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RESEARCH

Vulnerability of bats to climate change and the potential consequences for their populations in Aotearoa New Zealand

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Abstract: Globally, rapid human-caused climate change is posing one of the greatest emerging pressures on species and ecosystems**.** Uncertainty remains about how species will react to changing climate, particularly how vulnerable or adaptable and resilient they will be to changes and whether they can move to remaining favourable habitats. Here we report on a rapid trait-based climate change vulnerability assessment for all bat taxa resident in Aotearoa New Zealand. We use 16 traits across three dimensions (sensitivity, low adaptive capacity, exposure) that could make bats highly vulnerable to climate change, review the potential consequences on their long-term population viability and recommend research required to understand vulnerability and potential adaptive management requirements. We assessed all five known endemic bat taxa under two greenhouse gas concentration scenarios (representative concentration pathways: RCP4.5, RCP8.5) for two future time periods (2040, 2090). One taxon (the greater short-tailed bat *Mystacina robusta*) was categorised as Highly Vulnerable by 2040 under RCP4.5, and the other four taxa demonstrated Latent Risk profiles, indicating they should be monitored closely to determine whether their potential responses to projected climate change happen earlier than 2090. All taxa were categorised as Highly Vulnerable by 2090 under the high emission RCP8.5 scenario. Although no overall conclusion can be reached about whether climate change will have positive, negative or mixed consequences for bats, the likely negative consequences include increased risk of predation, reduced availability and quality of roosting and foraging habitats, and increased thermal stress. Future research should focus on understanding the costs and benefits of changing climate on productivity and survival of bats and determining if management responses are desirable and feasible.

Keywords: *Mystacina*, *Chalinolobus*, long-tailed bat, lesser short-tailed bat, climate change vulnerability assessment, representative concentration pathways, RCP4.5, RCP8.5

Introduction

The Earth is facing a period of unprecedented rapid human-caused environmental change, with climate change posing one of the greatest emerging pressures on species and ecosystems (Zalasiewicz et al. 2008; Intergovernmental Panel on Climate Change (IPCC) 2022; Clarke et al. 2022). There is strong evidence of the consequences of climate change on the environment (IPCC 2022) and the potential impacts of these changes on species distributions and population viability (Parmesan 2006; Bellard et al. 2012). However, while range shifts and lower survival in some species have already been observed or seem probable in the future, it remains uncertain how vulnerable many species are to these changes. Questions remain about how species react to changing climate, how adaptable or resilient they are to these changes, and whether there is intraspecific variation in the responses to changes and the capacity of species to move to remaining favourable habitats (Moritz & Agudo 2013; Garnett & Franklin 2014; Steen et al. 2017; Beaumont et al. 2019; Buchholz et al. 2019).

In conservation science, climate change vulnerability is generally defined following the IPCC Fourth Assessment Report (2007) as the extent to which a species is susceptible to or unable to cope with the adverse effects of climate change. It is a function of the character, magnitude, and rate of climate change to which a species and its habitat is exposed, a species' sensitivity, and its adaptive capacity (IPCC 2007). IPCC's vulnerability definition has since been updated (IPCC 2013), but the 2007 definition is still most used in conservation, for example, in the Red List assessments by the International Union for Conservation of Nature (IUCN) (Foden & Young 2016). Internationally, there has been a proliferation of climate change vulnerability assessments (CCVAs) in the last decade (Foden et al. 2019). Climate change vulnerability assessments provide a relative rank of vulnerability to climate change, as well as information about why a species may or may not be vulnerable (Williams et al. 2008; Glick et al. 2011; Pacifici et al. 2015; Foden et al. 2019). There are different approaches

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to CCVAs, the chosen method depending on the purpose of the assessment, and resource and data availability. The most used approach in conservation management is the trait-based CCVA, which is the least data and resource intensive CCVA method, allowing for a relatively rapid assessment process (Foden & Young 2016). Trait-based CCVAs use species' biological and ecological characteristics (traits) to estimate their sensitivity to climate change and their potential capacity to adapt to changes, and they often include assessment of direct projected exposure to different climate change variables. Trait-based approaches have been used globally to assess a wide range of taxonomic groups in different environments. For example, plants (Potter et al. 2017; Molano-Flores et al. 2019), herpetofauna (Harper et al. 2022; Vaz-Canosa et al. 2022; Zhao et al. 2022), birds (Foden et al. 2013; Carr et al. 2014), marine mammals (Albouy et al. 2020) and marine fish and invertebrates (Bueno-Pardo et al. 2021).

In Aotearoa New Zealand, climate change has been identified as a major threat in marine, freshwater, and terrestrial ecosystems and species (Department of Conservation 2020; Macinnis-Ng et al. 2021; Keegan et al. 2022). However, there have been few published quantified assessments of the potential effects of climate change in whole species groups in Aotearoa New Zealand. Examples include Egan et al. (2020) who published detailed trait-based vulnerability assessments for selected taonga (treasures of Aotearoa New Zealand's Māori people) freshwater fish, Roberts and Hendriks (2022) who undertook a first-pass climate change risk assessment of marine mammals, Jarvie et al. (2022) who developed distribution models that predicted significant reductions in range for most assessed lizard species, and Germano et al. (2023) who assessed future habitat suitability for Aotearoa New Zealand's three native frog species (*Leiopelma*). Foden et al. (2013) included Aotearoa New Zealand species in their global assessment of climate change vulnerability of all birds, amphibians, and corals. However, no assessments of the vulnerability of Aotearoa New Zealand's five endemic bat taxa have been undertaken until the authors participated in the development of the first large-scale CCVA for terrestrial taxa in Aotearoa New Zealand (Brumby et al. 2025). While these bat species face numerous contemporary threats, particularly reflecting habitat loss and the impacts of invasive pests, climate change is likely to exacerbate many of these pressures in the future (Christie 2014; O'Donnell et al. 2023).

Bats, the second-most species-rich group of mammals globally (after rodents), have been identified as a group likely to be affected by climate change in many ways, some positive or neutral, and some negative (Festa et al. 2023; Kerth & Wolf 2025). Effects may be direct (e.g. influencing physiology) or could impact bats indirectly by influencing resource availability, habitat, or interactions with other organisms. Positive effects might include range expansion, population increase, faster juvenile development, and increased food availability if conditions improve for species. Potential negative effects include range contraction, disruption of hibernation, spread of disease, and reduced water availability, all influencing survival (Adams 2010; Rebelo et al. 2010; Ancillotto et al. 2021; Festa et al. 2023). The indirect effects of climate change on bats may be cryptic and could reflect subtle interactions that influence survival and productivity (Burles et al. 2009; Mundinger et al. 2022; Power et al. 2023).

Brumby et al. (2025) noted that the next step following their initial CCVA of a wide range of threatened taxa in Aotearoa New Zealand was to use their rich dataset to determine what, if any, additional conservation management can be implemented in the future to assist taxa in adapting to the increased pressures of climate change, and what research is needed to support the development of these strategies. This study uses data collected by Brumby et al. (2025) to (1) assess the relative vulnerability of bat taxa in Aotearoa New Zealand in future climate change scenarios in detail, (2) predict the potential consequences of such vulnerabilities based on evidence found in the international literature on bats and climate change, as well as drawing inferences from published evidence in other animal groups, and (3) identify further research required to understand potential consequences, and the need for monitoring and/or climate change adaptation strategies, on bats in the future.

Methods

Scope

We assessed climate change vulnerability for all five endemic bat taxa breeding in Aotearoa New Zealand (Table 1) excluding the record of vagrant little red flying foxes (*Pteropus scapulatus*; Daniel 1975) and bats that have been intercepted at or near the border (e.g. O'Donnell 1998).

Assessing vulnerability

We used a rapid, trait-based CCVA method developed for terrestrial taxa in Aotearoa New Zealand (Brumby et al. 2025), which follows the framework of Foden et al. (2013). The potential vulnerability of each bat taxon to climate change was assessed in three dimensions (sensitivity, low adaptive capacity, exposure) comprising 16 traits in total (Table 2; Appendix S1 in Supplementary Material).

Sensitivity (7 traits)

These traits signal the lack of potential for a taxon to persist in situ because of inherent vulnerability of the species (e.g. an extremely small population size) or lack of flexibility to respond to changing climate due to specific physiological or behavioural requirements or dependencies that would make them intolerant of climate change. The broader the habitat and environmental requirements and physiological and behavioural tolerances, the greater the potential for flexible responses to climate change. In bats, sensitivity dimensions consider factors such as their ability to cope with thermal variability (McNab & O'Donnell 2018), to adapt through phenotypic plasticity (Charmantier et al. 2008), or their dependence on a specific food source that may be vulnerable to climate change (e.g. apparent co-dependence between the parasitic plant *Dactylanthus* and some populations of central lesser short-tailed bats, which feed on the pollen and nectar; Czenze & Thurley 2021).

Exposure (5 traits)

The extent to which each taxon's physical environment is exposed to climate change. These traits describe the magnitude of climatic and associated environmental changes experienced by a taxon across its range, and therefore, how much of the population would be vulnerable (Dawson et al. 2011; Foden et al. 2013; Stein et al. 2014).

Low adaptive capacity (4 traits)

A taxon's inability to avoid, or adjust to, the negative impacts of climate change through dispersal and/or micro-evolutionary change.

Table 1. Bat taxa in Aotearoa New Zealand assessed as part of this climate change vulnerability assessment (nomenclature and status follow O'Donnell et al. 2023).

Common name	Scientific name	Threat status	Distribution
Greater short-tailed bat	*Mystacina robusta*	Data Deficient (last confirmed record 1967)	Southern Tītī Islands, Stewart Island/Rakiura
Northern lesser short-tailed bat	*Mystacina tuberculata aupourica*	Nationally Vulnerable	Omahuta-Puketi forest and Little Barrier Island/Hauturu, Northland
Central lesser short-tailed bat	*Mystacina tuberculata rhyacobia*	Declining	Central North Island south to Wellington region
Southern lesser short-tailed bat	*Mystacina tuberculata tuberculata*	Nationally Increasing	Fiordland and Codfish Island/Whenua Hou
Long-tailed bat	*Chalinolobus tuberculatus*	Nationally Critical	Widespread throughout

Table 2. Summary of sensitivity, exposure, and adaptability traits and thresholds used to assess climate change vulnerability in Aotearoa New Zealand bat taxa (based on framework from Foden et al. 2013). See Appendix S1 for full descriptions of traits.

Trait	Lower vulnerability threshold	Higher vulnerability threshold	Primary data sources /evidence
A. Sensitivity traits			
1. Habitat specialisation	Taxon occurs in more than 2 major habitats	Taxon occurs in 1–2 major habitats	IUCN (2012); King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021)
2. Dependence on a particular microhabitat or single location	No microhabitat or single location dependency known for the taxon	The taxon has at least one microhabitat dependency and/or occurs in a single location	O'Donnell and Sedgeley (1999); Sedgeley and O'Donnell (1999a, 1999b, 2004); Sedgeley (2001a. 2001b, 2006)
3. Narrow temperature tolerance	Taxon with Broad or Medium temperature tolerances for all, or at critical parts, of the life cycle	Taxon with Narrow temperature tolerances for all, or at critical parts, of the life cycle	O'Donnell (2000a); Sedgeley (2001b); Czenze et al. 2017a, 2017b); McNab and O'Donnell (2018); Collier et al. (2022); Lloyd (2003a)
4. Narrow precipitation tolerance	Taxon with Broad or Medium precipitation tolerances for all, or at critical parts, of the life cycle	Taxon with Narrow precipitation tolerances for all, or at critical parts, of the life cycle	Czenze and Thurley (2021)
5. Declining positive interactions with other species	No known interactions likely to be disrupted by climate change	One or more known interspecific interactions likely to be disrupted by climate change	King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021)
6. Small population size	Taxon has > 5000 mature individuals or area of occupancy > 100 ha	Taxon has ≤5000 mature individuals or area of occupancy < 100 ha	O'Donnell et al. (2023); NZTCS https://nztcs.org.nz/
7. Small population size and heightened sensitivity to threatening processes	Taxon with large populations (> 20 000 mature individuals) and no behavioural vulnerabilities	Taxon with small populations (< 20 000 mature individuals) and has small, fragmented subpopulations or behavioural vulnerabilities (e.g. specialised breeding systems, highly skewed sex ratios, form significant seasonal congregations that are vulnerable)	O'Donnell (2000b; 2002); Lloyd (2003b); King and Lloyd (2021); Toth et al. (2015); NZTCS https://nztcs.org.nz/

Table 2. Continued.

Trait	Lower vulnerability threshold	Higher vulnerability threshold	Primary data sources /evidence
B. Exposure traits			
8. Habitat types exposed to sea level inundation and increased storm surges	Taxon does not occur largely in inundation or storm-surge exposed coastal habitats	Taxon occurs largely in inundation or storm-surge exposed coastal habitats	Bell et al. 2016; King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021); Department of Conservation (DOC) National Database for bat records; National Institute of Water and Atmospheric Research (NIWA) Climate projections[1]
9. Extent of species range exposed to changes in temperature	No substantial changes (> 2.5°C) in mean temperature projected across > 75% of taxon's range	Substantial changes (> 2.5°C) in mean temperature projected across > 75% of taxon's range	King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021); DOC National Database for bat records; NIWA Climate projections[1]
10. Extent of species range exposed to temperature extremes	No substantial projected increases in frequency, duration, and intensity of temperature extremes (cold or hot) across > 75% of the taxon's range during one or more critical season in the taxon's life cycle	Substantial projected increases in frequency, duration, and intensity of temperature extremes (cold or hot) across > 75% of the taxon's range during one or more critical season in the taxon's life cycle	King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021); DOC National Database for bat records; NIWA Climate projections[1]
11. Extent of species range exposed to changes in precipitation	No substantial changes (±15%) in annual mean rain or snowfall projected across > 75% of taxon's range	Substantial changes (±15%) in annual mean rain or snowfall projected across >75% of taxon's range	King and Lloyd (2021); O'Donnell and Borkin (2021); O'Donnell et al. (1999); Parsons and Toth (2021); DOC National Database for bat records; NIWA Climate projections[1]
12. Extent of species range exposed to precipitation extremes	No substantial changes in projected precipitation extremes across > 75% of taxon's range during one or more critical season in the taxon's life cycle	Substantial increases in projected precipitation extremes across > 75% of taxon's range during one or more critical season in the taxon's life cycle	King and Lloyd (2021); O'Donnell and Borkin (2021); Parsons and Toth (2021); DOC National Database for bat records; NIWA Climate projections[1]
C. Low adaptive capacity traits			
13. Limitations to dispersal	No known limitations to dispersal in a taxon	Significant limitations to dispersal in a taxon	O'Donnell (2001); Griffiths (2007); Christie and O'Donnell (2015); Davidson-Watts Ecology (Pacific) Ltd (2019); Author's unpubl. data
14. Low genetic diversity	No evidence of low genetic diversity or known genetic bottleneck in the taxon	Evidence of low genetic diversity or known genetic bottleneck in the taxon	Lloyd (2003a; 2003b); O'Donnell et al. (2016); Dool et al. (2016)
15. Slow turnover of generations	Rapid maturation rate in a taxon or generation length < 6 years	Slow maturation rate in a taxon or generation length ≥ 6 years	O'Donnell et al. (2010); Colchero et al. (2019)
16. Low reproductive capacity	High numbers of young produced or high number of breeding events per season	Low numbers of young produced or low number of breeding events per season	O'Donnell (2002); King and Lloyd (2021); Parsons and Toth (2021)

[1]National Institute of Water and Atmospheric Research (NIWA) temperature and precipitation projections for two greenhouse gas concentration scenarios (RCP 4.5 and 8.5) for two time periods (2040 and 2090) (https://ofcnz.niwa.co.nz/#/nationalMaps) with regional summaries lodged internally in Department of Conservation (http://intranet/natural-heritage/threats-to-biodiversity/climate-change/regional-projections/).

Scoring vulnerability traits

Each taxon was assessed for 16 traits against pre-defined descriptions of the traits and thresholds using a combination of quantitative data and interpretation of the available literature by expert bat researchers. Data were transformed in the analysis to categorise each trait as 'higher vulnerability', 'lower vulnerability', or 'unknown vulnerability' (Table 2; Appendix 1). In addition, experts recorded the data quality for each trait by using information adequacy categories Unknown, Low, Medium or High. Each information adequacy category was assigned with a score from 0 (Unknown) to 3 (High) to create an overall confidence score for each taxon. The maximum overall confidence score was = 48 (16 traits × 3; 3 = max. score).

Climate scenarios

To assess taxon's direct exposure to significant changes in climate, we used the climate change projections based on the IPCC atmospheric greenhouse gas concentration scenarios, known as representative concentration pathways (RCPs; IPCC 2013). The projections are from six global climate models downscaled to a 5 km resolution and then averaged for Aotearoa New Zealand, with projections relative to a 1986–2005 baseline (Ministry for the Environment 2018; https://ofcnz.niwa.co.nz/#/nationalMaps). We also used factsheets developed by National Institute of Water and Atmospheric Research that provided regional summaries of projections (procured by the Department of Conservation). To provide a plausible range for the assessment, exposure to climate change was assessed for two scenarios for two time periods: (1) 2040 (mid-century): RCP4.5 (mid-range emissions), (2) 2090 (late century): RCP4.5, (3) 2040: RCP8.5 (high-end emissions), and (4) 2090: RCP8.5.

The main features of the climate projections include progressive warming in average air temperature, with warming greatest under the RCP8.5 scenario by the end of the century. More extremes, at higher altitudes and lower latitudes and from summer to autumn are also projected (Ministry for the Environment 2018). Temperature extremes are projected to increase, with 30–50% decreases in number of frost days, paralleled by increases in hot days (> 25°C). Similarly, mean precipitation will vary, with marked increases in some parts of the country (e.g. west and south of Aotearoa New Zealand), and reductions in others (e.g. more dry days throughout North Island, and in inland South Island). Seasonal extremes are also a feature of the projections and overall, snowfall is predicted to decrease considerably. Sea temperatures will also increase in parallel.

Analysis of vulnerability

A taxon that recorded higher vulnerability under any trait within a dimension triggered a score of Highly Vulnerable for the dimension to which it belonged (e.g. a taxon with at least one higher vulnerability score under habitat specialisation was then considered to be Highly Vulnerable under the sensitivity dimension). To qualify as Highly Vulnerable to climate change overall, a taxon required Highly Vulnerable scores for all three dimensions. Foden et al. (2013) further classified vulnerable species as being Potential Adapters if they were exposed and sensitive but did not have low adaptive capacity; as being Potential Persisters if they were exposed and had low adaptive capacity but were not sensitive; and as Latent Risk if they were sensitive and had low adaptive capacity but were currently not predicted to be exposed to significant climate change. Foden et al. (2013) highlighted an important caveat that, due to the scarcity of direct evidence to support trait scoring thresholds, climate change vulnerability scores must be interpreted as relative measures.

Following the Foden et al. (2013) method, analyses were run for pessimistic and optimistic vulnerability to climate change scenarios to deal with 'unknown vulnerability' scores. For the pessimistic analysis, all unknown scores were replaced with higher vulnerability scores, whereas, for the optimistic scenario, all unknown scores were replaced with lower vulnerability scores.

Results

Vulnerability of bats in Aotearoa New Zealand

Sensitivity of bat taxa largely reflected their occupancy of a limited number of habitat types (forest interior specialisation) and their communal behaviours where they depend on specific trees with specialised characteristics and microhabitats for roosting and breeding (sensitivity traits 1 & 2, Table 3). While only the northern lesser short-tailed bat triggered sensitivity because of its small population (trait 6), which is thought to be < 5000 mature individuals, the other taxa triggered sensitivity trait 7 (small populations < 20 000 mature individuals with heightened sensitivity to threatening processes) because large proportions of, or all individuals, in their populations are communal breeders dependent of the sustainability and longevity of their roost trees, which in turn are vulnerable to climate change (e.g. because of predicted increases in storm events that may cause windthrow and erosion in forests putting specialised tree roosts at risk). Otherwise, bats in Aotearoa New Zealand likely have relatively broad temperature and precipitation tolerances. Until recently, both long-tailed and short-tailed bats were abundant and distributed continuously from the northern North Island to southern Stewart Island/Rakiura where they were likely to experience a wide range of environmental conditions (O'Donnell 2000a; Lloyd 2001; Lloyd 2003a).

The relatively broad distributions of bat taxa in Aotearoa New Zealand mean that based on the climate change projections utilised in this study, they are unlikely to be exposed to average temperature increases of > 2.5°C across > 75% of their ranges until 2090 (Table 3). The taxa with the widest distributions, the long-tailed bat and the central lesser short-tailed bat, had parts of their ranges (potential refugia) in the central North Island highlands and lower South Island highlands registering lower exposure to temperature and precipitation extremes. When considering increases in temperature extremes, northern lesser short-tailed bats, which only occur in two locations in Northland, are likely to experience marked increases in hot days per year and substantial changes in evapotranspiration deficit by 2090 under the mid-range emission scenario RCP4.5 (Table 3). Only greater short-tailed bats, if still extant on southern Stewart Island/Rakiura, are less likely to experience temperature extremes by 2090 under RCP8.5. Greater than 75% of the ranges of all taxa are less likely to be exposed to substantial changes in precipitation for any scenario, except the southern lesser short-tailed bat, with most of its current range in Fiordland. We scored all taxa as likely to experience substantial changes in precipitation extremes (expressed in the projections as intensity of 1-in-50-year storms and and increases in the number of heavy rain (> 25 mm) days) by 2090 under RCP8.5.

Table 3. Climate change vulnerability scores (higher vulnerability H, lower vulnerability L, unknown vulnerability U) for five indigenous bat taxa in Aotearoa New Zealand for 16 climate change vulnerability traits (see Table 2 for definitions).

Trait	RCP (years)	Greater short-tailed bat	Northern lesser short-tailed bat	Central lesser short-tailed bat	Southern lesser short-tailed bat	Long-tailed bat
A. Sensitivity traits						
1. Habitat specialisation		H	H	H	H	L
2. Dependence on microhabitat or location		U	H	H	H	H
3. Narrow temperature tolerance		L	L	L	L	L
4. Narrow precipitation tolerance		L	L	L	L	L
5. Interactions with other species		U	L	L	L	L
6. Small population size		U	H	L	H	L
7. Sensitivity to threatening processes		H	H	H	H	L
B. Exposure traits						
8. Exposed to sea level inundation/storm surges		H	L	L	L	L
9. Range exposed to changes in temperature	4.5 2040/2090	L/L	L/H	L/L	L/L	L/L
	8.5 2040/2090	L/H	L/H	L/H	L/H	L/H
10. Range exposed to temperature extremes	4.5 2040/2090	L/L	L/L	L/L	L/L	L/L
	8.5 2040/2090	L/L	L/H	L/H	L/H	L/H
11. Range exposed to changes in precipitation	4.5 2040/2090	L/L	L/L	L/L	L/H	L/L
	8.5 2040/2090	L/L	L/L	L/L	L/H	L/L
12. Range exposed to precipitation extremes	4.5 2040/2090	L/L	L/L	L/L	L/L	L/L
	8.5 2040/2090	L/H	L/H	L/H	L/H	L/H
C. Low adaptive capacity traits						
13. Limitations to dispersal		U	L	L	L	L
14. Low genetic diversity		H	L	L	L	L
15. Slow turnover of generations		U	H	H	H	H
16. Low reproductive capacity		U	H	H	H	H

Table 4. Overall climate change vulnerability of indigenous breeding bats in Aotearoa New Zealand under RCP4.5 and RCP8.5 mid- (2040) and late- (2090) century scenarios. Results were the same for both optimistic and pessimistic scenarios, where unknown vulnerability scores were transformed to lower vulnerability or higher vulnerability scores respectively. The higher the confidence score, the better data there were for the taxon, and therefore more certainty in the results.

Common name	RCP4.5 Mid-century	RCP4.5 Late-century	RCP8.5 Mid-century	RCP8.5 Late-century	No. 'unknown' scores	Confidence score (max. 48)
Greater short-tailed bat	Highly Vulnerable	Highly Vulnerable	Highly Vulnerable	Highly Vulnerable	8	24
Southern lesser short-tailed bat	Latent Risk	Highly Vulnerable	Latent Risk	Highly Vulnerable	0	41
Northern lesser short-tailed bat	Latent Risk	Highly Vulnerable	Latent Risk	Highly Vulnerable	0	39
Central lesser short-tailed bat	Latent Risk	Latent Risk	Latent Risk	Highly Vulnerable	0	43
Long-tailed bat	Latent Risk	Latent Risk	Latent Risk	Highly Vulnerable	0	42

All extant bat taxa are capable of strong flight, even across open habitats (Table 2), so dispersal is unlikely to be a limiting factor. Nightly movements can be > 50 km, with straight line distances of up to 25 km between roosting and feeding areas being recorded (Trait 13, Table 2). Similarly, extant taxa have relatively high measured genetic diversity. However, because all extant taxa have long generation times and produce single young each year, they scored higher vulnerability for adaptive capacity for these traits (Tables 2 & 3).

The greater short-tailed bat scored as Highly Vulnerable for all scenarios but also had the highest number of unknown vulnerability scores and thus low certainty compared to other taxa (Table 4). The major difference between greater short-tailed bats and other taxa was that they inhabited sea caves in their last known habitats on the Tītī Islands off southern Stewart Island/Rakiura, which would potentially be exposed to sea level inundation and increased storm surges under all scenarios. Overall, bat taxa were either classed as Latent Risk or Highly Vulnerable to climate change for the RCP4.5 and RCP8.5 scenarios for mid- and late century and there were no differences in the overall numbers of Highly Vulnerable species between the optimistic and pessimistic scenarios (Table 4).

Discussion

This CCVA was based on relatively good, published data on the traits related to sensitivity and adaptive capacity that will likely influence the vulnerability of bats to climate change in Aotearoa New Zealand. However, assessing exposure to temperature and precipitation extremes, which arguably may influence bats significantly, was challenging because of the uncertainty about how to qualitatively define substantial changes, and how increasing frequencies of extremes will ultimately manifest themselves across the complex distributional ranges of the bat taxa assessed. Thus, we may have underestimated their potential impacts on bat populations. Despite this limitation, we are confident that the results are useful as a first step towards prioritising further work on taxa that are likely to be most vulnerable to climate change.

Our review of the potential vulnerability of bats in Aotearoa New Zealand to climate change yielded a wide range of potential negative consequences for their long-term population viability, which were related to warming temperatures, increased intensity and frequency of rainfall, reduced snowfall, increasing storm frequency and interactions among these factors (Table 5). Bats in general have biological and ecological traits that may make them sensitive to climate change. Temperate zone bats such as those in Aotearoa New Zealand will likely be vulnerable because many aspects of their ecology, such as use of torpor and reproduction, are linked to variations in environmental cues such as temperature (Sherwin et al. 2012; Czenze et al. 2017a). The use of torpor affords some behavioural flexibility in relation to changes in temperature. For example, early parturition can occur following warm springs, while parturition can be delayed following colder spring and summer temperatures, with subsequent consequences for growth and survival of offspring (Ransome & McOwatt 1994; Sherwin et al. 2012; Mundinger et al. 2022). However, there was no overall conclusion from our literature review about whether climate change will be positive, negative or have neutral consequences for bats globally once temperature extremes are reached, and consequences are likely to be age, sex, species, habitat and range specific (Sherwin et al. 2012; Smeraldo et al. 2021; Stapelfeldt et al. 2022). Festa et al. (2023) found evidence for potential positive effects such as range expansion, population increase, faster juvenile development, and increased food availability but juxtaposed to these, was evidence for the opposite scenarios, with the addition of disruption of hibernation in temperate bats, increased stress related to water deficits and spread of disease (Table 5).

Bats in general are vulnerable to environmental change because of their long lifespans, slow development, and slow reproductive rates (Barclay & Harder 2003), and bats in Aotearoa New Zealand are no exception, producing one offspring per year and having long-generation times and life spans (> 12 and > 25 years respectively, O'Donnell et al. 2010; Colchero et al. 2019). Long-lived species usually have stable adult survival rates with low mortality, but severe impacts on bat survival have been linked to extreme weather events (Table 5; Fleischer et al. 2017; Reusch et al. 2019). Furthermore, the rate of evolutionary adaptation through genetic variation and selection in such k-selected species may lag the rapid pace of environmental change, leaving them further vulnerable to decline and extinction (Hoffman & Sgro 2011).

Bats are more susceptible to water loss through cutaneous

Table 5. Predicted negative impacts of climate change hazards on productivity, survival, and resilience of bat populations in Aotearoa New Zealand. Climate change hazard categories used here are based on Table C4-1 in Ministry for the Environment (2019).

Climate change hazard category	Impact on bats	Mechanism
Warming temperatures[1]	Physiological stress Habitat fragmentation and changes in habitat distribution Habitat loss Reduction in food quantity and availability Increased predation rates Increased infection rates from pathogens	Seasonal overheating, dehydration or increased water deficit in adults and/or young in their roosting habitats Reductions in habitat suitability (e.g. edge effects, food supplies); increased energetic costs of searching for suitable habitats for roosting, feeding and movements Loss of suitable habitat for roosting, feeding and/or movement through changed habitat Changes in phenology of food supplies (fruiting/flowering/invertebrate populations) or reductions or changed distribution of food supplies Increased frequency and magnitude of predator irruptions resulting from increases in predator food supplies and overwinter survival Increased habitat suitability, or rates of arrival, of harmful diseases and pathogens Increased infection rates
Rainfall and hail[2]	Reductions in aquatic invertebrate food availability Reduction in number of summer feeding nights and food supplies Reductions in roost site quality and availability	Increases in frequency, depth, duration and changed seasonality of flooding Increased frequency of rain nights Increased erosion and storm damage to specialised roost sites
Dryness and drought[3]	Habitat loss Reduction in food quantity and availability	Loss of suitable habitat for roosting, feeding and/or movement through changed habitat (e.g. through increased frequency and intensity of wildfires or increased stress of tree species) Reductions or changed distribution of food supplies resulting from increased drought frequency and magnitude and changes in soil moisture with substrate hardening/drying of ground
Snow and ice[4]	Complex changes in food webs and food supplies	Complex changes in food webs and food supplies; changes to timing and magnitude of downstream river flow patterns
Storminess and wind[5]	Reductions in roost site quality and availability	Increased erosion and storm damage to specialised roost sites
Coastal change: sea-level rise, waves, ocean circulation and carbon dioxide uptake[6]	Loss or displacement from sea cave roosting habitats (greater short-tailed bat)	Increased erosion and storm wash over coastal habitats

Hazard definitions (Ministry for the Environment 2019)
[1]**Warming temperatures** include changes in seasonality, fewer frost or cold days, higher day and night temperatures, more heat waves and warm spells.
[2]**Rain and hail** include changes in extreme rainfall (high intensity and persistence), changes in rainfall seasonality, floods, higher or lower mean annual rainfall and rain induced landslides.
[3]**Dryness and drought** include fire weather (harsher, prolonged season), higher drought frequency and persistence, increase in dry spells, changes in seasonality.
[4]**Snow and ice** include earlier snow melt and reduced snow and glacier cover.
[5]**Storminess and wind** include changes in extreme wind speed, mean wind speed and direction, an increase in convective weather events, increase in storminess (frequency, intensity).
[6]**Coastal change: sea-level rise, waves, ocean circulation and carbon dioxide uptake** include changes in waves and swells, coastal and cliff erosion, and more frequent coastal flooding (storm-tide, waves).

evaporation than other mammals of similar body size because of the large surface area of their uninsulated, highly vascularised wing and tail membranes (Gearhart et al. 2020), so warming temperatures facilitating increased drought frequencies and seasonal overheating may become significant issues (Table 5). During flight, evaporative water loss through wing membranes helps to dissipate the heat generated by the high metabolic rates required (Boratyński et al. 2015), and increased respiratory rates accelerate respiratory evaporation (Gearhart et al. 2020). Even at rest and during bouts of torpor, water loss tends to be higher in bats compared to non-volant mammals of a similar size because of their large surface-to-volume ratio and small body mass (Boratyński et al. 2015). In addition, the water requirements of pregnant and lactating female bats are high compared to other similar-sized mammals because bat gestation and the period of dependence of young are relatively long (Kurta & Kunz 1987; Cryan & Wolf 2003), and the warm microclimate needed to foster offspring development in maternity roosts is likely to promote faster rates of evaporative water loss (Fenton & Barclay 1980; Adams 2010).

Warming temperatures may have indirect consequences for bats in Aotearoa New Zealand (Table 5). For example, predator impacts on bats are likely to increase if the abundance of introduced mammalian predators increases because of greater food abundance, wider habitat suitability envelopes, and milder winters which increase predator survival, making predator control more challenging (Christie 2014; Walker et al. 2019). Insectivorous bats such as those in Aotearoa New Zealand that capture flying prey by aerial hawking are expected to be highly sensitive to climate change because of their reliance on a food resource that is spatially and temporally variable (Sherwin et al. 2012), with activity strongly influenced by environmental conditions, particularly temperature (e.g. O'Donnell 2000b) but also by the intensity and frequency of rainfall and habitat quality (Table 5). Similarly, lesser short-tailed bats that rely on fruit and nectar could also be vulnerable if plant phenology cycles are disrupted. Furthermore, the ground-feeding activity of this species (Jones et al. 2003) may be affected by disruptions in invertebrate food supplies if soil and litter profiles are dehydrated or compacted.

Climate change is unlikely to affect the dispersive capability of bats in Aotearoa New Zealand directly (Table 5). Just because bats are capable of movement doesn't mean they will move to locations where conditions are more favourable. Adams (2010) observed that in six of the years between 1996 and 2008, when conditions in the Colorado habitat of six species of vespertilionid bats mimicked anticipated long-term climate warming and increased drought, they continued to occupy traditional roost sites and reduce reproductive output, rather than travel further to find water or use alternative roost sites. Bats in Aotearoa New Zealand display high site fidelity to maternity roosting areas, so whether this dependence limits their flexibility to find new roosting areas is unknown (Monks & O'Donnell 2017; O'Donnell 2000c) although genetic evidence shows some long-distance dispersal to nearby colonies on at least a scale of c.50 km (O'Donnell et al. 2016).

Bats that use specialised roost types, such as tree roosts, at distinct life history stages are likely to be vulnerable to a changing climate and associated changes in vegetation (Sherwin et al. 2012). Severe weather events, for example, could destroy roost features or reduce the long-term survival of roost trees. If range-shifts occur but these are not matched to suitable vegetation communities, bats may be forced to use suboptimum roosts (Sedgeley & O'Donnell 2004; Keegan et al. 2022).

Torpor is a strategy used by bats to avoid times of low resource availability (Table 5; Findlay-Robinson et al. 2023; Kerth & Wolf 2025), which may allow bats to cope with extreme climate events that reduce food availability. Both involve reducing body temperature and metabolic rate to conserve energy, but torpor is characterised by bouts of shorter duration (typically < 24 hours) and higher minimum body temperatures than hibernation (Geiser & Ruf 1995). Hibernation is strictly seasonal (occurring during the coldest months) and requires physiological preparation in the form of energy (fat) storage, whereas short-term torpor can be used opportunistically at any time of year and when body condition is poor (Nowack et al. 2017). However, storage of winter fat can be compromised by increasing frequency of waking due to warmer winter temperatures (Speakman et al. 1991), which may represent a threat if more rapid use of winter fat storage is not matched with increased food availability.

Responses of bat populations to climate change are likely complex and subtle, based on the wide range of potential influences summarised in this paper. How positive and negative effects balance themselves long-term is complicated and the overall consequences unknown. For example, as breeding seasons become warmer, Bechstein's bats (*Myotis bechsteinii*), have been observed breeding at an earlier age, with evidence of shorter generation times and reduced longevity (Mundinger et al. 2021, 2022). Thus, life-time productivity may remain the same under favourable environmental conditions, and any potential benefits neutral. Both New Zealand species also tolerate a wide range of temperatures in controlled laboratory conditions (McNab & O'Donnell 2018), suggesting some individuals may adapt to higher ambient temperatures. In addition, they switch roosts frequently (O'Donnell & Sedgeley 1999; O'Donnell et al. 1999), so have the potential to select roosts with internal microclimates that buffer the inhabitants against external extremes. Balanced against this, if long-tailed and short-tailed bats are intolerant of temperature extremes at certain life stages (e.g. if young become impacted by overheating and water loss in roosts) then the impact of climate change may be significant.

Adaptability to climate change may manifest itself at a species, subspecies, population or individual level. Evidence of adaptive phenotypic plasticity to environmental changes linked to climate change, expressed as behavioural or physiological responses, has been observed in some mammal and bird species (Charmantier et al. 2008; Boutin & Lane 2014). Dunbar and Brigham (2010) found intraspecific variation in thermoregulatory traits of bats across a latitudinal gradient and suggested that this could be the result of phenotypic plasticity. A study on two populations of *Myotis nattereri* in Germany found that survival was higher in larger individuals, but that warmer temperatures led to increased body size only in the more northern population (Stapelfeldt et al. 2023). Whether bats in Aotearoa New Zealand will display such adaptations in response to climate change is unknown.

Understanding variations in roost use and interactions with thermal ecology will be essential to understanding the plasticity of bats to climate change. Both long-tailed and lesser short-tailed bats depend on the stable microclimates of their maternity roosts in cool temperate forests to successfully raise their young (Sedgeley 2001a, b). In markedly warmer habitats in northern Aotearoa New Zealand, Czenze et al (2017a) found that northern lesser short-tailed bats on Little Barrier Island/ Te Hauturu-o-Toi preferred thermally unstable roosts during winter. In contrast, central lesser short-tailed bats, which inhabit much cooler forests in the central North Island, preferred more thermally buffered roosts during winter (Czenze et al. 2017c).

Understanding dietary requirements and foraging behaviour are important gaps in our understanding of tolerance and adaptability of bats to climate change in Aotearoa New Zealand. For example, in studies in both Canada and the United Kingdom, unfavourable weather conditions affected prey availability during critical periods, adversely affecting breeding phenology and reproductive success to different degrees in sympatric bat species with different foraging strategies (Burles et al. 2009; Linton & Macdonald 2018). There may be situations where food abundance is reduced. For example, long-tailed bats frequently consume aquatic invertebrates (O'Donnell & Borkin 2021); if increases in extreme storm events and flooding reduces aquatic food availability, this may have a negative impact on fitness.

Potentially, there may be benefits from warmer temperatures for Aotearoa New Zealand bats. Activity of long-tailed bats increases with night-time temperature because there is a linear relationship between temperature and numbers of flying invertebrates, their primary food source (O'Donnell 2000b). Thus, if food abundance increases and breeding seasons are longer because of warmer temperatures, particularly in the shoulder seasons of spring and autumn, young may enter winter in better condition and survival may be higher. Another positive effect of warmer temperatures during lactation could be lower thermoregulatory costs during the day if temperatures are not extremely hot. This may allow bats to avoid torpor use, which may compromise juvenile development (McAllan & Geiser 2014; Wolf et al. 2025). Potential trends such as these are currently unpredictable given the myriad of plausible direct or indirect influences of climate change on bats.

While numerous vulnerabilities have been identified for bat taxa in Aotearoa New Zealand, continued improvement of models will increase our certainty in the climate change projections and how they will manifest themselves in bat populations. Understanding the vulnerabilities of bat taxa in Aotearoa New Zealand will help to determine what, if any, additional conservation management or adaptation plans will be required in the future to aid their ongoing survival. Currently, there has been a low research effort examining the potential impacts of climate change on bats compared to other vertebrate groups, and a bias towards modelling approaches and northern hemisphere temperate species (Festa et al. 2023). This CCVA indicates that all Aotearoa New Zealand bat taxa either display latent risks or are highly vulnerable to projected climate change. Understanding the consequences of climate change likely depends on implementing long-term bat monitoring programmes that measure trends in productivity and survival in relation to climate change and are vigilant of new and existing threats (Findlay-Robinson et al. 2023; Kerth & Wolf 2025).

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Supplementary material

Additional supporting information may be found in the online version of this article.

Appendix S1. Trait definitions used for climate change vulnerability assessments for bats in Aotearoa New Zealand.