and resilience are the lowest or hardest to improve with current conservation efforts and anticipate how exposure might affect them even more (68).

Biological mechanisms and knowledge gap

According to Urban et al. (2016), six biological mechanisms are key to understanding a species' reaction to climate change and need to be better understood and most importantly included in models to get more realistic predictions (62) and are as follows: "*Physiology; demography, life history, and phenology; species interactions, evolutionary potential, and population differentiation; dispersal, colonization and range dynamics; responses to environmental variation*" [8]. As seen in Part II, some of these mechanisms were already showing traces of modifications due to global warming and, since they are affected by climate change, would be useful if implemented in models to get more accurate outcomes (62).

[7] Williams SE, Shoo LP, Isaac JL, Hoffmann AA, Langham G. Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. PLOS Biology. 2008 Dec 23;6(12):e325.
[8] Urban MC, Bocedi G, Hendry AP, Mihoub JB, Pe'er G, Singer A, et al. Improving the forecast for biodiversity under climate change. Science. 2016 Sep 9;353(6304):1113-+.

However, as important as those mechanisms are, a great knowledge gap exists, preventing the optimization of models (62, 65). Indeed, it can be hard to collect data on those biological mechanisms even for one species thus the collection of data for entire ecosystems seems impossible (62). Reporting extinctions due to climate change is not enough and the actual causes of the extinction and other impacts on living species need to be at least partially understood to formulate efficient strategies and conservation efforts in the future (4, 62, 65). As seen throughout the examples, the only long-term record of a population in New Zealand is the rockhopper penguin which has been monitored since 1945 (48, 50) and allowed some long-term analysis but their case is an exception, and it makes it hard to show that the observable warming has truly affected New Zealand biotas and in which proportion (53). Another level of knowledge gap resides in the interrogation regarding future climate in general (13) for instance the interaction of new conditions and existing "*natural climate patterns*"[9] such as El Niño which are greatly influencing New Zealand's climate (13) or how much conditions will likely change depending on the RCP followed as mentioned in the introduction. This incomplete understanding of the concrete factors affecting a given species' distribution or abundance might lead to misinterpretation and erroneous actions which do not really help biodiversity (71).

Conservation in New Zealand

International agreements and the Department of Conservation

The national Department of Conservation, abbreviated DOC is the governmental agency responsible for the biodiversity management of over a third of New Zealand land areas (69) and regarding global warming is responsible for "*both managing and facilitating the responses to climate change impacts on biodiversity in the country*" [10]. The main challenge regarding fight against climate change is that its effects are complex to predict precisely, making the formulation of efficient and robust conservation practices and frameworks complicated (70). By being a signatory to many international agreements such as the Convention on Biological Diversity (CBD), the Ramsar Convention, the United Nations Framework Convention on Climate Change(UNFCCC) or the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), New Zealand is mandated to act and put out projects to protect the environment, the biodiversity, and the atmosphere (71). For example, the country is aiming to reduce its greenhouse gases emissions to 30% below their 2005 level by 2030 (72). However, even with a drastic drop in global emissions, some effects of global warming are going to be affecting the planet for at least a few decades, making the adaptation to a warmer climate necessary no matter the emissions level (19).

Conservation and global warming

Seeing how global warming is likely to impact the native terrestrial wildlife of New Zealand, many challenges are present and could impair the conservation effort. Prioritizing certain issues seems necessary to tackle the problem and fighting against major ongoing threats might give native species the most resilience and capacity to adapt in face of a changing climate. Indeed, while it is sometimes demanding to find a tight correlation between population decline and climate change (4), some other already mentioned human activities are clearly and tremendously affecting New Zealand's terrestrial biodiversity and might become even more severe with global warming. Overall, the best bet seems to be *"to maintain and enhance ecosystem resilience, and to conserve biodiversity and ecosystem services"* [11], considering what has been discussed regarding vulnerability.

[9] Royal Society of New Zealand (2016). Climate change implications for New Zealand.
[10] Christie J. Adapting to a changing climate A proposed framework for the conservation of terrestrial native biodiversity in New Zealand. 2014.
[11] Idem

Since resources are limited and choices must be made, the DOC decided to prioritize the research that can bring positive outcomes at greater scales than a single ecosystem, population, or species (27). Additionally, one goal of the DOC for the years to come is to make sure that climate change is considered in almost all other conservation discussion (27) by integrating and including the predicted or expected impacts from a changing climate into current programs (73).

Ambitious projects

With the intent to relieve native terrestrial species from ongoing pressure which would be even more deleterious in a warming climate, some ambitious programs have been launched by the DOC in the past decades and are targeting the most harmful threats to endemic biodiversity. While the next few examples represent some popular and ambitious programs they are only a tiny portion of the nationwide actions being taken to improve the conditions of endemic species whether they are marine, terrestrial, animal or vegetal. Some single species programs have already been showing great results such as the "Kakapo recovery"(74) which helped this vulnerable bird population go from 51 individuals in 1995 to more than 150 currently (75).

One example is the program named "Predator Free 2050" or PF2050, first announced in 2016 (76). As stated in this work, introduced mammalian species are probably the most impacting threats to terrestrial endemic species, especially the avifauna (22, 75). For a few decades, many eradication campaigns have been launched with some success, but this project is much more important both in the time and spatial scales but also in the budget allocated to the actions (76). Focusing on key species which are stoats, ferrets, weasels as well as possums and rats (22, 76), the program aims in the long-term to rid the entire country of those critically impacting species (76). The magnitude of this project, and thus its importance for the New-Zealand government can be seen in the substantial amount of money invested which is estimated at $300 million since 2016 (76). The nearest short-term goal is an increment of "*1 million hectares for the area of New Zealand mainland where predators are suppressed*" [12]. Many other goals are to be achieved in the ultimate hope that predators will not be controlled anymore but eradicated from New Zealand, or at least a significant portion of the mainland and offshore islands (76). Since 2016, improvements in some populations of birds such as kea, kaka, and kakariki have been reported, namely in the Perth River valley (77). This great-scale intervention should allow at least the 150 prioritized bird species to thrive and have better resilience against future conditions (75).

Another example, which is part of PF2050, is the "Battle for our Birds" strategy, which has been thought to relieve birds from the increased predator pressure that follows mast-seeding years in beech forests (75, 78). While being under pressure all year round, the outbursts of some mammals following these episodes can be particularly harmful to native birds (75). By using pest control means such as the mammals targeting poison named 1080 (79) and trapping, the goal is to increase pest control periodically (75). Indeed, if timed correctly in the predator plague cycle seen before, namely before the phase where those mammals start to prey intensively on birds, the impacts on birds can be reduced immensely (27).

Even more nationwide projects are currently in action and will hopefully help maintain or improve the threat level on the terrestrial species and allow them to thrive in their natural habitats and have the best chances to survive future challenges.

[12] New Zealand, Department of Conservation. Predator free 2050 5-year progress report. [Internet]. 2021 [cited 2022 Mar 1].

IV. CONCLUSION

All along this monograph, the complexity of the question "*How is climate change going to affect biodiversity ?*" has been illustrated in several different aspects. Arising from knowledge gaps, suboptimal predictive tools, or the unprecedented nature of the problem, these uncertainties certainly complexify this interrogation, and most importantly our ability to reach the ambitious goal of preserving as much of this incredible diversity as possible. Although it does seem impossible to get the full grasp of the potential repercussion and how they could affect each ecosystem and community, many pathways are currently being explored and discussed to get us as close to this objective as possible.

Nonetheless, the fraction of biodiversity mentioned in this work represents a minuscule portion of the global biodiversity, and even of the biodiversity from New Zealand itself. Indeed, some aspects were purposefully not tackled for a practical purpose but are also heavily investigated by national conservation agencies and the source of many concerns for the future. For instance, the marine and freshwater native species or the extremely rich invertebrate fauna which was only glossed over, are numerous and need protection from future conditions, such as the progressive acidification of the ocean, pollution, or even the extreme weather which will make drought much more frequent than they currently are. Being able to understand the dynamics of these ecosystems is just as important as land biomes and further research and efficient conservation programs need to be applied as well.

Additionally, other implications of climate change are of interest and are frequently discussed by the New Zealand government, such as the impacts made on ecosystem from services, tourism, and human life in general, especially in the critical coastal zone where the effects of global warming could be the harshest on both biodiversity and human populations. Those topics usually dominates the discussion on climate change and result in many frameworks, projects, and guidelines to protect both the nature and the people. Altogether, the future of Aotearoa's biodiversity has some hope of being as complex and rich as it is today, but this result will depend on today's action. As an Island, New Zealand will be facing the consequences of global warming in an unique way and by tackling current issues regarding biodiversity the country might be able to provide the best adaptation and resilience to those species. From reading many guidelines and yearly reports published by the Ministry for the Environment, I do think that climate change is a topic that is being taken seriously and worked on in New Zealand and that, by following and honoring the many frameworks and convention goals, future generations should possess good tools to work with and continue protecting its unique and precious native fauna and flora.

This being said, and as it has been repeated over and over by climate scientist, ecologist and conservation agencies, we must act now and reduce drastically the global GHG emissions if we want to follow the goals decided in the Paris Agreement and hopefully stay under the 1.5°C warming point. This threshold has indeed been shown to be a critical tipping point and only under these circumstances can we hope to conserve our current suitable conditions and adapt to our new climate. I am convinced that a positive foreseeable future can only be obtained by our generation taking responsibility for the anthropogenic climate change and willingly working towards a safer world for our ecosystems.

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ILLUSTRATIONS

Figure 1 : NIWA (data source), obtained from (13) Ministry for the Environment & Stats NZ (2020a). New Zealand's Environmental Reporting Series: Our atmosphere and climate 2020. Available from www.mfe.govt.nz and www.stats.govt.nz.

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