



## Storm surge impacts on a coastal lizard community: a case study on how climate change may affect endemic species

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**Abstract:** Climate change threatens many species, and Aotearoa | New Zealand's lizards may be particularly vulnerable due to their limited dispersal ability and exacerbating threats such as invasive predators. In April 2020, a storm surge on the Wellington south coast inundated habitats occupied by northern grass skinks (*Oligosoma polychroma*) and Raukawa geckos (*Woodworthia maculata*). We compared pre- and post-inundation abundance, body size, and spatial distribution at inundated and unaffected sites. Inundation did not significantly affect the relative abundance of either species. However, inundation appeared to decrease *O. polychroma* body sizes on average in the populations and cause lizard distributions within study sites to contract. The lack of significant effects on abundance suggests that these populations had a degree of natural resilience to an acute flooding event. However, the frequency of significant storm surges is likely to increase within the next decades and it is unknown whether lizard populations are resilient to repeated disturbance.

**Keywords:** gecko, inundation, sea level rise, skink, snout-to-vent length

### Introduction

Climate change has begun to reshape nature at a global level, most noticeably by shifting the timing of biological events like migration and affecting morphological traits like body mass in some species (Yom-Tov et al. 2006; Cohen et al. 2018). Species typically respond to climate pressures by shifting their distribution or adapting their behaviour and physiology over time (Parmesan 2006). However, anthropogenic climate change may escalate too quickly for these responses to be effective (Radchuk et al. 2019). Common traits among Aotearoa | New Zealand's lizards may make them particularly vulnerable, including low reproductive capacity, slow turnover of generations, habitat specialisation, and limited dispersal ability (Huey 1982; Tingley et al. 2013; Brumby et al. 2025). Many of New Zealand's endemic lizard species are already threatened, exacerbating their vulnerability further (Hare et al. 2016). Predation from invasive mammals and habitat loss occurring since human arrival to Aotearoa has already caused one lizard species to become extinct and 96% of the remaining known species to become At Risk or Threatened (Hitchmough et al. 2021).

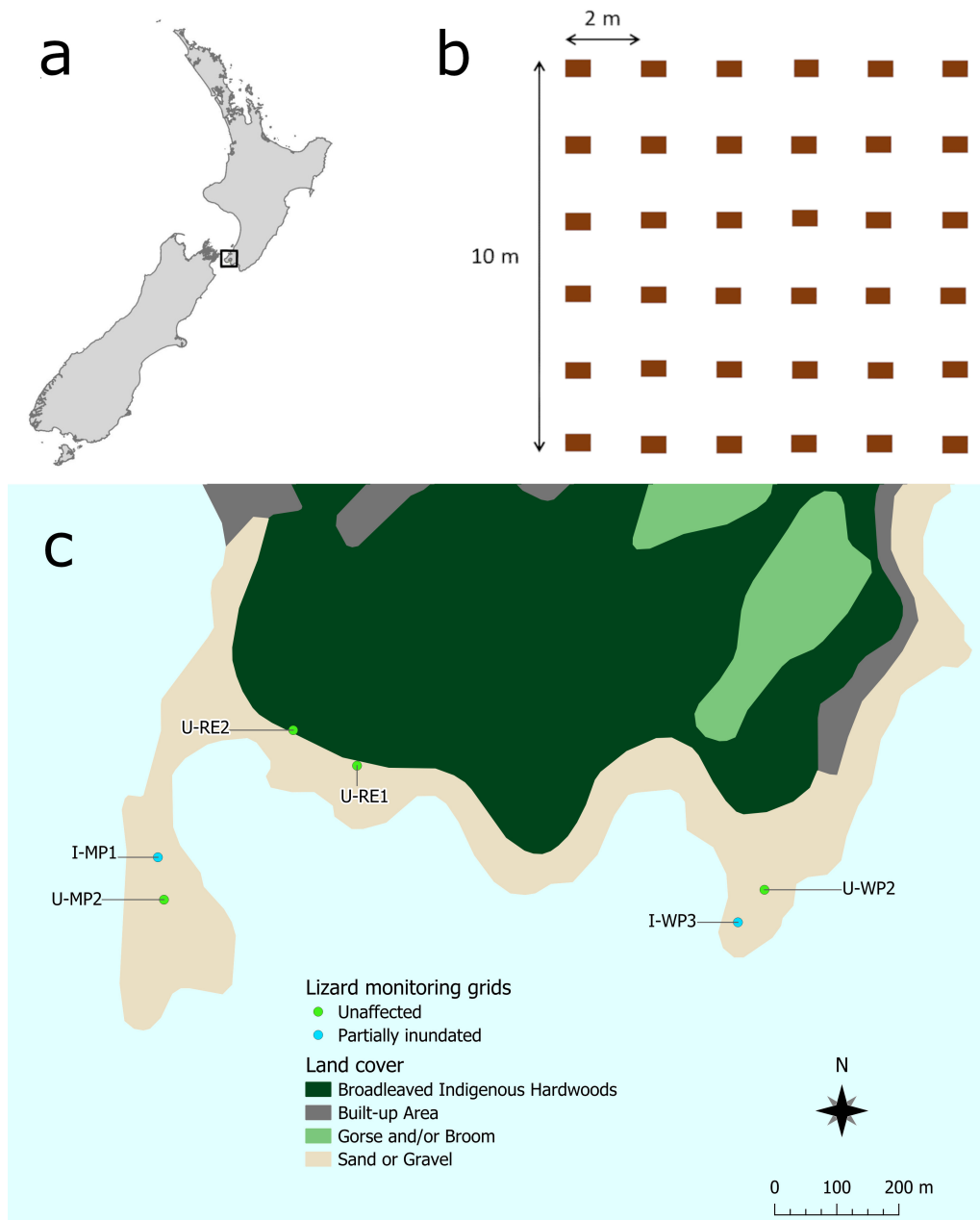
The impact of sea level rise on coastal ecosystems has been identified as the most significant climate change risk to the natural environment in Aotearoa, and a priority risk for further research (Ministry for the Environment 2020). Coastal habitats may be gradually inundated, eroded, and experience an increase in the frequency and severity of storm surge events

(Parliamentary Commissioner for the Environment 2015). In April 2020, a storm surge inundated the southern coastline of Wellington, New Zealand. The flooding affected several sites on the Miramar Peninsula where ongoing monitoring since 2017 has resulted in a dataset of lizard abundance, body size, and spatial distribution (Herbert et al. 2025). This existing dataset presented a unique opportunity to examine whether and how endemic lizards are affected by storm surge inundation. To investigate this, we used a before-after-control-impact approach to examine the abundance and body size of northern grass skinks (*Oligosoma polychroma*) and Raukawa geckos (*Woodworthia maculata*) in inundated and unaffected sites before and after the storm surge event. We also examined the spatial distributions of these species in inundated grids before and after the storm surge.

### Methods

#### Study sites

Six study grids within 150 m of the Miramar coastline were monitored across three sites (coded MP, WP, and RE) between 2017 and 2021 (Fig. 1). These represented a subset of 12 grids that had been monitored continuously since their establishment in 2017 for a habitat enhancement study completed in 2019 (Herbert et al. 2025). The habitat at each site was a mixture of coastal shrubland, cobble beach, and regenerating native shrubland (Herbert et al. 2025). Each site contained two c. 100



**Figure 1.** (a) General location of Wellington city on the North Island of Aotearoa New Zealand. (b) Layout of the lizard monitoring stations in each study grid. (c) Location of the grids and their status after the April 2020 storm surge. Land cover layers are from the Land Cover Database version 5.

m<sup>2</sup> non-contiguous monitoring grids each comprised of 36 monitoring stations spaced c. 2 m apart and arranged in a six-by-six grid (Fig. 1). Stations consisted of a pitfall trap covered with a double-layered Onduline artificial cover object (ACO).

Four of the six grids were unaffected during the April 2020 storm surge (coded as U: U-MP2, U-WP2, U-RE1, U-RE2), while two grids were partially inundated and able to be re-established for monitoring (coded as I: I-MP1 and I-WP3). Rocks and native plants had been previously added to I-MP1, U-RE2, and I-WP3 for habitat enhancement (Herbert et al. 2025). Damaged lizard stations at the partially inundated grids were re-established two days before the first post-inundation monitoring period began and recorded as disturbed traps (Appendix S1 in Supplementary Material).

#### Data collection

Six monitoring sessions occurred between October and April from 2017 until the storm surge in April 2020. An additional two post-storm monitoring sessions occurred in November 2020 and March 2021 (at seven and eleven months after the storm surge). Monitoring sessions varied from 5–12 days, and all pitfall traps and ACOs were checked daily during these sessions. The monitoring station in which each lizard was captured was recorded, and body size was recorded as snout-to-vent length (SVL) (Lettink & Monks 2016). Each individual was uniquely marked with a xylene-free pen (geckos) or toe code (skinks), then released into vegetation within one metre of the point of capture. Minimum daily temperatures during each monitoring session at the nearby (3.5–4 km) Wellington Airport weather

station were sourced from The National Climate Database (cliflo.niwa.co.nz) to account for weather effects on capture rates. Vegetation coverage after inundation was mapped in inundated grids for comparison with pre-existing maps.

### Calculation of abundance indices

Despite individuals being uniquely marked, we could not estimate abundance using a unified mark-recapture modelling approach because daily skink recapture rates were too low and geckos only received temporary marks (Herbert et al. 2025). As such, two indices were calculated to describe relative abundance; catch per unit of effort (CPUE) and the minimum number of known individuals ( $M_{t+1}$ ). These indices were calculated for every monitoring session at each grid as: CPUE = Number of lizards observed per grid (C) / days of monitoring (unit effort); and

$M_{t+1}$  = Number of marked individuals (M) / days of monitoring (unit effort)

CPUE includes marked lizards and lizards that were observed but not identified, so reflects the upper end of the possible range of abundance.  $M_{t+1}$  was also calculated to avoid over-estimating abundance due to multiple captures of some individuals and to minimise the effects of weather conditions and individual variation on lizard activity, which influences recapture probabilities.  $M_{t+1}$  therefore reflects a conservative estimate and the lower end of the possible range of abundance.

### Data analysis

Linear mixed-effects models (LMMs) were used to analyse the responses of relative abundance (CPUE and  $M_{t+1}$ ) and body size (SVL) to inundation. LMMs were initially specified with a random slope effect (Date|Grid) to account for temporal pseudo-replication introduced by repeating the monitoring sessions eight times at each grid. A simplified LMM with a random intercept effect (1|Grid) was considered if a random slope model resulted in singular fits and adopted if there was no significant effect on model likelihood (i.e. if the likelihood ratio test  $p(\chi^2) > 0.05$ ; Table 1). Response variables were transformed using the natural logarithm ( $M_{t+1}$  and CPUE) or Tukey's Ladder of Powers (SVL) prior to analysis to ensure model assumptions of normally distributed residuals and constant variation about the mean were met (Tukey 1977). Two fixed factors and their interaction were included in LMMs (Table 1; Wauchope et al.

2021). The Before-After (BA) term described whether each monitoring session occurred before or after the April 2020 storm surge. The Control-Impact (CI) term described whether a grid was inundated (grids I-MP1 and I-WP3) or unaffected by the storm surge (grids U-MP2, U-WP2, U-RE1, and U-RE2). The BA  $\times$  CI interaction term described whether a response variable was affected by inundation resulting from the storm surge. The average daily minimum temperature per session and whether traps were disturbed from re-establishment were also included in the models for relative abundance to account for their potential effects on lizard captures (Table 1). Linear Mixed-effects Models were performed in R version 4.3.1 with the "lme4" and "lmerTest" packages, and LMM fits were assessed with the "DHARMA" package (Bates et al. 2015; Kuznetsova et al. 2017; Hartig 2022; R Core Team 2023).

The spatial distribution of lizard captures in inundated grids was mapped before and after the storm surge. Vegetation coverage before and after inundation and the suspected area of inundation were overlain with capture distribution. Inundated areas were inferred from damage to monitoring stations. Skink toe codes were checked before and after the storm surge to identify survival of known individuals.

## Results

We made 584 observations of northern grass skinks (*Oligosoma polychroma*) and 430 observations of Raukawa geckos (*Woodworthia maculata*) in total across all six grids over 144 monitoring days between 2017 and 2021. No individuals found in I-WP3 or I-MP1 before the storm surge were encountered after inundation. One individual *O. polychroma* was found in an unaffected grid (U-MP2) before and after the storm surge. Fifteen observations of copper skinks (*Oligosoma aeneum*) were made at U-RE1 and U-RE2, but this species was not encountered in inundated grids.

Both relative abundance metrics responded similarly to inundation, therefore we only present the CPUE results here (Table 2; Fig. 2) and the  $M_{t+1}$  results can be found in Appendix S2-S3. Inundation did not significantly affect the relative abundance of either species (Table 2). However, we observed a temporary reduction in relative abundance of *O. polychroma* and *W. maculata* in inundated grids seven months after the storm surge (Fig. 2a). There was no significant

**Table 1.** Linear mixed effects models constructed for the responses of lizard relative abundance (CPUE and  $M_{t+1}$ ) and body size (SVL) to inundation. Abbreviations used: Date = date of the midpoint of each monitoring period, CI = control-impact BA = before-after, disturbance = number of monitoring stations where the pitfall and/or ACO was replaced prior to a monitoring period. A mixed effects model with a random slope effects structure (Date|Grid) was initially specified for all response variables. We investigated simplification to a random intercept (1|Grid) mixed effects model if a random slope model resulted in singular fits. A simpler model was accepted if the likelihood ratio test  $p(\chi^2)$  was greater than 0.05.

Fixed effects	Random effects
<b>All CPUE models and <math>M_{t+1}</math> models for <i>W. maculata</i>:</b>	
BA + CI + BA $\times$ CI + minimum temperature + disturbance	(Date   Grid)
<b><math>M_{t+1}</math> models for <i>O. polychroma</i>:</b>	
BA + CI + BA $\times$ CI + minimum temperature + disturbance	(1   Grid)
<b>Body size (SVL) response models:</b>	
BA + CI + BA $\times$ CI	(Date   Grid)

**Table 2.** Estimated fixed effects of linear mixed effects models of the responses of relative abundance as the catch per unit effort per grid (CPUE) and body size (SVL) to inundation. Significant effects ( $p < 0.05$ ) are indicated in bold. SE = one standard error, DF = degrees of freedom.

Response	Effect	Estimate	SE	DF	<i>t</i>	<i>p</i>
CPUE	<i>Oligosoma polychroma</i> <sup>a</sup>					
	Intercept	<b>2.122</b>	<b>0.592</b>	<b>33.940</b>	<b>3.584</b>	<b>0.001</b>
	BA (after storm surge)	0.473	0.323	37.355	1.464	0.152
	CI (inundated)	<b>-0.798</b>	<b>0.273</b>	<b>6.281</b>	<b>-2.920</b>	<b>0.025</b>
	Minimum temperature	<b>-0.134</b>	<b>0.043</b>	<b>32.591</b>	<b>-3.112</b>	<b>0.004</b>
	Disturbance	-0.027	0.037	31.989	-0.740	0.465
	BA (after) × CI (inundated)	-0.851	0.591	36.880	-1.439	0.158
	<i>Woodworthia maculata</i> <sup>a</sup>					
	Intercept	-0.172	1.521	29.028	-0.113	0.911
	BA (after storm surge)	-0.139	0.762	36.650	-0.182	0.857
	CI (inundated)	1.715	1.500	5.623	1.143	0.299
	Minimum temperature	0.024	0.097	31.528	0.250	0.804
	Disturbance	-0.002	0.082	31.889	-0.030	0.976
	BA (after) × CI (inundated)	-0.874	1.398	36.958	-0.625	0.536
SVL	<i>Oligosoma polychroma</i> <sup>b</sup>					
	Intercept	<b>20314.142</b>	<b>363.906</b>	<b>568.000</b>	<b>55.822</b>	<b>&lt;0.001</b>
	BA (after storm surge)	<b>3265.984</b>	<b>672.091</b>	<b>568.000</b>	<b>4.859</b>	<b>&lt;0.001</b>
	CI (inundated)	-1663.615	997.828	568.000	-1.667	0.096
	BA (after) × CI (inundated)	-3602.421	1909.364	568.000	-1.887	0.060
	<i>Woodworthia maculata</i> <sup>c</sup>					
	Intercept	<b>1.205 × 10<sup>8</sup></b>	<b>1.271 × 10<sup>7</sup></b>	<b>4.486</b>	<b>9.484</b>	<b>&lt;0.001</b>
	BA (after storm surge)	1.862 × 10 <sup>6</sup>	1.005 × 10 <sup>7</sup>	43.265	0.185	0.854
	CI (inundated)	-2.433 × 10 <sup>7</sup>	2.026 × 10 <sup>7</sup>	3.665	-1.201	0.302
	BA (after) × CI (inundated)	2.303 × 10 <sup>7</sup>	1.606 × 10 <sup>7</sup>	31.834	1.434	0.161

<sup>a</sup>Transformation applied to response variable:  $\ln(\text{CPUE} + 0.01)$

<sup>b</sup>Transformation applied to response variable: Tukey's Ladder of Powers,  $\lambda = 2.475$

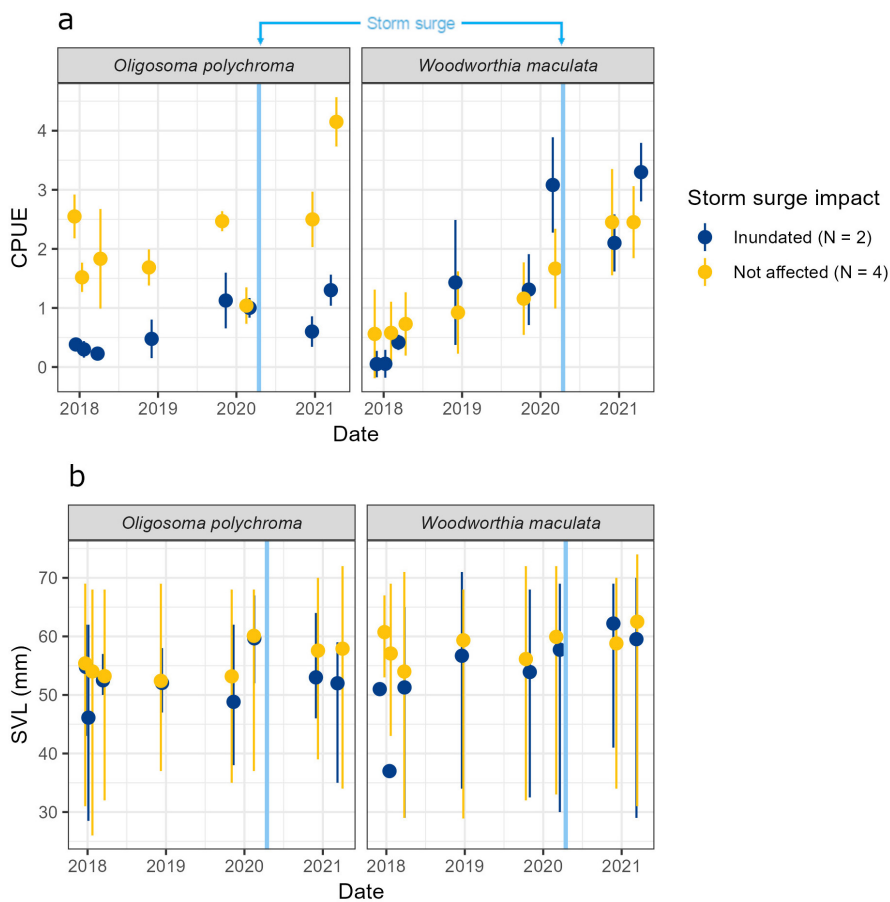
<sup>c</sup>Transformation applied to response variable: Tukey's Ladder of Powers,  $\lambda = 4.500$

difference in the average SVL of *O. polychroma* in inundated grids before versus after inundation (Table 2). In contrast, the average SVL of *O. polychroma* in unaffected grids was significantly higher after the storm surge (Table 2; Fig. 2b). Inundation did not significantly affect the average SVL of *W. maculata* (Table 2).

Changes to the spatial distribution of both species were observed in inundated grids. Prior to the storm surge, both species had gradually expanded their range across each grid. At I-MP1, lizards initially preferred the north-eastern corner, but by two months before the storm surge most areas of the grid were in use (Fig. 3). The storm surge is suspected to have inundated the south-eastern corner due to most traps in that area being washed away. No lizards were recorded in the inundated area at seven months following the storm surge, and by eleven months the southern side was still mostly vacant while the eastern side was once again in frequent use. At I-WP3, most of the grid was in use by *W. maculata* by two months pre-inundation. Seven months after the storm surge both species were found within the inundated area, but instead of being widely dispersed across the grid, *W. maculata* were found closer to vegetation (Fig. 3). The two species also overlapped less than before the storm surge, with *O. polychroma* mostly in the eastern half and *W. maculata* in the western half. The inundated areas had less vegetation coverage than before the storm surge (Fig. 3).

## Discussion

Inundation did not significantly affect the average relative abundance of the studied lizard species, nor the average body size of *Woodworthia maculata*. However, inundation may have had a negative effect on the *Oligosoma polychroma* population, given that average body sizes increased after the storm surge only in unaffected grids. Lower relative abundance of *O. polychroma* and *W. maculata* observed in inundated grids seven months after the storm surge may indicate that inundation had a negative effect on relative abundance in the short term. We did not collect data at enough time points after the storm surge (i.e. there were  $n = 2$  post-storm surveys) to allow us to statistically evaluate the impact of inundation on temporal trends or short-term changes in the measured response variables (Wauchope et al. 2021). Rather, our before-after-control-impact analyses were only able to compare average values before and after inundation (Wauchope et al. 2021). Therefore, a decrease in a response variable observed in the first survey after inundation would not necessarily result in a lower post-inundation average if more intensive monitoring had been conducted. Furthermore, the impacts of inundation may have been under- or over-represented in our analyses due to the small sample size. Nevertheless, the lack of a significant effect of inundation on average relative abundance suggests that these populations had some level of natural resilience



**Figure 2.** Relative abundance as (a) catch-per-unit-effort (CPUE) and (b) body size as snout-vent length (SVL) of study lizard species (*Oligosoma polychroma* and *Woodworthia maculata*) in grids that were inundated or unaffected by a coastal storm surge in April 2020. The storm surge is indicated by the vertical blue line. The data points after this line therefore demonstrate the potential impacts of the storm surge at seven months (November 2020) and eleven months after the storm surge (March 2021). Vertical bars around the mean CPUE are  $\pm 1$  SE, whereas error bars around mean SVL show the range of body sizes recorded from captured lizards. Points have been jittered along the x-axis for visibility.

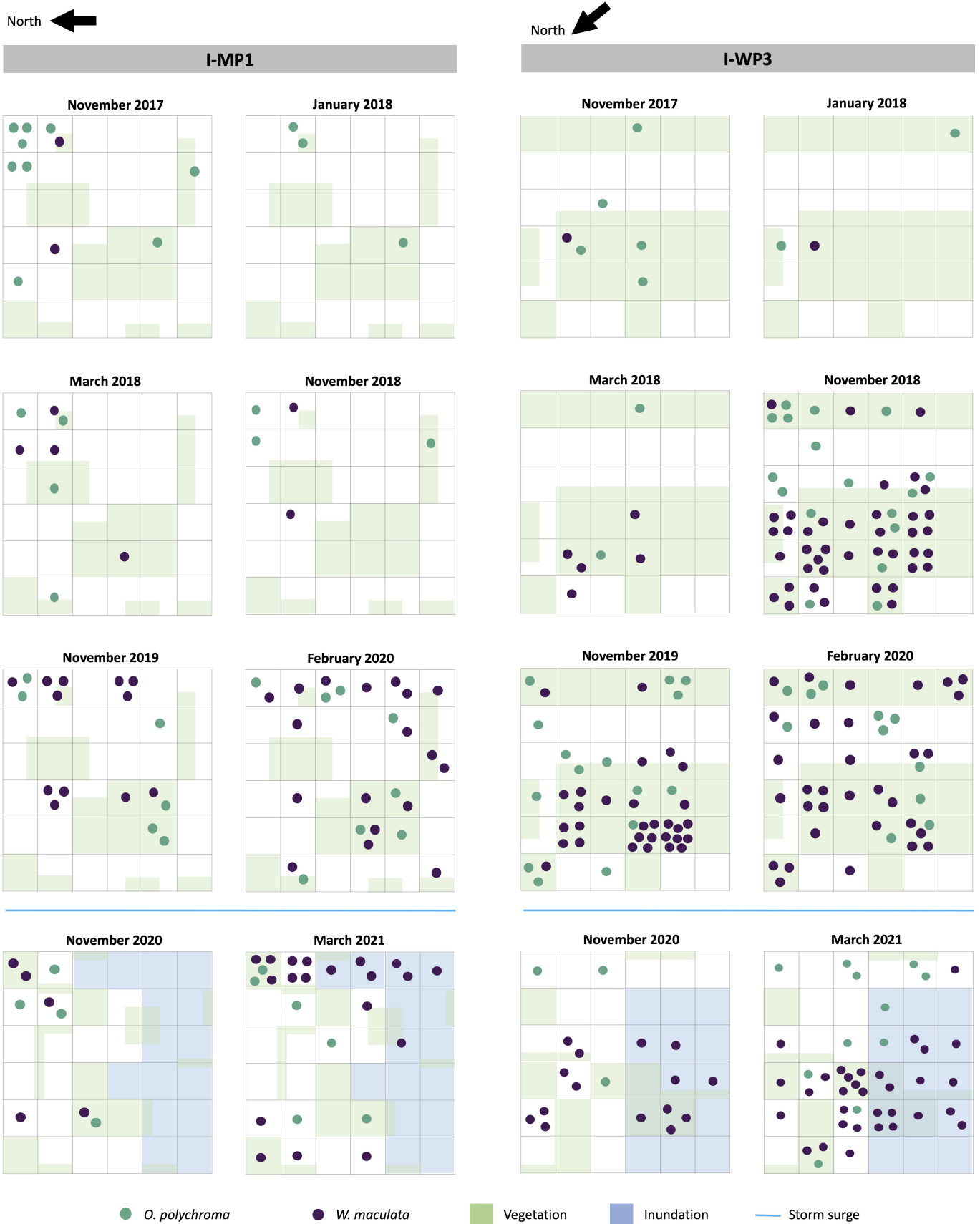
in the longer-term to an acute coastal flooding event. The apparent resilience to climate-related disruption may have been enhanced by an extensive predator free initiative in the area and previous habitat enhancement (Predator Free Wellington 2021; Herbert et al. 2025).

It is unclear whether the populations persisted through lizard survival or replacement from neighbouring sites. To have persisted by survival, individuals would have needed to withstand the flooding and then survive in damaged habitat. There was no evidence that individual lizards present before inundation were still present after, while estimated between-season recapture rates of *O. polychroma* before inundation were around 22% ( $21.9 \pm 5.3\%$ , Herbert et al. 2025). This drop in recapture rates supports replacement as the reason why the sites were populated following inundation. An increase in average SVL of *O. polychroma* after the storm surge was found in unaffected grids but not in inundated grids, suggesting that adult skinks may have been disproportionately negatively affected or that proportionally more juveniles were captured after inundation. A previous study found that average SVL decreased in male lizards after a hurricane; this study also identified that morphological characteristics such as longer limbs and large toepads increased clinging ability, and therefore survival (Donihue et al. 2018). The average SVL of *W. maculata* in inundated grids did not change significantly relative to SVL in unaffected grids following the storm surge. The differences in post-inundation body size metrics between the two species suggest three possible (non-exclusive) explanations: (1) that geckos had a greater clinging ability compared to skinks, and thus higher adult survival, (2) that there was an advantage of smaller bodies in skinks but not in geckos, thus juvenile

*W. maculata* experienced the effects of inundation at similar rates to adults, or (3) that inundated sites were repopulated by both juvenile and adult *W. maculata*, but predominantly by juveniles of *O. polychroma*, thus resulting in lower mean SVLs for *O. polychroma*.

Our observations can only serve as a record of how the studied populations of two lizard species responded to the April 2020 storm surge, and cannot be used to predict lizard population responses to other coastal flooding events. Resilience may not be demonstrated in response to events of greater magnitude or repeated inundation. The frequency and severity of storm surges are increasing on the south Wellington coast. The April 2020 event was considered significant but came only seven years after another similarly severe storm surge in 2013. Several other storm surges of varying severities have occurred in Wellington since April 2020. Based on the median of several climate change scenarios, a 1-in-100 year storm surge event may occur annually by 2065 with 30 cm of sea level rise, and on each tide by 2100 with 1 m of sea level rise (Parliamentary Commissioner for the Environment 2015). Available habitat for these populations may become completely inundated at this point, and topographical and infrastructure barriers along the south Wellington coast may prevent lizards from retreating inland.

Sea level rise poses a risk to all of New Zealand's coastline, so there may be implications for coastal lizards nationwide. The land area in New Zealand impacted by storm surges could increase by 27–31% under some climate scenarios after 2060, with some areas more vulnerable than others due to topography and tectonic activity (Paulik et al. 2023). *Woodworthia maculata* and *O. polychroma* also occupy non-coastal habitats, so



**Figure 3.** Lizard distribution at the inundated grids I-MP1 and I-WP3 from November 2017 to March 2021. These charts present the known lizard distribution over time and do not account for capture effort.

these species are likely to persist despite impacts on coastal populations (van Winkel et al. 2018). However, there are several threatened species that are restricted to coastal areas, such as the egg-laying skink (*Oligosoma suteri*), Taumaka skink (*Oligosoma taumakae*), Fiordland skink (*Oligosoma acrinasum*), shore skink (*Oligosoma smithi*), Tāhahi skink (*Oligosoma* aff. *smithi* “Three Kings, Te Paki, Western Northland”), and Chesterfield skink (*Oligosoma salmo*), and some of these species have multiple other traits that trigger high vulnerability to climate change (Brumby et al. 2025). The cobble skink (*Oligosoma* aff. *infrapunctatum* “cobble”), is specifically adapted to coastal habitat but faces threats from invasive predators, sea level rise, storms, and habitat loss from the development of storm surge infrastructure (van Winkel et al. 2018; Department of Conservation 2021). Eventually, intervention may be necessary for several habitat specialist or range restricted species that inhabit coastlines. In other ecosystems, New Zealand lizards will also face climate-induced impacts of habitat contraction, such as in alpine ecosystems which may grow smaller as atmospheric temperatures warm (Keegan et al. 2022).

Without further research and a plan to support affected lizards, Aotearoa | New Zealand’s vulnerable populations and species may be lost. Therefore, we recommend further research to identify: (1) the species and populations that are exposed to climate change risks; (2) what inherent factors, including morphological or behavioral characteristics, enable their resilience to climate change impacts, such as repopulation of disturbed areas; and (3) the potential of external factors such as predator control and habitat enhancement initiatives to enhance resilience to climate change. Significant progress has already been made on (1) and (2) with the release of the Department of Conservation’s Climate Change Vulnerability Assessment in January 2025, however there are further factors and interdependencies that should be explored, so (3) should be a priority area for future research. These findings should inform management planning to reduce species extinction risk.

This case study is an example of how one lizard community may be affected by just one type of climate impact. There will be numerous layers of climate impacts for all ecosystems once all variables are taken into account. Research is key to understanding and mitigating these effects.

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## Additional information and declarations

**Data availability:** The lizard monitoring data associated with this article have been provided in the supplementary material and online at <https://github.com/ms-sherbert/stormy-lizards>. Weather data can be accessed at <https://cliflo.niwa.co.nz/>.

**Code availability:** All code associated with this article is publicly available online at <https://github.com/ms-sherbert/stormy-lizards>.

**Author contributions:** Madeleine Deacon carried out most of the research for this article, conducted observational data analysis and drafted the manuscript. Sarah Herbert reviewed

and revised the draft, collected the lizard capture data at the grids between 2017 and 2019, and conducted statistical data analysis. Nicola J. Nelson reviewed and revised the article, and contributed to the design of the approach.

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## Supplementary material

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

**Appendix S1.** Table of Onduline artificial cover objects and pitfall traps replaced at each grid, two days before the first post-storm surge monitoring session began in November 2020.

**Appendix S2.** Figure showing  $M_{t+1}$  of lizard species (*Oligosoma polychroma* and *Woodworthia maculata*) in grids that were inundated and unaffected by a coastal storm surge in April 2020.

**Appendix S3.** Table showing estimated fixed effects of linear mixed effects models of the responses of relative abundance ( $M_{t+1}$ ) to inundation.

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