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The impacts of Cyclone Gabrielle on North Island ecosanctuaries

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Abstract: The direct impacts of tropical cyclones on species and ecosystems have been widely studied, but their indirect impacts via damage to conservation infrastructure have been largely overlooked. New Zealand ecosanctuaries are large-scale conservation projects that are closely connected to local communities, provide a vital refuge for local and threatened native biodiversity, and represent a subset of the national conservation infrastructure. Cyclone Gabrielle was a Category 3 tropical cyclone that affected New Zealand between 12–14 February 2023. Here we profile its impacts on 65 North Island ecosanctuaries. Specifically, we (1) report the frequency and severity of different types of cyclone damage experienced by ecosanctuaries, (2) describe the frequency and severity of impacts on conservation infrastructure and activities, and (3) offer recommendations to help ecosanctuaries prepare for future extreme weather events. Eighty-two percent of North Island ecosanctuaries suffered cyclone damage. Damage from wind and erosion were frequently reported (by 91% and 85% of affected ecosanctuaries, respectively) and of moderate severity on average. Flooding (45%) and sediment deposition (36%) were less common, and their impacts mostly minor. Multiple impacts on conservation infrastructure or activities were experienced by 63% of ecosanctuaries. Of particular concern, 50% of cyclone-affected ecosanctuaries with pest exclusion fencing suffered at least one breach, with rapid pest incursions detected in three out of the five cases of fence damage. Impacts on other infrastructure (e.g. buildings, roads, tracks) were widespread and often accompanied by disruption to pest management and native species monitoring. Longer term issues include lost access to management areas, sustained reductions in pest management efficiency and conservation workforce capacity, and opportunity costs associated with recovery instead of progress. Although Cyclone Gabrielle set back many individual conservation projects, the resilience of the broader network of ecosanctuaries was encouraging. We conclude with management recommendations focussed on preparation, response, recovery, and data and research needs.

Keywords: biodiversity; climate change; conservation; extreme weather; hurricane; monitoring; pest exclusion fence; pest management; resilience; tropical cyclone

Introduction

Ecosanctuaries are a vital part of the New Zealand conservation infrastructure, defined as "a project larger than 25 ha implementing multi-species, pest mammal control for ecosystem recovery objectives, and with substantial community involvement" (Innes et al. 2019). Some ecosanctuaries are predator-free offshore islands, a few are protected with a pest exclusion fence, and others conduct intensive trapping and baiting programmes on mainland islands to maintain low to zero predator densities. Their overarching goal is to restore ecosystems to a state dominated by diverse and abundant native species and their interactions. This is typically achieved through eradication (or near-zero densities) of the full suite of pests (e.g. rats, mustelids, cats, brushtail possums, ungulates, invasive plants), and the reintroduction and protection of species that are directly threatened by pests, which has historically focussed on vertebrates. Moreover, by providing a place to observe and connect with endemic, local, and threatened biodiversity, and opportunities for active participation in projects, ecosanctuaries play an important role in linking communities with conservation. In essence, ecosanctuaries protect some threatened species, connect people with nature, and represent a significant contribution to conservation efforts throughout New Zealand (Innes et al. 2019). Because they require substantial investment to establish and maintain, ecosanctuaries are highly valuable conservation assets that face a high risk of severe consequences if damaged by extreme weather events such as ex-tropical cyclones.

Tropical cyclones are large-scale, extreme weather events that can inflict catastrophic impacts on human wellbeing, economies, and the environment (Estrada et al. 2015). Their strong winds, intense rainfall, and storm surges are widely regarded to have significant consequences for the extent, structure, composition, and functioning of ecosystems (Bellingham 2008; Lugo 2008; Xi 2015; Lin et al. 2020). New Zealand experiences an average of one tropical cyclone per year (between December and April) (Sinclair 2002), and a few have wide-ranging and major impacts. For example, Cyclones Ida (March 1959), Giselle (April 1968), Alison (March 1975),

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and Bernie (April 1982) all caused severe damage to native forest, especially in the North Island (Shaw 1983a, 1983b; Martin & Ogden 2006). Similarly, the high rainfall of Cyclone Bola (March 1988) caused major damage to infrastructure and arable land in the Gisborne and Hawke's Bay regions, while the 130 km per hour wind gusts of Cyclone Ita (April 2014) inflicted large-scale blow-down of native forest in the West Coast of the South Island (Platt et al. 2014).

Originating in the Coral Sea, Cyclone Gabrielle tracked along the northeast coastline of the North Island of New Zealand between 12 and 14 February 2023. During this period, over 500 mm of rain fell in parts of the Hawke's Bay and Gisborne, with the strongest wind gusts of up to 140 km per hour experienced in Auckland, Northland, and the Central North Island (Harrington et al. 2023; Hawke's Bay Independent Flood Review 2024). Waves reached as high as 11 m in the Bay of Islands, contributing to storm surges of over 0.5 m, with coastal erosion and flooding being most severe along the eastern coastlines of Northland and the Coromandel Peninsula (Harrington et al. 2023). The impacts of Cyclone Gabrielle were exacerbated by the preceding Cyclone Gale (10–11 January 2023) and the Auckland Anniversary storm (27 January 2023), with the already saturated landscape leaving many regions vulnerable to a low probability, high impact "black swan" event (Harrington et al. 2023; Macinnis-Ng et al. 2024). These extreme weather events caused a combined estimate of $9–14.5 billion of physical asset damage, making this New Zealand's costliest non-earthquake natural disaster (Ministry for the Environment & Statistics New Zealand 2023; New Zealand Treasury 2023). Although it is challenging to assign monetary value to many impacts of the cyclone, including those experienced by conservation projects, it is important to document the damage that occurred and to use these experiences to better prepare for future extreme weather events.

A major focus of climate change research has been the direct effects of climatic conditions or extreme weather events on species' populations and ecosystem extent and condition (Ministry for the Environment & Statistics New Zealand 2023). The impacts of cyclones on ecosanctuaries could be direct and immediate, including the death or injury of individual organisms, and habitat destruction. However, other impacts may be indirect or occur over a longer time. For example, damage to critical infrastructure may reduce capability to carry out core ecosanctuary activities. Similarly, changes in habitat quality or species interactions (i.e. increased predation pressure through pest incursions or reduced pest management) could mediate indirect cyclone impacts on threatened species. Impacts may also take time to become apparent, with changes in species abundances lagging behind any cyclone-related resource fluctuations. There is also an opportunity cost associated with recovery to a previous state rather than advancement towards future goals.

To safeguard the valuable conservation assets of ecosanctuaries against extreme weather events, there is a need to understand how these weather events affect ecosanctuaries and what we can learn to minimise future harm to conservation infrastructure, ecosystems, and threatened species. Here we profile how Cyclone Gabrielle affected 65 ecosanctuaries across the North Island of New Zealand. Our specific objectives were to: (1) report the frequency and severity of different types of cyclone damage experienced by ecosanctuaries, (2) describe the frequency and severity of impacts on conservation infrastructure and activities, and (3) offer recommendations to help ecosanctuaries prepare for future extreme weather events.

Methods

We interviewed representatives from ecosanctuaries across the entire North Island, which was selected as the study area based on the path of Cyclone Gabrielle and reports of impacts. Ecosanctuaries were identified from Innes et al. (2019), the Sanctuaries of New Zealand Inc. website (www.sanctuariesnz.org), and word of mouth. Three projects smaller than 25 hectares but with a pest exclusion fence (identified from Burns et al. 2012) were also included because they host vulnerable biodiversity and represent significant conservation investment. These criteria resulted in data from 65 ecosanctuaries (Fig. 1, Appendix S1 in Supplementary Material).

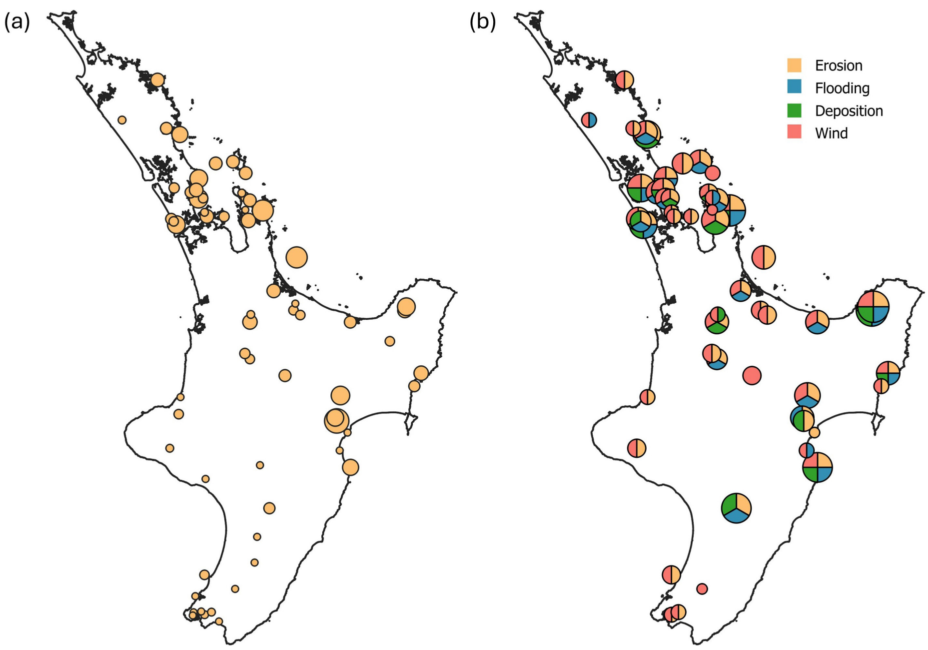

Figure 1. Map showing the 65 ecosanctuaries from the North Island of New Zealand that were interviewed to assess the impacts of Cyclone Gabrielle. (a) point size is scaled according to the mean severity of cyclone impacts on conservation activities for each ecosanctuary. (b) point size is scaled and coloured according to the mean severity and identity, respectively, of the damage types experienced by each ecosanctuary (only ecosanctuaries with recorded cyclone damage are shown).

Ecosanctuary representatives were prompted with a set of standardised questions. Responses were recorded as presence/absence of each type of cyclone damage or disruption to conservation activities, and detailed notes were taken on the types and severity of impacts. If a particular type of conservation activity was not present at an ecosanctuary (e.g. no pest exclusion fence), data were coded as NA. Based on these responses, we classified each type of cyclone damage or disruption to conservation activities into one of three severity categories: minor, moderate, or severe. Minor impacts were those that might be expected from a typical storm, such as the occasional small landslide or fallen tree, or a few lost traps, tracking tunnels, or native plantings. Moderate impacts were more widespread, consequential, and not able to be immediately fixed or ignored, such as the loss of coastal dunes or restoration plantings, obstructed pest management lines, or some recorded mortality of threatened species. Severe impacts were large-scale, long-lasting, expensive to repair, or constituted major setbacks for individual ecosanctuaries, such as breaches in a pest exclusion fence or sustained loss of access to pest management areas. By assigning these damage categories as ranked values (1, 2, and 3, respectively), we quantified a mean severity score for individual ecosanctuaries, and for each type of cyclone damage and impact on conservation activities. The questions asked were:

As a result of Cyclone Gabrielle, did your ecosanctuary experience damage from: (1) flooding, (2) sediment deposition, (3) erosion, and/or (4) wind?

As a result of Cyclone Gabrielle, did your ecosanctuary experience damage or disruption to: (1) pest exclusion fencing, (2) other fencing, (3) other infrastructure, (4) culturally significant sites, (5) native wildlife, (6) monitoring of native species, (7) pest management, and/or (8) restoration plantings?

Results

Prevalence, severity, and examples of different types of cyclone damage

Of the 53 ecosanctuaries that suffered some type of damage from Cyclone Gabrielle (Fig. 2a), 91% were damaged by wind, 85% by erosion, 45% by flooding, and 36% by sediment deposition (Fig. 2b). Most ecosanctuaries (74%) experienced multiple types of cyclone damage. Only 18% of ecosanctuaries experienced no damage at all (Fig. 2a), with most of these being located in the southwest of the North Island (Fig. 1). Erosion damage had the highest severity score (1.80 ± 0.81; mean ± SD), followed by wind (1.65 ± 0.76), flooding (1.38 ± 0.58), and sediment deposition (1.26 ± 0.56) (Fig. 2c).

Wind damage ranged from minor defoliation to wind throw of hundreds of mature trees and building damage. Major wind damage to infrastructure was reported from Mayor Island / Tūhua, where the roofs of buildings were blown off. One of the worst examples of wind damage to native ecosystems occurred at Bream Head Scenic Reserve in Northland, where the cyclone flattened large stands of naturally regenerating kānuka (*Kunzea ericoides*) forest on slopes exposed to southwest winds. Several ecosanctuaries reported wind-thrown trees throughout native forest, resulting in many canopy light gaps, including some up to 0.2 ha in size at Aongatete Forest Project in the Bay of Plenty (Allen et al. 2024).

Erosion damage was also widespread and varied in severity (Fig. 2). Landslides were frequently reported, ranging

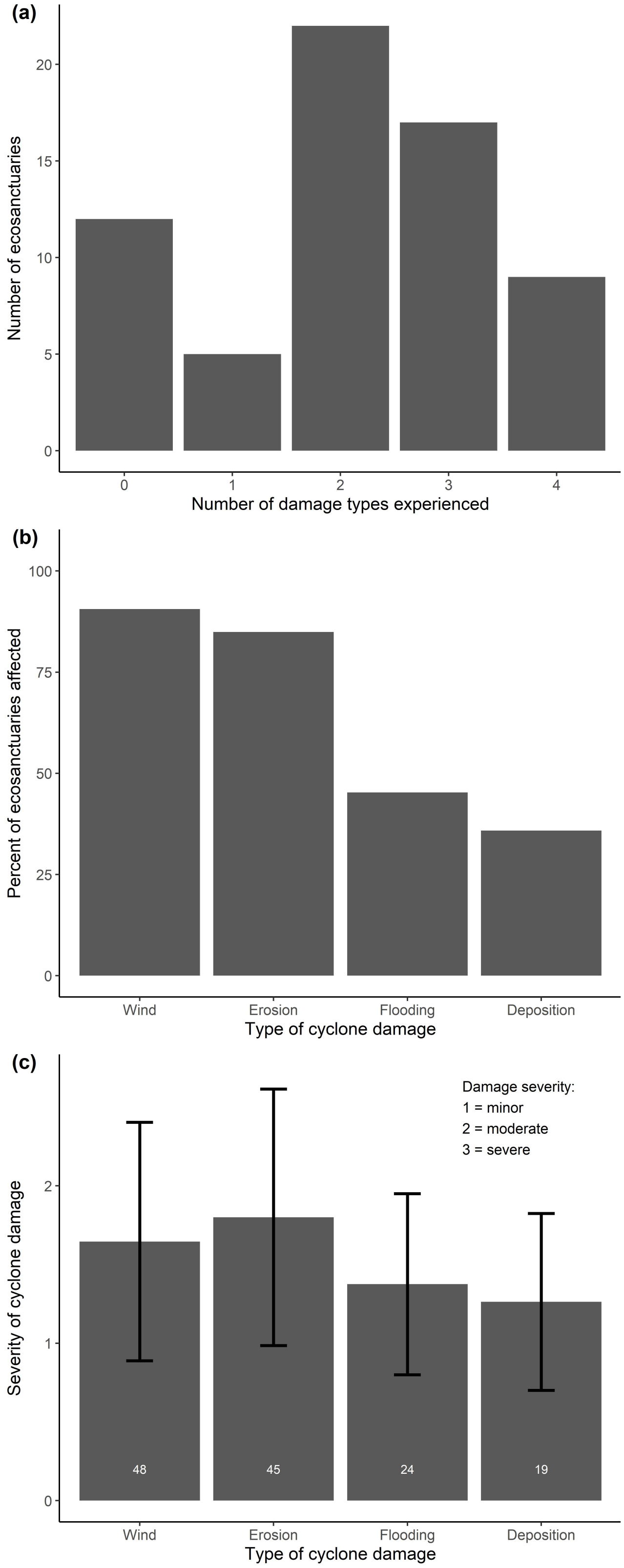

Figure 2. (a) frequency of the number of damage types from Cyclone Gabrielle that were experienced by ecosanctuaries from the North Island of New Zealand (n = 65). (b) the percentage of ecosanctuaries that experienced each type of damage, presented from most to least frequent (n = 53 ecosanctuaries that suffered some type of damage). (c) mean (± SD) severity of cyclone damage to ecosanctuaries that experienced each damage type (sample size, which was the number of ecosanctuaries affected by each damage type, is shown at the bottom of each bar).

in size from just a few metres to a 500 × 100 m (5 ha) slip that affected up to seven trap lines at Ark in the Park in the Waitākere Ranges near Auckland. Mahakirau Forest Estate on the Coromandel Peninsula experienced numerous landslides that deposited sediment and debris into streams and forest and damaged several tracks used to service pest management lines. Similar large-scale impacts were reported from multiple Hawke's Bay ecosanctuaries, including Maungataniwha Native Forest, Cape Sanctuary, Boundary Stream Mainland Island, and Opouahi kiwi crèche. Storm surges also caused significant coastal erosion, especially at ecosanctuaries around Auckland and Northland, where active dunes were washed away (Allen et al. 2024) and restoration plantings, historical midden sites, and coastal tracks damaged.

Flooding and sediment deposition were the least reported types of cyclone damage to ecosanctuaries, reflecting the scarcity of native vegetation (and hence ecosanctuaries) in lowland, flood-prone areas where historical clearance has been most comprehensive (Ewers et al. 2006; Allen et al. 2013). However, flooding did impact infrastructure at some ecosanctuaries, especially around Auckland. For example, the pumphouse at Tāwharanui Regional Park was rendered inoperable, while floodwaters damaged the pest exclusion fence (Fig. 3b) and prevented visitor access for multiple days

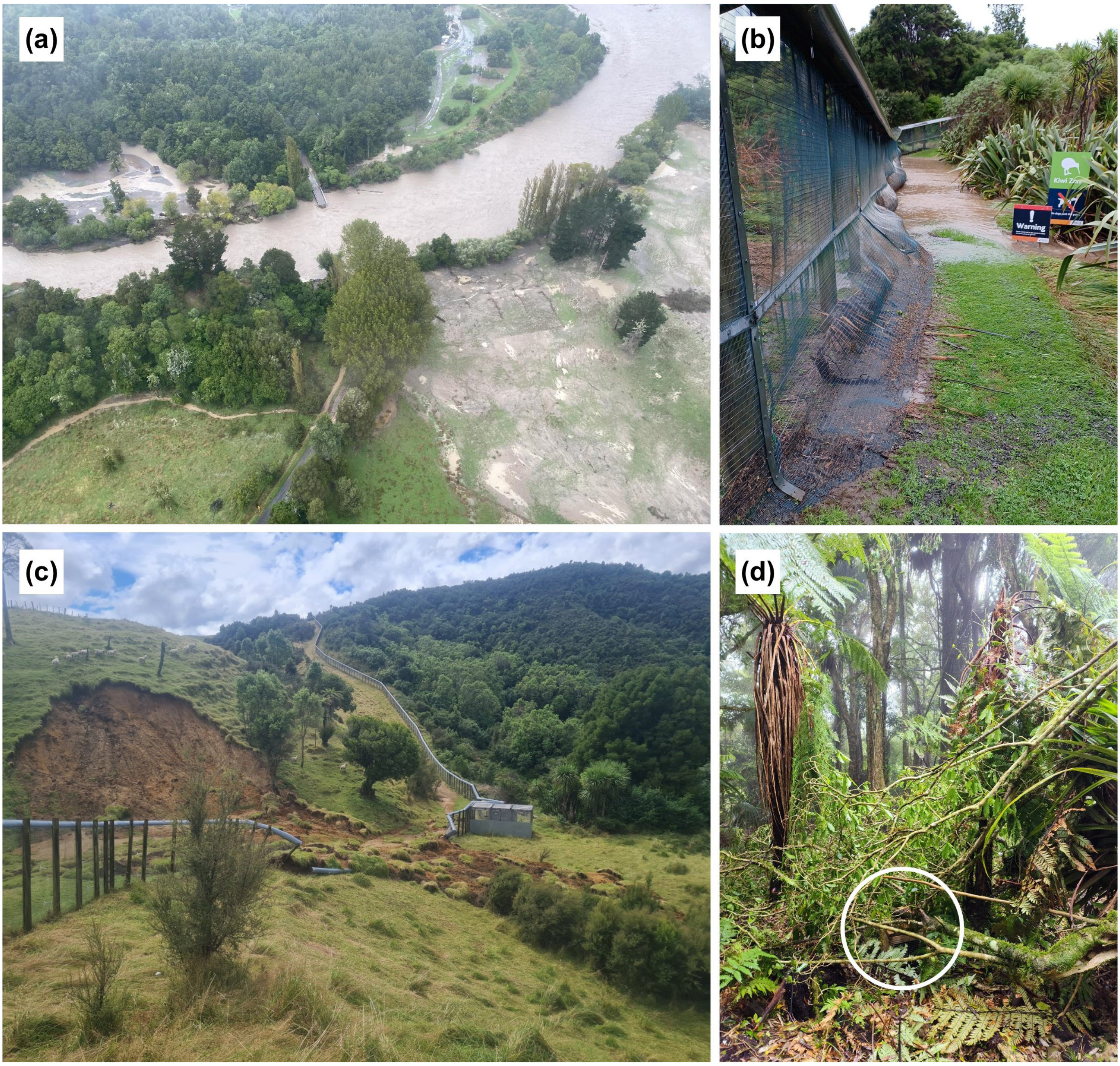

Figure 3. Examples of Cyclone Gabrielle impacts experienced by ecosanctuaries from the North Island of New Zealand. (a) impeded access, flooding, and sediment deposition through the forest and campground at Tōtara Reserve Regional Park, Manawatū-Whanganui (photo: Horizons Regional Council); (b) flooding damage to the pest exclusion fence at Shakespear Regional Park, Auckland (photo: Auckland Council); (c) landslide damage to the pest exclusion fence at Opouahi kiwi crèche, Hawke's Bay (photo: Deb Harrington); (d) windfall obstructing a trap line and covering a trap (circled) at Mahakirau Forest Estate, Waikato (photo: Sara Smerdon).

at Shakespear Regional Park. Perhaps the most consequential example of flooding occurred at Tōtara Reserve Regional Park in Manawatū-Whanganui, a region that received relatively little attention after the cyclone. Due to its location on the banks of the Pohangina River, it experienced severe flooding, with campsite facilities completely underwater (Fig. 3a) and 1–2 m of sediment deposited through buildings and up to 100 m into low-lying forest.

Prevalence, severity, and impacts on conservation infrastructure

Although 23% of ecosanctuaries experienced no impacts on conservation infrastructure or activities, most (63%) suffered from multiple impacts (Fig. 4a). Perhaps most concerningly, half of the ten cyclone-affected ecosanctuaries that maintain a pest exclusion fence reported that their fence was compromised during the cyclone, with rapid pest incursions detected in three out of the five cases (Fig. 4b). Damage to pest exclusion fences also had the highest severity score of any impact on conservation activities (2.00 ± 1.00) (Fig. 4c). At Opouahi kiwi crèche, a ring-fenced and predator-free ecosanctuary, landslides flattened the pest exclusion fence in two locations (Fig. 3c). It took several weeks for the fence to be repaired due to problems with access and availability of contractors, allowing the incursion of rats (*Rattus* spp.), stoats (*Mustela erminea*), ferrets (*Mustela furo*), and stock. After several months of intensive trapping, surveillance, and multiple visits by mustelid detection dogs, staff are optimistic that Opouahi kiwi crèche is once again predator free. At Sanctuary Mountain Maungatautari in the Waikato, New Zealand's largest mainland predator-free ecosanctuary, the 47 km pest exclusion fence was damaged by treefalls in six locations, comparable to the annual average of nine breaches that require fence replacement. Despite fence repairs being completed within 48 hours, five weasels (*Mustela nivalis*), seven ship rats (*Rattus rattus*) and three possums (*Trichosurus vulpecula*) were trapped or detected near to where the fence was compromised within one year of the cyclone; these incursions are thought to be related to the cyclone damage. At predator-free Wairakei Golf & Sanctuary, near Taupō, some of the approximately 1800 treefalls (mostly non-native conifers) damaged the pest exclusion fence in two locations. Despite the fence also being cleared and fixed within 48 hours, two ferrets were captured following increased trapping efforts. Finally, flooding caused the pest exclusion fence to give way at the base in one location at Shakespear Regional Park (Fig. 3b). This minor damage was repaired the following day, and the fence and other hydrology infrastructure have since been re-engineered to improve drainage in preparation for future flooding events.

Impacts on other fences were only reported from 22% of the 27 cyclone-impacted ecosanctuaries that had stock or feral ungulate fencing (Fig. 4a). A severity score of 1.33 ± 0.52 also indicated that these impacts were relatively minor (Fig. 4c). One of the more severe examples was damage to approximately half the riverside fencing at Waikereru Ecosanctuary and Longbush Reserve in Gisborne. Minor damage to stock fencing occurred at Bream Head Scenic Reserve, Mataia Homestead in the Kaipara, Shakespear Regional Park, and Boundary Stream Mainland Island near Napier, allowing stock to temporarily access some forested areas. A fenced exclosure protecting the nationally critical ngutukākā (kākābeak, *Clianthus maximus*) from mammalian herbivores was damaged at Boundary Stream, but was repaired before any plants were browsed.

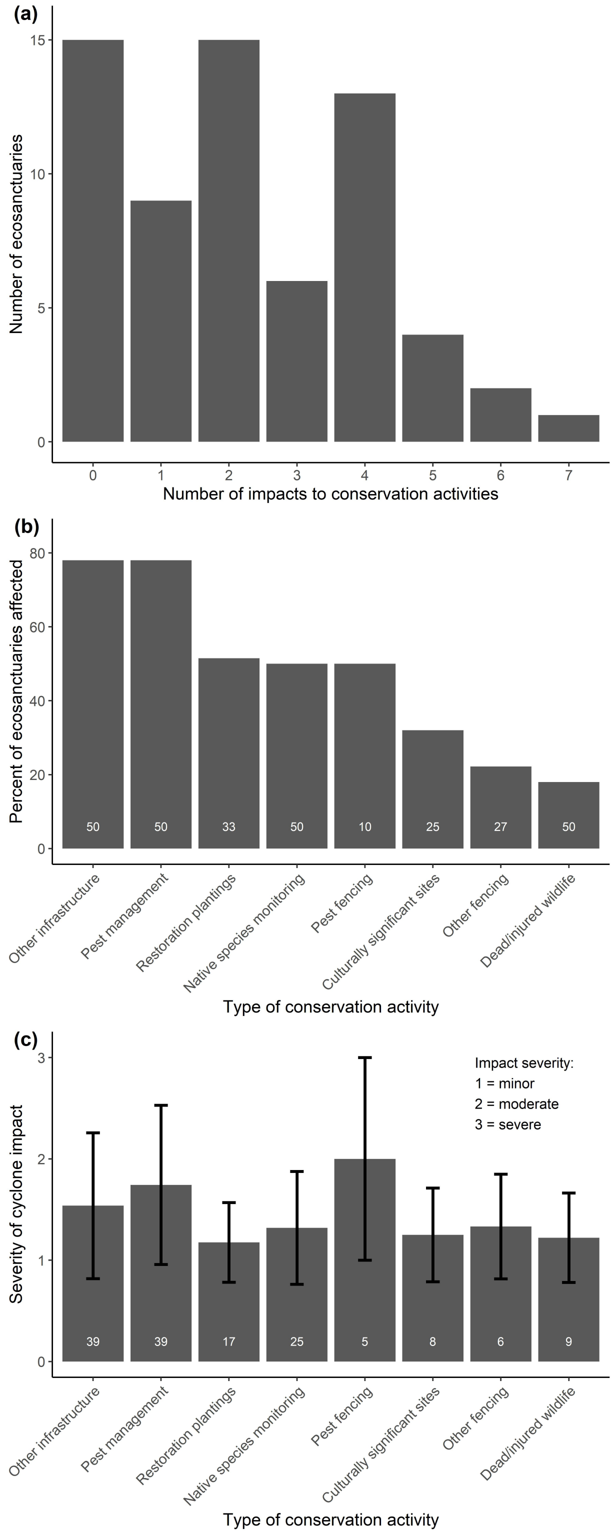

Figure 4. (a) Frequency of the number of impacts from Cyclone Gabrielle on conservation activities that were experienced by ecosanctuaries from the North Island of New Zealand ($n = 65$). (b) The percentage of cyclone-affected ecosanctuaries that experienced impacts on each type of conservation activity, presented from most to least frequent (sample size of cyclone-affected ecosanctuaries that were undertaking each activity prior to the cyclone is shown within the bar for each category). (c) mean (± SD) severity of cyclone impacts on ecosanctuary conservation activities for each damage type (sample size, which was the number of ecosanctuaries that experienced each impact type, is shown at the bottom of the bar for each category).

Damage to other infrastructure was the most widely reported cyclone impact, occurring at 78% of affected ecosanctuaries (Fig. 4a). Severity ranged from minor and inexpensive to critically important and costly, and had the third highest severity score overall of 1.54 ± 0.72 (Fig. 4c). A major and ongoing issue for several ecosanctuaries was impeded access due to infrastructure damage. Public road closures restricted access for up to several weeks in places, and hundreds of kilometres of roads and tracks through ecosanctuaries suffered damage, with some areas remaining inaccessible. In some instances, the damage has required hundreds of person-hours to fix, and some tracks will be permanently retired due to windfall, landslides, logistics of access, and risks to health and safety. Maungataniwha Native Forest is one such ecosanctuary, and suffered massive destruction to its road and track infrastructure, with a digger operator still clearing roads over 18 months after the cyclone. Recreational and operational facilities were also affected at many ecosanctuaries, ranging from washed out walking tracks, boardwalks, and bridges, through to buildings, campgrounds, and gates damaged by flooding, wind, or tree falls.

Impacts on sites of cultural significance occurred at 32% of the 25 impacted ecosanctuaries for which data was collected (Fig. 4a) and tended to be relatively minor in nature, with an average severity score of 1.25 ± 0.46 (Fig. 4c). Middens were washed away at Young Nicks Head / Te Kurī in Gisborne and buried by landslides at Muriwai Penguin Project near Auckland. Access was also affected in some ecosanctuaries, such as via damage to tracks that restricted access to historic pā and whare sites at Maungataniwha Native Forest.

Prevalence, severity, and impacts on monitoring, pest management, and restoration

Direct observations of dead or injured native wildlife were reported from only 18% of ecosanctuaries (Fig. 4a), most of which were just a few individuals of relatively common species. This was reflected in the second lowest severity score of 1.22 ± 0.44. Two of the eleven North Island brown kiwi (*Apteryx mantelli*) chicks that were being cared for at Opouahi kiwi crèche were presumed to have died in landslides, and another kiwi was found dead, presumed drowned, at Sanctuary Mountain Maungatautari. Beach-wrecked seabirds (e.g. ōi [grey-faced petrel, *Pterodroma gouldi*], pakahā [fluttering shearwater, *Puffinus gavia*] and kororā [little penguin, *Eudyptula minor*]) were found at multiple coastal and island ecosanctuaries (e.g. Tāwharanui Regional Park, Shakespear Regional Park, Rotoroa Island), but not in the vast numbers seen after some winter storms (e.g. an estimated 300 000 prions [*Pachyptila* spp.] thought to have perished in 2011; Miskelly 2011). At Mahakirau Forest Estate and Otawa Scenic Reserve, pepeketua (Hochstetter's frog, *Leiopelma hochstetteri*) were assumed to have been affected by flooding and sediment deposition through their favoured streamside habitat during breeding. On a more positive note, the pāteke (brown teal, *Anas chlorotis*) at Cape Sanctuary were reported to have enjoyed the flooded landscape.

Pest management was disrupted with varying severity (second highest severity score of 1.74 ± 0.79) at 78% of ecosanctuaries affected by the cyclone (Fig. 4c), and native species monitoring was affected at 50% (severity score of 1.32 ± 0.56; Fig. 4a). Impeded access and the slow process of clearing tracks were the primary issues facing monitoring and pest management, delaying programmes by anything from a few days to indefinitely. For example, operations at some ecosanctuaries (e.g. Maungataniwha Native Forest, Boundary Stream Mainland Island and Bream Head Scenic Reserve) had still not returned to full capacity when interviews were conducted more than six months after the cyclone, while parts of several ecosanctuaries are considered unsafe to access due to ongoing landslide or treefall risk. The cyclone also affected the conservation workforce, with disruptions to personal lives (e.g. damage to homes or businesses), competition for contractors, and health and safety concerns all contributing to reduced capacity of the paid and volunteer workforce. Finally, because many monitoring programmes are seasonal, an entire year of monitoring data was lost for some species, creating gaps in valuable long-term time series that underpin effective conservation management.

A key type of disruption to pest management was the damage to or loss of traps, bait stations, and surveillance equipment (Fig. 3d). This ranged from losing a single tracking tunnel to entire lines of traps and bait stations being buried or washed away. For example, Te Hauturu-o-Toi / Little Barrier Island lost about half of its 80 surveillance stations around the coastline, while Boundary Stream Mainland Island lost over 100 traps. At Cape Sanctuary, an entire trap, bait station, and monitoring line was lost in one gully, while another 45 traps and 50 bait stations washed away when a dam burst behind accumulated slash in a creek. These events each represent several thousand dollars of lost pest management equipment, before considering the labour cost to reestablish the same level of pest management. Several ecosanctuaries also reported that their traps were filled with sediment or constantly wet, resulting in them rusting more rapidly, being heavier to move, and bait decaying faster. Overall, some of the worst affected ecosanctuaries estimated their trapping efficiency to be as low as 30% of normal for at least six months after the cyclone.

The impacts of Cyclone Gabrielle on pest species are unclear. Some ecosanctuaries reported a decline in pest numbers (e.g. Windy Hill Sanctuary on Aotea / Great Barrier Island noted fewer kiore [*Rattus exulans*], hypothesising that this was due to consistent wet weather), while others reported increases, mostly of other rat species. New predator incursions were also detected for some island ecosanctuaries. For example, rats were presumed to have arrived with floodwaters on Matakohe Limestone Island, while a cat was found on Motu Kaikōura. The cyclone also caused delays to invasive plant management programmes at several ecosanctuaries.

Of the 33 ecosanctuaries with restoration plantings, 52% reported that they had been damaged (Fig. 4a). With an average installation cost of $23 000 per ha (Forbes 2021), damage to or destruction of restoration plantings is a significant loss of investment. Fortunately, most reports from ecosanctuaries involved relatively small areas, as reflected in the lowest overall severity score of 1.18 ± 0.39 (Fig. 4c). Approximately 400 m² (0.04 ha) of restoration plantings at Young Nicks Head / Te Kurī suffered from wind throw, some planted mānuka (*Leptospermum scoparium*) were lost to windburn and salt spray on Matakohe Limestone Island in the Whangārei Harbour, and around 1.5 km of dune plantings at Shakespear Regional Park were eroded away by storm surges. Tōtara Reserve Regional Park reported that their restoration plantings were thriving after the cyclone, with floodwaters suppressing non-native plants to the benefit of several native tree species that had been planted 1–2 years before the cyclone.

Discussion

The force of Cyclone Gabrielle was widely felt by North Island ecosanctuaries, with 85% suffering at least one type of damage or impact on conservation activities. There were a range of impacts with variable severity, but wind and erosion damage to conservation infrastructure (e.g. fences, buildings, roads, and tracks) was the most widespread and consequential. Indirect impacts accompanied the direct and immediate damage, with loss of access, incursions by mammalian predators, and disruption to monitoring and pest management programmes all limiting the ability of ecosanctuaries to perform their core functions, sometimes for an extended period. A few individual ecosanctuaries took the brunt of the impact, yet no local extinctions were reported and the national network of ecosanctuaries was resilient to the cyclone impacts. Despite this positive collective outcome and a steely resolve to rebuild through new and existing conservation projects, the immediate impacts and cost of repairs were significant for some ecosanctuaries.

The size and topography of each ecosanctuary may have influenced the types and severity of damage. For example, the time-consuming and expensive clearing of monitoring and pest management lines scaled with ecosanctuary size, with the largest ecosanctuaries maintaining hundreds of kilometres of roading, tracks, and pest management lines. However, conservation projects of all sizes were affected, from large areas of public conservation land managed by the Department of Conservation to backyard trapping projects. The combined 245 000 ha area of ecosanctuaries included in this study represents just a small portion of the total land being managed for pests in the North Island, indicating that the impacts of Cyclone Gabrielle would have been widely felt by many large and small conservation projects. Finally, the general topography of an ecosanctuary appeared to be a useful indicator of the types of damage and impacts it was likely to experience. Coastal and low-lying ecosanctuaries tended to experience more flooding and sediment deposition, while ecosanctuaries in steeper landscapes were more likely to suffer from erosion. Thus, cyclone impacts were likely to reflect those more frequently experienced during smaller storms, but at a far larger scale. This suggests that individual ecosanctuaries can predict the most likely types and locations of cyclone damage, thereby helping with planning, preparation, and rapid response.

Damage to conservation infrastructure was the most significant issue facing ecosanctuaries after Cyclone Gabrielle. Pest exclusion fences are highly valuable conservation assets and were particularly vulnerable to damage from landslides and tree fall. Pest incursions rapidly follow fence damage (Connolly et al. 2009), highlighting the importance of damage prevention, speedy repair, and mitigation measures like temporary fencing and intensive pest surveillance and control measures around compromised areas. There was also a significant loss of traps, bait stations, tracking tunnels, and trail cameras, which are expensive and time consuming to replace, thus limiting the ability of ecosanctuaries to achieve their core goals. Cleaning up and clearing of tracks has taken over 18 months in some cases, causing further disruptions to native species monitoring and pest management programmes. New and recurring landslides and wind fall of trees also remained an issue for many ecosanctuaries for months after the cyclone, requiring clearance whenever roads or tracks became blocked. Restoration plantings were also lost or damaged in some locations. Although replacement and additional plantings would help to stabilise disturbed land and limit plant invasions, significant further investment will be required. Promoting natural revegetation may be more cost-effective in some situations (Forbes et al. 2023).

Conservation is expensive, and in New Zealand it commonly requires active interventions. Infrequent climate events, amplified by ongoing climate change (Harrington et al. 2023; Stone et al. 2024), will diminish our capacity to maintain those interventions and will incur a substantial lost opportunity cost (Macinnis-Ng et al. 2024). This will leave ecosanctuaries running to stand-still without greater investment to merely maintain the conservation gains achieved to date. Financial impacts can be challenging to quantify and often involve commercially sensitive information. However, the financial costs of Cyclone Gabrielle were disproportionately distributed across ecosanctuaries based on their size, topography, and assets, with costs incurred by some of the worst-affected ecosanctuaries estimated at upwards of $1 million per ecosanctuary.

Although dead or injured native wildlife was the least reported conservation impact, this was likely an underestimate of wildlife mortality. For example, slips and flooding potentially affected seabirds breeding on Te Hauturu-o-Toi / Little Barrier Island, such as was observed on other nearby offshore islands (Bell et al. 2023; Ray & Burgin 2023). Other impacts on wildlife may not have been immediately apparent, such as wind damage to trees affecting flowering or fruiting and altering resource availability for higher trophic levels. For example, hihi (*Notiomystis cincta*) and tūī (*Prosthemadera novaeseelandiae*) detection rates on Te Hauturu-o-Toi / Little Barrier Island were 64–69% lower in 2007 compared to 2006, speculated to be because of a particularly severe winter storm that caused widespread defoliation and may have reduced food availability for nectivorous birds (Toy et al. 2018). There is surprisingly little known about how pest mammals and invasive plants respond to extreme weather events in New Zealand. Pest densities may decline in the immediate aftermath of a cyclone, temporarily offsetting disruptions to management programmes, although this remains to be tested. The impacts of cyclones on animals are understudied in general, and future research should aim to quantify and understand impacts on species across multiple trophic levels, their interactions, and consequences for ecosystem functioning (Wang et al. 2025). However, a general lack of baseline monitoring data for many of ecosanctuaries' most precious conservation assets—their biodiversity—makes it challenging to assess biodiversity outcomes (Binny et al. 2021). Our capacity to prepare for future events would be enhanced by focusing on biodiversity responses to cyclones using longitudinal studies replicated across several sites.

Large-scale cyclone disturbance is a natural process that harms some species but promotes others, contributing to the maintenance of biodiversity. Besides direct damage to infrastructure and biodiversity, the most serious threats to ecosanctuaries may arise from interactions between cyclone damage and other anthropogenic pressures (Macinnis-Ng et al. 2021), such as invasive plants and mammalian herbivores altering or arresting natural regeneration processes (Richardson et al. 2014). For example, cyclones create disturbed areas where invasive plants can establish (Restrepo & Vitousek 2001; Murphy et al. 2008; Lynch et al. 2009; Catford et al. 2012) and have been implicated in the spread of invaders at the landscape scale (Bhattarai & Cronin 2014). Furthermore, although flooding and sediment may provide fresh substrate and a potential flush of nutrients, they can also spread invasive species (Martiniello et al. 2024) and deposition around trees can starve roots of oxygen, eventually leading to mortality (Redpath & Rapson 2015; Allen et al. 2024). Ultimately, the intensity and scale of any extreme weather event will determine the types of microsites available for vegetation recovery (Duncan 1993). Plant invasions may only become apparent with time, suggesting that targeted surveys of disturbed areas for invasive species will be important for several years after a cyclone. If they remain unmanaged, ecosystem condition could deteriorate over the long term, with the cumulative area affected increasing with each subsequent extreme weather event.

Some reassuring findings emerged from the mess that the cyclone left behind. Considering the overarching goal of protecting native biodiversity, the network of ecosanctuaries collectively weathered the storm. It was encouraging that no local extinctions or major animal mortality events were reported, even from the hardest hit ecosanctuaries. However, there is potential for stronger impacts to occur with future cyclones. For example, if a large ecosanctuary with diverse and high-value species (e.g. Sanctuary Mountain Maungatautari) were to experience pest exclusion fence damage and a prolonged lack of access, such as occurred at Opouahi kiwi crèche (Fig. 3c), the impacts of sustained incursions of multiple pest species could be devastating. Even in such a scenario, the distribution of some highly sensitive species across multiple ecosanctuaries (e.g. tīeke [saddleback, *Philesturnus* spp.]) builds in resilience and an insurance policy against local extinction. However, species such as takahikare-raro (New Zealand storm petrel, *Fregetta maoriana*) and tāiko (Westland petrel, *Procellaria westlandica*), both with breeding sites from just one location (Te Hauturu-o-Toi / Little Barrier Island and Punakaiki, respectively), remain particularly vulnerable to the impacts of extreme weather events or other natural disasters (e.g. Waugh et al. 2015). This vulnerability highlights the need to investigate translocation or enhanced protection of challenging species such as seabirds. Moreover, there is an urgent need to assess the vulnerability and protection status of less charismatic species such as native invertebrates, plants, and fungi, and to incorporate them into spatial conservation planning (Brumby et al. 2025).

Another positive discovery from the cyclone was that native forest suffered comparatively less erosion than non-native forest and pasture (McMillan et al. 2023), indicating that the majority of ecosanctuaries, as landscapes primarily covered in native forest, may already have resilience to some impacts of future extreme weather events. However, slips that do occur in native forest may be more damaging than those in pasture, leaving a mess that is more difficult to clean up. Similarly, although sanctuaries in a forested matrix may provide spillover benefits for the surrounding community (Fitzgerald et al. 2019; Burge et al. 2021), repairs of pest exclusion fences and other infrastructure may also be more frequent and challenging than in a pastural landscape. A final positive aspect was the stories of ecosanctuaries working together to respond to cyclone damage. Notably, the rapid deployment of a fencing team to Wairakei Golf & Sanctuary was assisted by Sanctuary Mountain Maungatautari, where rapid fence repairs had just been completed.

Although still a contentious issue, current evidence indicates that the frequency of tropical cyclones may be slightly decreasing over the South Pacific basin, but that the cyclones which do form are of greater strength (Chand et al. 2022; Roberts et al. 2020; Ministry for the Environment & Statistics New Zealand 2023). Other studies find that the locations of tropical cyclone landfall and peak wind intensity have shifted poleward in recent decades (Kossin et al. 2016; Altman et al. 2018; Feng et al. 2021; Studholme et al. 2022). This is predicted to continue, which could mean that stronger cyclones reach New Zealand more regularly, counteracting the decrease in frequency of development. Undoubtedly, tropical cyclones will continue to intersect with the growing network of ecosanctuaries and conservation projects throughout New Zealand. Increased cyclone intensity may result in more ecosanctuaries being impacted across a greater area, and more severe impacts overall. A poleward shift of cyclones could further mean that more ecosanctuaries are exposed to cyclone impacts, including those in the South Island. Any increase in cyclone frequency would also reduce the recovery time between events, potentially exacerbating cumulative impacts with each subsequent event.

To best protect New Zealand's ecosystems, species, and conservation assets, we must embed lessons from Cyclone Gabrielle into practice. To help guide preparation and response of New Zealand ecosanctuaries to future extreme weather events, we recommend the following actions be implemented, acknowledging that many may already be addressed by some ecosanctuaries:

Preparation, response, and recovery

(1) Create, review, and regularly update ecosanctuary climate adaptation and disaster response plans. These should anticipate individual and collective risks to ecosanctuaries from extreme weather events and focus on mitigating impacts.

(2) Promote natural revegetation or plant suitable native vegetation to help stabilise existing landslides and secure areas vulnerable to future erosion, especially around high-value infrastructure such as pest exclusion fences. In high-risk areas, species should be carefully selected for known resilience to wind, flooding, salt spray, and sediment deposition.

(3) Remove large trees and overhanging branches adjacent to pest exclusion fences and other infrastructure to minimise potential for tree fall damage.

(4) Maintain a pest management buffer zone around pest exclusion fence boundaries to reduce pest densities and limit incursions if fences are damaged.

(5) Assemble a disaster response kit to facilitate rapid response and recovery after extreme weather events. This should depend on ecosanctuary size, type, and location, and might include items such as traps, bait stations, tracking tunnels, and trail cameras; temporary pest exclusion fencing and fencing materials; and shovels, machetes, chainsaws, and other tools.

(6) Use cyclone warning periods to prepare for the storm arrival. Depending on priorities, resources, safety, and likelihood of impacts, preparation activities might include clearing drains and slipways, installing sandbags, stowing valuable infrastructure, securing or moving pest management equipment away from waterways and coastlines, establishing monitoring around pest exclusion fences to rapidly detect incursions, and relocating high value species. Human resources are also an important consideration, as many of the people who work in ecosanctuaries are also involved in Civil Defence and other emergency services. This includes engaging contractors ahead of time so that critical infrastructure (e.g. pest exclusion fences) can be prioritised and rapidly repaired. These operating procedures should be developed and included as part of any

ecosanctuary disaster response plan.

(7) Conduct post-cyclone monitoring for non-native plant and animal invasions, especially in disturbed areas. Act swiftly to manage new and existing invasive species to prevent establishment and spread.

(8) Continue to improve capability, communication, and cooperation across the ecosanctuary network and with other stakeholders. These actions will enhance cross-project resilience and could improve financial security through insurance, corporate sponsorship, and local and central government support for extreme weather preparation and recovery.

Data, monitoring, and research

(1) Establish and/or maintain standardised monitoring programmes for at risk species and ecosystems. Standardised, long-term monitoring across multiple independent ecosanctuaries is crucial to quantifying change in ecosystem condition and populations of threatened species so that management responses in the aftermath of extreme weather events can be informed and effective. For example, simple biodiversity inventories could be used for spatial conservation planning, while more intensive approaches would be required to assess cyclone impacts and recovery (e.g. 5-minute bird counts and vegetation plots).

(2) Using the standardised monitoring data collected above, conduct a spatial conservation risk assessment of threatened species and ecosystems under a range of natural disaster scenarios. This analysis would identify gaps in our understanding of which species and ecosystems are being managed and where, so that risk can be distributed spatially, and swift action taken when a regional event is forecast. These data could also be used to develop intensity-impact functions for cyclones, which might inform trigger points to enact various parts of a disaster response plan.

(3) Non-charismatic and lesser-known taxa should be explicitly integrated into monitoring programmes and the ecosanctuary network. This would help to protect greater taxonomic and functional diversity, and to restore functioning and resilient ecosystems, a stated goal of many ecosanctuaries.

(4) Use the spatial conservation risk assessment to inform new and additional conservation translocations to better distribute risk, especially for range-restricted and intractable species (i.e. species that continue to decline despite conservation efforts; Hare et al. 2019). This could include assisted migration beyond a species' historical range.

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Supplementary material

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

Appendix S1. Table of North Island ecosanctuaries that were interviewed for the study.

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