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RESEARCH

Challenges in alpine lizard conservation: evaluating monitoring methods for cryptic alpine geckos

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Abstract: Long-term monitoring is pivotal to understanding population trends in threatened species and quantifying the impact of conservation interventions. Effective monitoring methods are generally underdeveloped or absent for taxa inhabiting the alpine zone. In Aotearoa | New Zealand (NZ), the alpine zone covers c. 11% of the land mass and supports a diverse fauna of at least 34 native lizard species. We developed and tested the effectiveness of footprint tracking tunnels and rock lifting for monitoring two cryptic alpine gecko taxa, cascade geckos (*Mokopirirakau* "Cascades") and orange-spotted geckos (*Mokopirirakau* "Roy's Peak"), in NZ's Southern Alps during the austral summer. Field sampling occurred within defined strip transects and included two variants of rock lifting (one highly constrained involving lifting just 30 pre-selected marked rocks per transect; the other involving lifting all rocks judged suitable) and baited footprint tracking tunnels. All sampling methods resulted in low capture rates, plus highly variable detection rates for tracking tunnels. Rock turning counts of cascade geckos were consistently higher than those of orange-spotted geckos, and marked rocks returned counts 2.5–6.3 times higher than other rocks lifted within the transects. We used simulations to assess the ability of our trialled methods to detect a 20% change in gecko counts (hand searching via rock lifting) or detection rates (tracking tunnels) over a 10-year period, across 10 years for rock lifting and 15 years for tracking tunnels. None of our methods were capable of reliably detecting a rate of change equivalent to a 20% increase or decline, even if sampling effort was increased. Our results highlight the difficulties in developing effective monitoring methods for species that are sparse or difficult to detect. We conclude that alpine geckos will require longer monitoring timeframes than their lowland counterparts due to their slow life histories and cryptic nature.

Keywords: long-term monitoring, method development, *Mokopirirakau*, monitoring techniques, Open Bay Island gecko, systematic searching, tracking tunnels

Introduction

Alpine ecosystems possess high levels of species diversity and endemism and act as refugia for species severely affected by anthropogenic change, including habitat destruction and more intense predation and competition by invasive species, at lower elevations (Tocher & Marshall 2001; Hilbert et al. 2004; Koumoundouros et al. 2009; Grabherr et al. 2010; Popescu et al. 2013; Hitchmough et al. 2016; Knox et al. 2021). However, the inaccessible nature of the alpine zone, and the fact that its resident species are often cryptic and thus hard to detect and/or present at low densities over large areas, has hampered the development of reliable methods for long-term monitoring (Hitchmough et al. 2016; Knox et al. 2019; Monks et al. 2021). Long-term monitoring is crucial to quantify the impacts of climate change and inform conservation management in alpine systems (Christie 2014; Jarvie & Monks 2014; Lettink & Monks 2016; Monks et al. 2021; Lettink et al. 2022; Bertoia et al. 2023). Innovative monitoring methods tailored for alpine ecosystems are thus desperately required to capture current and future declines in populations and to implement management actions in a timely manner (Koumoundouros et al. 2009; Hitchmough et al. 2016; Monks et al. 2021). Research is required to determine and develop appropriate methods for alpine taxa. Practical methodologies must balance cost and manual labour with robust population size and trend estimates (Jarvie & Monks 2014; Lettink & Monks 2016; Monks et al. 2021; Lettink et al. 2022).

Alpine lizards are perilously situated as some of the first indicators of how alpine ecosystems will be affected by climate change and the additive effects of other anthropogenic stressors (Koumoundouros et al. 2009; Grabherr et al. 2010;

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Sinervo et al. 2010; Wang et al. 2021). Climate change will cause the upwards contraction of the alpine zone as the climate progressively warms (Popescu et al. 2013; Bender et al. 2019; Walker et al. 2019). Alpine lizards rely on specific climatic and ecosystem conditions present in the alpine zone (Koumoundouros et al. 2009; Aragón et al. 2010; Caldwell et al. 2017; Bertoia et al. 2021). Species distribution modelling predicts alpine lizard distributions will change (in most cases detrimentally via contraction) in tandem with progressive thermal changes in their environment (Aragón et al. 2010; Sinervo et al. 2010; Popescu et al. 2013; Jarvie et al. 2022). Ultimately, such populations may become restricted to small and isolated ranges on mountain peaks, drastically impacting the genetic health and long-term persistence of these species (Hilbert et al. 2004; Koumoundouros et al. 2009; Sinervo et al. 2010; Caldwell et al. 2017; Bender et al. 2019). Yet, despite this dire outlook, alpine lizard populations are under-surveyed and rarely the subject of long-term monitoring (Hitchmough et al. 2016; Knox et al. 2019; Bertoia et al. 2023). Consequently, we currently lack basic ecological information on alpine lizards needed to verify species distribution models (Aragón et al. 2010; Caldwell et al. 2017; Chukwuka et al. 2023).

In Aotearoa | New Zealand (NZ), the alpine zone covers c. 11% of the landmass and supports a diverse fauna including at least fourteen gecko and twenty skink species (O'Donnell et al. 2017; Hitchmough et al. 2021; Knox et al. 2021). All NZ alpine lizards are "Data Poor" according to national conservation assessment guidelines (Townsend et al. 2008; Hitchmough et al. 2021). Without robust monitoring to estimate population sizes and trends, it remains unclear whether most alpine lizard taxa in New Zealand are genuinely rare or simply very difficult to detect (Tocher & Marshall 2001; Jarvie & Monks 2014; Hitchmough et al. 2016, 2021; Knox et al. 2021). Worldwide, a higher proportion of Data Deficient species are predicted to be threatened with extinction than their data-sufficient counterparts (Nori & Loyola 2015; Borgelt et al. 2022). There are widespread concerns that an inability to detect deleterious trends in a timely manner and subsequently deploy effective conservation initiatives could lead to the extinction of alpine lizard populations and species (Sinervo et al. 2010; Nori & Loyola 2015; Borgelt et al. 2022).

Global threats to alpine ecosystems pertinent in NZ include climate change, invasive species, and, to a lesser extent, anthropogenic development (Christie 2014; O'Donnell et al. 2017; Macinnis-Ng et al. 2021; Wang et al. 2021; Chukwuka et al. 2023; McAulay & Monks 2023). Notably, the distribution of invasive mammalian predators is currently climate-limited (Christie 2014; Foster et al. 2021a). As the climate warms, the distributions of invasive mammalian predators are predicted to shift upwards in elevation, thereby jeopardising alpine lizard populations via greater predation pressure through a combination of greater abundance and predator diversity (Towns & Daugherty 1994; Christie 2014; O'Donnell et al. 2017; Foster et al. 2021a, b; Macinnis-Ng et al. 2021; Jarvie et al. 2022; Bertoia 2023). Mammalian predator control programmes in NZ have started explicitly protecting alpine fauna, albeit in limited areas, in addition to well-known fauna below the treeline (McAulay & Monks 2023). Yet, our understanding of the effectiveness of predator control for the alpine zone is currently limited to NZ's avian fauna (Weston et al. 2018; Rawlence 2019). Thus, there is limited understanding of the effects of such control measures on alpine lizards, or ways to adjust these controls to protect a wide range of animal types.

For the most part, monitoring methods well-developed and used for lowland lizard taxa have not been trialled for alpine lizards for reasons such as access and cost (Tocher & Marshall 2001; Bertoia et al. 2023). Systematic searching, artificial retreats, and live-trapping are all widely used to monitor ground-dwelling lizard species at low elevations (Lettink & Hare 2016; Lettink & Monks 2016). For example, pilot work aimed at the detection of alpine orange-spotted geckos (*Mokopirirakau* "Roy's Peak") has indicated that baited tracking tunnels and systematic hand searching by rock lifting have the potential for effective use in long-term monitoring (Knox et al. 2019). However, repeated rock lifting may damage gecko habitat, degrading refuges used for behavioural thermoregulation and shelter, even when care is taken to replace rocks as found (Bertoia et al. 2021; Chukwuka et al. 2023). Other techniques such as spotlighting and artificial retreats, which can be useful at low elevations (Lettink & Monks 2016), resulted in relatively few detections of alpine orange-spotted geckos (Knox et al. 2019). Trail cameras have been successfully used to monitor alpine skink and gecko behaviour (Bertoia et al. 2021, 2023). However, their utility for monitoring is currently limited due to the extensive person-hours required to process footage compared to the area covered (Bertoia et al. 2023). As such, there is a need to expand and trial other techniques for monitoring alpine lizards given the limitations of current techniques used for lowland lizard populations when applied to the alpine zone.

We compared the effectiveness of three sampling methods to monitor trends in alpine gecko populations by trialling these methods on two alpine gecko taxa in the Southern Alps, NZ. The methods we trialled were footprint tracking tunnels and two variants of hand searching by rock lifting. We analysed the resultant gecko counts and presence–absence data via predictive modelling and assessed the sensitivity of each method, and any species-specific differences, via simulation. Our modelling focussed on whether any sampling method could detect an increase or decrease equivalent to a 20% rate of change over ten years, a rate which represents meaningful change in a conservation management context. Our overarching aim was to find a suitable method that would enable evaluation of population trends in alpine geckos that could inform conservation planning and adaptive management.

Methods

Study sites and species

Our study focused on two gecko taxa within the genus *Mokopirirakau* (Reptilia: Diplodactylidae), which encompasses four described and four putative species that occur in the alpine zone (Knox et al. 2021). The NZ lizard taxonomy is dynamic; *Mokopirirakau* has five formally described species with a further six awaiting formal description; all are considered diurno-nocturnal (Tocher & Marshall 2001; King 2009; Hitchmough et al. 2021; Knox et al. 2021; Lettink et al. 2025). We focused on the largest known populations of two putative species that are geographically adjacent: the cascade gecko (currently *Mokopirirakau* "Cascades")[1] and

[1]A note on *Mokopirirakau* "Cascades": Due to preliminary findings from recent conservation genetic research, the population we focussed on is now considered to belong to the Open Bay Island gecko taxon (*Mokopirirakau* "Open Bay Islands"; Hitchmough et al. 2026). However, given that the genetic research is still in progress, and to retain consistency with recently published work on the same population (Lettink et al. 2025), we have chosen to retain the name cascade gecko throughout.

a b

Figure 1. Representative habitat at gecko sites in (a) South Westland and (b) Queenstown-Lakes district.

the orange-spotted gecko. Although these putative species represent divergent mitochondrial clades (Tocher & Marshall 2001; Nielsen et al. 2011), the boundary delineating these taxa is currently unknown.

Cascade geckos were studied at a single alpine site in South Westland, comprising boulder fields with exfoliating surface rocks in a tall-tussock grassland matrix (Fig. 1a) at elevations between 1000 and 1400 m (Lettink et al. 2025). Orange-spotted geckos were studied at a single site in the Queenstown Lakes District of Otago, referred to as "QL-A" in previous studies (Knox et al. 2019; Bertoia et al. 2021). Queenstown Lakes-A is an alpine scree (Fig. 1b) containing some rocky bluffs, tors, and boulder fields between 1300 and 1650 m. Exact locations are not given due to a significant risk of illegal collection for the pet trade (Auliya et al. 2016; Hitchmough et al. 2016).

Methods evaluated and selected for the monitoring trial

We reviewed potential monitoring methods for alpine geckos based on sampling techniques used for NZ lizards at lower elevations (Table 1). We considered the overall practicality of each method for use in the alpine zone and specifically for monitoring nocturnally-foraging species, on the basis of their cost, habitat disturbance, required labour, and previous results from work aimed at detecting alpine orange-spotted geckos in NZ (Knox et al. 2019; Bertoia et al. 2021, 2023). We then selected two key methods with potential for monitoring alpine geckos to trial in this study: tracking tunnels and systematic hand searching via rock lifting. Other methods including live trapping, artificial retreats, drones, and trail cameras were dismissed due to being impractical for long-term monitoring of alpine geckos in this habitat (Table 1).

Tracking tunnels were selected as a method to trial for alpine gecko monitoring because they are low-cost, involve low disturbance and require significantly less effort (i.e. fewer person-hours) to implement than most other monitoring techniques (Lettink & Hare 2016; Lettink et al. 2022). In the alpine zone, tracking tunnels can be installed and remain in the field for prolonged periods, potentially providing important long-term data on gecko activity. We were further encouraged by recent findings that tracking tunnels were twice as likely to detect skinks than pitfall traps at a lowland site (Lettink et al. 2022).

Systematic hand searching by rock lifting was selected in our monitoring trial because it is an effective survey method for alpine geckos in NZ (Tocher & Marshall 2001; Knox et al. 2019; Bertoia et al. 2021). However, it is labour-intensive, involves additional disturbance to gecko habitat, and can only be undertaken during weather conditions that favour gecko occupancy of liftable surface rocks. Previous work has focused on surveys (cf. monitoring) that involved rock lifting unsystematically across the entire area of suitable habitat (Knox et al. 2019; Bertoia et al. 2021). A variation to this method, involving systematic hand searching of pre-selected marked rocks, was trialled to reduce habitat disturbance even further (in comparison to indiscriminate rock lifting) and to help standardise sampling.

Implementation of selected methods

We trialled tracking tunnels and two variants of systematic hand searching, giving a total of three methods: (1) tracking tunnels, (2) hand searching by over-turning all liftable rocks potentially used by geckos within a defined area, and (3) a highly constrained version of hand searching that involved only lifting pre-selected, marked rocks within a defined area. At both sites, we trialled all three methods concurrently along the same pre-defined strip transects. Starting points and bearings for gecko monitoring transects were randomly selected from polygons of suitable habitat. Transects were 135 m in length, 10 m wide, and at least 50 m apart. The orange-spotted gecko site had eight transects; the cascade gecko site had seven transects due to the restrictive topography of the environment. Sampling of marked and unmarked rocks occurred simultaneously to avoid repeated disturbance.

Method 1: Hand searching by rock lifting along strip transects
A variable number of rocks (hereafter unmarked rocks) were turned along each strip transect (approx. 10 m in width). Experienced field workers walked the strip transect lifting all rocks that looked suitable as a retreat site and recorded all gecko encounters. Suitable rocks were chosen based on data from previous surveys of these alpine *Mokopirirakau* geckos

Table 1. Potential sampling methods considered for alpine geckos based on field surveying methods widely used for New Zealand lizards and/or previously trialled on alpine lizards.

Method	Description	Pros	Cons	References
Pitfall traps	Daily checks of baited traps	Pitfall trapping is a proven long-term monitoring technique for some skink populations in NZ (e.g. Towns & Elliott 1996; Monks et al. 2014).	Geckos are known to readily climb in and out of pitfall traps. Rockland habitats can impede or prevent the installation of pitfall traps. Traps must be checked daily to reduce physiological stress for the lizards. Short and changeable weather windows in the alpine zone can prohibit cost-effective monitoring and daily checks of live traps required under the Animal Welfare Act 1999. Alpine kea (*Nestor notabilis*) may interfere with traps.	Lettink & Hare 2016; Lettink & Monks 2016
Funnel traps	Daily checks of baited traps	Funnel traps are more likely to constrain geckos than pitfall traps. Funnel traps can be installed almost anywhere including the variable landscapes of the alpine environment.	Funnel traps are more expensive to deploy than pitfall traps, possibly an issue for long-term monitoring. Funnel traps must also be checked daily, and there is a risk of gecko mortality from by-catch of mice. Short and changeable weather windows in the alpine zone can prohibit cost-effective monitoring and daily checks of live traps required under the Animal Welfare Act.	Lettink & Hare 2016; Lettink & Monks 2016; Woolley et al. 2022
Footprint tracking	Detection of lizard activity by ink cards placed in baited tracking tunnels	Footprint tracking is widely used to measure mammalian pest activity and shows promise as a lizard monitoring method. Tracking tunnels have potential as a monitoring technique as they can remain functional for long periods, require few person-hours and are cheap. Tracking tunnels have been successful in detecting orange-spotted geckos. It is possible to discern gecko footprints from those of skinks.	Footprint tracking cannot identify individuals, rather it gives an index of gecko activity.	Jarvie & Monks 2014; Lettink & Hare 2016; Knox et al. 2019; Lettink et al. 2022
Systematic hand searching	Manually checking likely natural retreats along a transect or as a timed search	Hand searching is widely used in surveys and occasionally in monitoring of NZ lizards. A low-cost method, it is useful for geckos in open habitats with easily accessible/identifiable retreats. In many alpine environments lifting rocks is effective, especially where refugia are limited (e.g. Roughton & Seddon 2006). Rock-lifting surveys have been successful in detecting orange-spotted geckos and many other alpine lizards.	Repeated habitat disturbance and subtle degradation of retreat sites is a concern, particularly for geckos that require rocky refuges with specific dimensions for social aggregation, protection from small mammalian predators, shelter from the elements and thermoregulation.	Tocher & Marshall 2001; Pike et al. 2010, Lettink & Monks 2016; Knox et al. 2019; Bertoia et al. 2021
Systematic visual searching	Spotlighting for the reflective eye-shine and bodies of emerged lizards along a transect or as a timed search using a torch at night	Visual searching is an established cheap, quick, and proven method for nocturnal lizard surveying.	Previous survey work for alpine geckos resulted in extreme variability in counts, likely due to the inevitably variable weather conditions experienced on alpine field trips and observer bias. Further, it's not always safe to spotlight in boulder fields, and geckos spotlighted from a distance often evade capture in complex boulder fields.	Lettink & Monks 2016; Knox et al. 2019
Artificial retreats	Checks of artificial (Onduline) retreats for lizards	A good method for sampling lizards inhabiting environments where retreats are naturally limited. Artificial retreats are a low-effort method that has been effective for some habitats and species.	Artificial retreats may be less successful in rocky alpine environments where natural retreats are abundant. Further, occupancy of artificial retreats may increase with placement period or be affected by territorial behaviour. Alpine kea may interfere with retreats.	Lettink & Cree 2007; Bell 2009; Batson et al. 2015; Lettink & Monks 2016; Knox et al. 2019

Table 1. Continued.

Method	**Description**	**Pros**	**Cons**	**References**
Drones	Surveying inaccessible habitats using drones equipped with cameras	An emerging method for the detection of NZ lizards inhabiting inaccessible areas including the forest canopy, bluffs, cliffs, and rock outcrops. Possibly an effective technique for detecting lizards inhabiting inaccessible alpine areas.	The use of drones is underdeveloped in terms of monitoring, and drone approach distance could sometimes be an issue for species identification. Importantly, it has never been trialled for nocturnally-foraging species. Orange-spotted and cascade geckos spend most of their time under or obscured by rocks, and thermal imaging may not be sufficient to detect their presence because ectothermic geckos are generally at a similar temperature to the environment (Chukwuka et al. 2023).	Monks et al. 2022; Dubos et al. 2023; Davidge et al. 2024
Trail cameras	Camera station to record lizard activity	Camera stations allow species identification and reduce effort in the field. They have been informative for more in-depth analysis of lizard behaviour and ecology.	Camera stations are not suitable for landscape-level monitoring of small-bodied alpine lizards because they are expensive, have a narrow field of view, and require a large amount of image processing.	Lettink & Hare 2016; Bertoia et al. 2021, 2023

(Knox et al. 2019; Bertoia et al. 2021; Lettink et al. 2025). The smallest rocks (L × W × D) which have previously resulted in cascade and orange-spotted gecko encounters were 31 × 10 × 3 cm and 17 × 18 × 1.5 cm, respectively. The upper limit of rock size was determined by what could be safely lifted without risking injury to either personnel or geckos. Each lifted rock was returned to its pre-existing position (Bertoia et al. 2021; Chukwuka et al. 2023). The number of rocks checked along each strip transect varied between sites due to differences in the prevalence of potential retreat rocks along each transect; they also differed among surveys due to observer variability and logistical constraints.

Method 2: Hand searching by lifting marked rocks along transects

At 15 m intervals along each transect, we aimed to select and mark three rocks (hereafter marked rocks) within a 5 m radius of the centre line to ensure representativeness. However, up to five rocks were selected if there was a shortfall of suitable rocks from previous intervals. The rocks were selected on the basis of their ability to receive sunlight and in concordance with published dimensions for rocks used by orange spotted geckos as daytime refugia (mean dimensions of 88.7 × 62.6 × 9.6 cm, L × W × D) (Bertoia et al. 2021). A total of 30 marked rocks were identified per transect aiming to represent the best retreat sites available to geckos. Each rock was marked with a dot of orange spray paint to aid relocation.

Method 3: Tracking tunnels

Along each of these 135 m transects, we placed 10 tracking tunnels spaced c. 15 m apart, but with an allowance to choose an appropriate micro-site within 3 m of the designated spot. Tracking tunnels were constructed of 0.5 m lengths of 50 mm-diameter low-density black alkathene pipe (PGG Wrightson Ltd). A bait bag (small, perforated zip-lock bag containing either canned pear or both canned pear and a raspberry lolly (i.e. a sweet that captures the essence of ripe raspberries)) was stapled to the middle of each pre-inked card (Gotcha Traps Ltd.) and inserted into each tunnel. Cards were taped to both tunnel entrances using duct tape or skewered with a metal peg that was driven through a hole drilled in the alkathene pipe and into the ground to secure the tracking tunnel in place. Geckos are attracted to the tunnel via the bait and pick up ink on the soles of their feet when accessing the bait in the centre of the card. They then leave a trail of footprints on the white card on exiting the tunnel. Gecko footprints are highly distinctive from those of other taxa (Jarvie & Monks 2014), and there is only one gecko species at each study site, so we could be certain of identification to species level. One or more gecko footprints on a card was considered a positive detection for that tunnel.

Sampling sessions

We sampled each site over three trips during the 2020–2021 austral summer. Tracking tunnels were installed on our first trip. On the following two trips, they were checked for gecko footprints and replaced. Marked and unmarked rocks were lifted and checked for geckos on all three trips across the austral summer season at the orange-spotted gecko site and twice in the season at the cascade gecko site due to weather constraints.

We targeted weather windows encompassing at least three days of predominantly fine and sunny weather with light winds and day-time ambient temperature maxima exceeding 10 °C, ideally after multiple days of cold and wet weather to maximise occupancy of rocks by geckos. Ambient temperatures were measured at the start and end of all hand searches, c. 1.3 m above ground and in the observer's shade, using a Kestrel 3000 hand-held weather meter to confirm weather suitability for sampling. Hand searching was undertaken only when ambient temperatures fell within an optimal range (9.5−19.2 °C; based on 95% of captures of orange-spotted geckos from the QL-A site having occurred within this range; Bertoia et al. 2021). As such, we minimised variability associated with weather by restricting search effort to these optimal conditions.

Statistical analyses

All analyses, graphing, and examination of diagnostics occurred in R (version 4.5.1) (R Core Team 2008). Our assessment of the sensitivity of the field methodologies was accomplished through a two-stage process. In the first stage, we undertook empirical modelling to predict the coefficients associated with the gecko capture rates from rock lifting and presence-absence from footprint tracking using an information-theoretic multi-model inference approach (via Akaike's Information Criterion small sample correction, AICc, sensu Burnham & Anderson 2002). In the second stage, we simulated the ability of each of the three monitoring methods to detect a 20% change (increase or decrease over a 10-year period) in presence–absence and capture rates via Monte Carlo simulation, using the coefficients estimated from the highest ranked empirical models associated with each modelling scenario.

To analyse gecko capture rates associated with any type of rock lifting, we initially fitted a Poisson regression with an offset term to account for variation in the number of rocks lifted (by rock type i.e. marked and unmarked) between transects (thereby modelling captures as a rate per rock), utilising a generalised linear mixed model (GLMM) on the expectation that the effect of transect could be modelled as a random effect. However, our preliminary analyses failed to support the existence of random effects on this occasion. Subsequently, we fitted generalised linear models (GLMs). Our candidate model suite of GLMs contained additive combinations of explanatory variables: transect, species, rock type (i.e. marked or unmarked), temperature (average of that taken at the start and end of the survey) modelled as both a linear and quadratic function (given that lizard activity was expected to decline at both high and low temperatures), and the month of the survey (as a possible proxy for temperature). We also included a null model as an uninformative model baseline, and a model with an interaction between species and rock type. Model assumptions were checked using the "DHARMa" (Hartig 2020) and "car" (Fox & Weisberg 2018) packages. Model diagnostics found no issues associated with zero-inflation, over-dispersion, or multicollinearity.

To model presence-absence from tracking tunnels, we applied a similar process beginning with a logistic regression utilising a GLMM. In this particular scenario random effects were estimable. Subsequently, we tested whether transect or tracking tunnel nested within transect was better at describing the random error. We found that transect alone was best at describing the random effect and, consequently, it was included in each of the candidate models. Thereafter, we followed the model selection process using AICc as outlined above. However, the number of explanatory variables in this model was heavily reduced consisting only of: (1) species, and (2) the number of days the tracking cards were deployed for.

Simulation

We simulated the probability of correctly identifying a 20% increase or decrease over a 10-year period in the capture rate from rock-lifting (two scenarios: marked rocks only, and unmarked + marked rocks) or the presence-absence detection rate from tracking tunnels for both species across our three methods. This was accomplished by iteratively modelling the data through time and recording how often model selection was able to correctly identify the true model (under which the data were simulated) as the top-ranked model over a null model given the innate variation present in the data. The required equation of decline or increase for each of the scenarios was determined algebraically through the incorporation of a temporal effect that yielded the correct year-on-year adjustment sufficient to fulfil a 20% change over 10 years on the required scale of the link function (i.e. log for counts and logit for presence-absence).

For the rock-lifting simulation, the top-ranked model predicting the number of captured geckos: *species * type + offset(log(rocks))* was used to generate the coefficients that fuelled the simulations. Given the existence of strong species effects in the model, these simulations were disaggregated by species (see Results). While random effects were not supported in the empirical analysis, we felt it was reasonable to assume random effects might be present, but not necessarily discernible. Consequently, for each iteration in the rock-lifting simulation we generated random effects for each transect with a mean of zero and a standard deviation of 0.1. For simulations of combined marked and unmarked rocks when type = marked the number of rocks was set at 30, and when type = unmarked the number was based on the average number of rocks lifted: 83 unmarked rocks for the cascade geckos and 222 unmarked rocks for the orange-spotted geckos (thereby giving rise to 113 and 252 total rocks respectively for each species). Furthermore, we examined how the outcome varied with respect to the number of times the transects might be repeatedly sampled within a field season (i.e. 1, 2, or 3 times).

For each iteration of the rock-lifting scenario, the simulated data was subject to a four-model model selection process (*~1 (a null model), ~rock type, ~year,* and an additive *~year + rock type model* – as the data was already disaggregated by species). The top-ranked model was recorded for each iteration. This information was then summarised to find the rate at which the true model (*~year + rock type*), under which the data were simulated, was correctly identified as the top-ranked model across a 10-year monitoring period.

The presence-absence data from tracking tunnels were simulated using an analogous method to that of the count data, but without species disaggregation (which was not supported by the top-ranked GLMM). We used the time-varying model (ranked second via AICc; see Results) that included the variable 'days' as the model for simulation because: (1) it is reasonable to assume the detection of presence in tracking cards would be a function of the duration of the monitoring period, and (2) the second-ranked model had only fractionally less support than the top-ranked model (Table 1). We simulated 27 monitoring scenarios. These involved different numbers of transects (8, 10, 12), tracking card tunnels (10, 15, 20) and annual monitoring periods (10, 12, or 15 years). In the simulated GLMMs, random effects associated with each transect were simulated through a Monte Carlo approach using the mean and standard deviation of the random effects we had previously recorded empirically for the transects. Each iteration was subjected to a two-model model selection process comparing a null model against a ~year model (the true model) under which the data was simulated. Each scenario was simulated 250 times and repeated the analytical process of the previous simulation.

Results

Empirical analysis

Both alpine gecko species were infrequently detected regardless of method. At the orange-spotted gecko site, tracking tunnel cards were checked and replaced twice with an interval of 1.5–2 months (47 and 59 days respectively) between sampling sessions. This resulted in gecko footprint tracking rates of 11.3% (9/80 cards tracked) and 5.0% (4/80 cards tracked) in the first and second sampling periods, respectively. The eight transects were searched three times (also with 47 and 59 days respectively between sampling sessions) resulting in 26 gecko encounters of 19 individual geckos (five geckos were captured twice and one gecko was captured three times based on photo ID). Overall encounter rates were 1.7% (12 encounters from 720 rocks lifted) for marked rocks and 0.3% (14 encounters from 5327 rocks lifted) for unmarked rocks.

At the cascade gecko site, trips were one or two months apart, with cards replaced at intervals of 29–31 days, then 58 days. Tracking tunnels had rates of 4.3% (3/70 cards tracked) and 18.6% (13/70 cards tracked) for the corresponding time periods. The seven transects were searched twice, yielding 23 gecko encounters of 20 individuals (i.e. three geckos were caught during both searches), with an encounter rate of 2.3% (11 encounters from 480 rocks lifted) for marked rocks and 1.1% (12 encounters from 1101 rocks lifted) for unmarked rocks.

The model selection revealed the top-ranked model for encountering geckos via rock lifting included an interaction between species and rock type (marked or unmarked). The top ranked model had 35% model support and explained a moderate amount of the deviance in the data (unadjusted D^2 = 0.36). By comparison the second ranked model which suggested an additive effect between species and rock type had 30% model support and explained a similar amount of the deviance in the data (unadjusted D^2 = 0.34). The top six models (encompassing c. 96% of the model support) all shared species and rock type as explanatory variables (Table 2).

Back-transformed fitted counts (i.e. on the original count scale, but not corrected for bias introduced when back-transforming from a log link i.e. Jensen's inequality) for cascade gecko capture rates from the top-ranked model suggest that marked rocks generate c. 2.5 times higher gecko counts than unmarked rocks, while the effect is even stronger for orange-spotted geckos, with a c. 6.3 times higher gecko count (Fig. 2). Consequently, over 76 and 190 unmarked rocks would have to be lifted to equate to 30 marked rocks for cascade and orange spotted geckos, respectively. Additionally, expected counts of cascade geckos were higher than those of orange-spotted geckos (Fig. 2).

By comparison, tunnel tracking data were highly variable and relatively unpatterned. The top-ranked model describing the presence-absence of alpine gecko footprints on tracking cards was the null (intercept only) model (Table 3). The second-ranked model, which describes footprint tracking as a function of deployment time, predicted a slight increase in the probability of presence as deployment time increased. There was some model support (c. 41% between the third and fourth ranked models) for differences in tracking rates between cascade and orange-spotted geckos (Table 3).

Table 2. Model selection table exploring factors that best predict alpine gecko capture rates from rock lifting (encompassing all rock types) via generalised linear modelling. Models ranked by AICc (AIC with a small sample correction). Key: K = number of parameters, Δ AICc = difference in AICc value between the model and the top-ranked model, Weight = model weight, LL = log-likelihood (a measure of goodness of fit).

Model	K	AICc	Δ AICc	Weight	LL
species * type	4	157.12	0	0.35	−74.28
species + type	3	157.42	0.3	0.3	−75.54
species * type + mean.temp	5	159.32	2.19	0.12	−74.23
species + type + mean.temp	4	159.58	2.46	0.1	−75.51
species * type + poly(mean.temp, 2)	6	160.95	3.83	0.05	−73.87
species + type + poly(mean.temp, 2)	5	161.28	4.16	0.04	−75.21
species + type + month.year	6	162.52	5.4	0.02	−74.65
type	2	164.8	7.68	0.01	−80.32
type + mean.temp	3	166.85	9.73	0	−80.26
type + poly(mean.temp, 2)	4	169.08	11.96	0	−80.26
species	2	176.19	19.07	0	−86.01
type + transect	16	177.59	20.47	0	−68.19
species + type + transect	16	177.59	20.47	0	−68.19
species + mean.temp	3	178.24	21.12	0	−85.95
species + poly(mean.temp, 2)	4	179.86	22.74	0	−85.65
species	18	184.22	27.1	0	−68.11
null (intercept only) model	1	190.8	33.68	0	−94.37
species + transect	15	192.49	35.37	0	−77.24

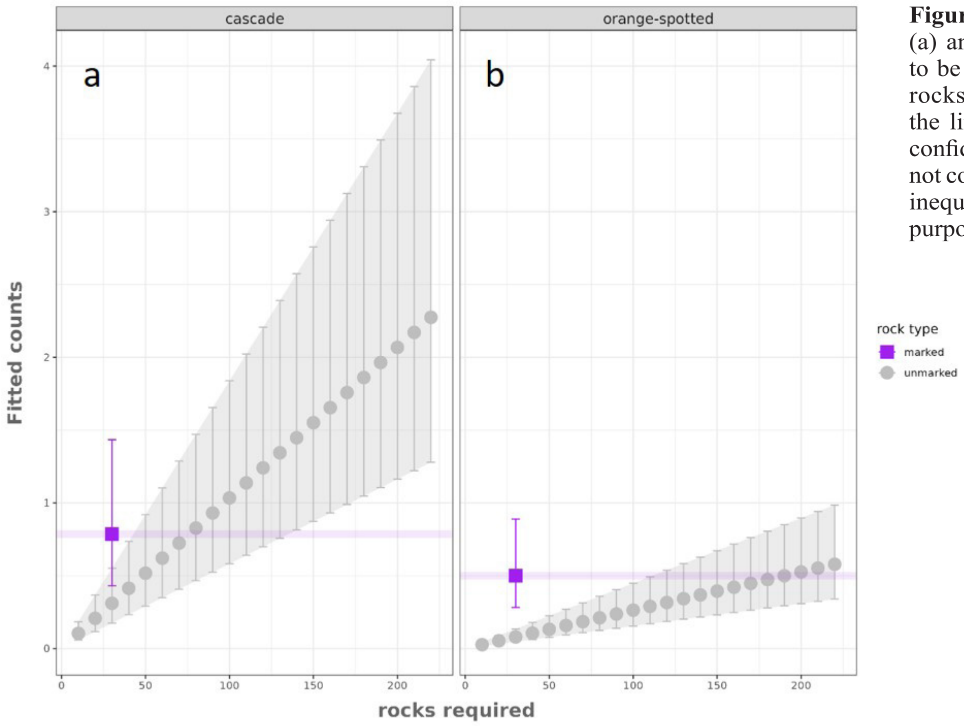

Figure 2. Fitted counts of cascade geckos (a) and orange-spotted geckos (b) predicted to be encountered on marked and unmarked rocks. Values are back-transformed from the linear predictor and shown with ± 95% confidence intervals. Note: these estimates are not corrected for potential bias under Jensen's inequality and are presented for comparative purposes only.

Table 3. Model selection table: factors influencing alpine gecko presence vs. absence from footprint tracking tunnels via generalised linear mixed-effect modelling. Key: K = number of parameters, AICc = Akaike information criterion with small sample correction, ΔAICc = difference in the AICc value between the model and the top-ranked model, Weight = model weight, LL = log-likelihood.

Model	K	AICc	Δ AICc	Weight	LL
null (intercept only) model + (1|transect)	2	192.81	0.00	0.30	−94.38
no. days + (1|transect)	3	192.90	0.09	0.29	−93.41
no. days + species + (1|transect)	4	193.14	0.34	0.25	−92.50
species + (1|transect)	5	194.07	1.26	0.16	−93.99

Simulation

Our simulations revealed that long-term monitoring based on rock-lifting with gecko capture using only marked or all rocks along a defined strip transect was not capable of reliably detecting an increase or decrease equivalent to a 20% change in capture rate over ten years (Figs. 3 & 4). While the ability to detect the true model increased with more monitoring sessions, at no point within any of the simulations did the probability of detecting the true model exceed 50%. Simulated scenarios where long-term monitoring was restricted to marked rocks performed substantially worse than those including all rocks (Fig. 3 vs. 4).

Simulations based on tracking tunnel data were not capable of detecting an increase or decrease equivalent to a 20% rate of change over ten years (Fig. 5). Again, the ability to detect the true model generally improved with increasing time (years of monitoring), number of tunnels and number of transects. However, even under the maximum scenario, in which the number of years of monitoring was increased to 15, the number of transects was increased to 12 and the number of tunnels per transect was increased to 20, at no point did the probability of detecting the true model over the null model exceed 50% (Fig. 5).

Simulations indicate that both rock lifting and tracking

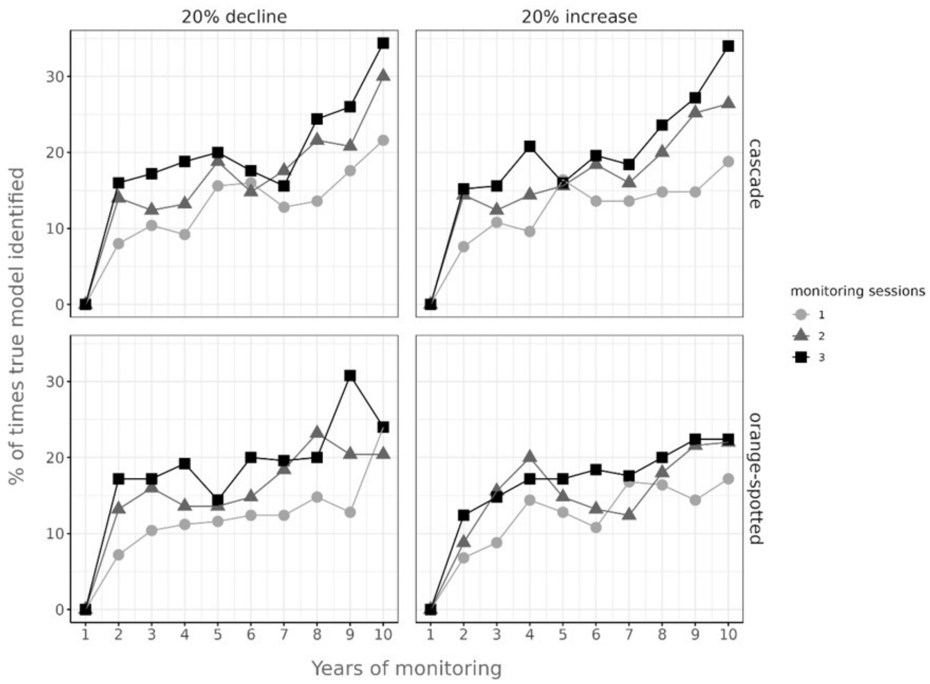

Figure 3. The percentage of times a two-model selection process, based on data simulating hand searching by rock lifting marked rocks only along strip transects, correctly identified the model describing a decline (a, c) or an increase (b, d) for cascade (top graphs) and orange-spotted (bottom) geckos as a function of the number of years of monitoring and number of monitoring sessions.

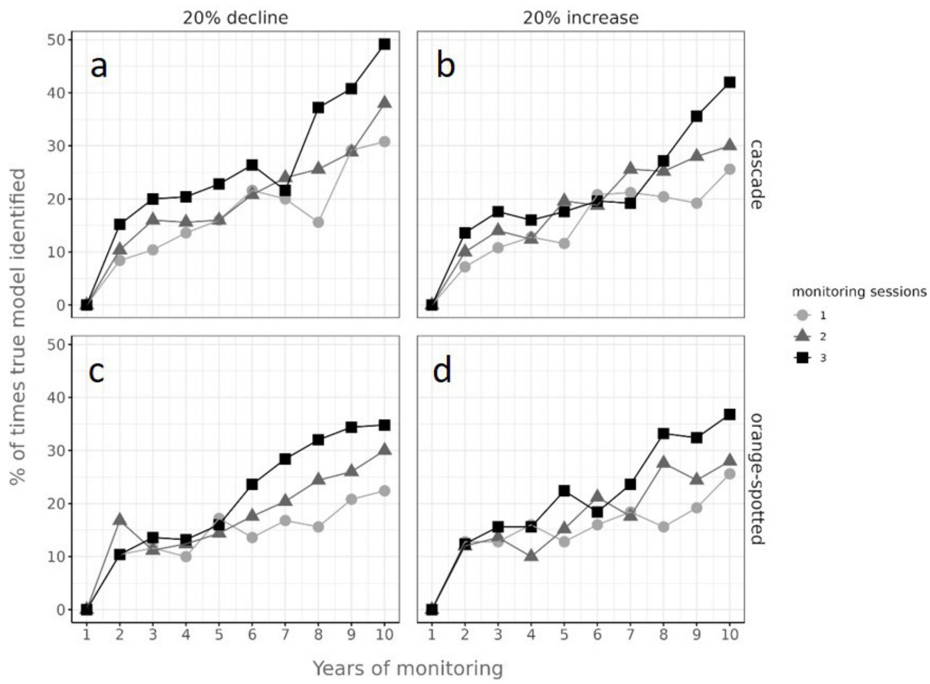

Figure 4. The percentage of times a two-model selection process, based on data simulating hand searching by rock lifting all rocks (marked and unmarked) along strip transects, correctly identified the model describing a decline (a, c) or an increase (b, d) for cascade (top graphs) and orange-spotted (bottom) geckos as a function of the number of years of monitoring and number of monitoring sessions.

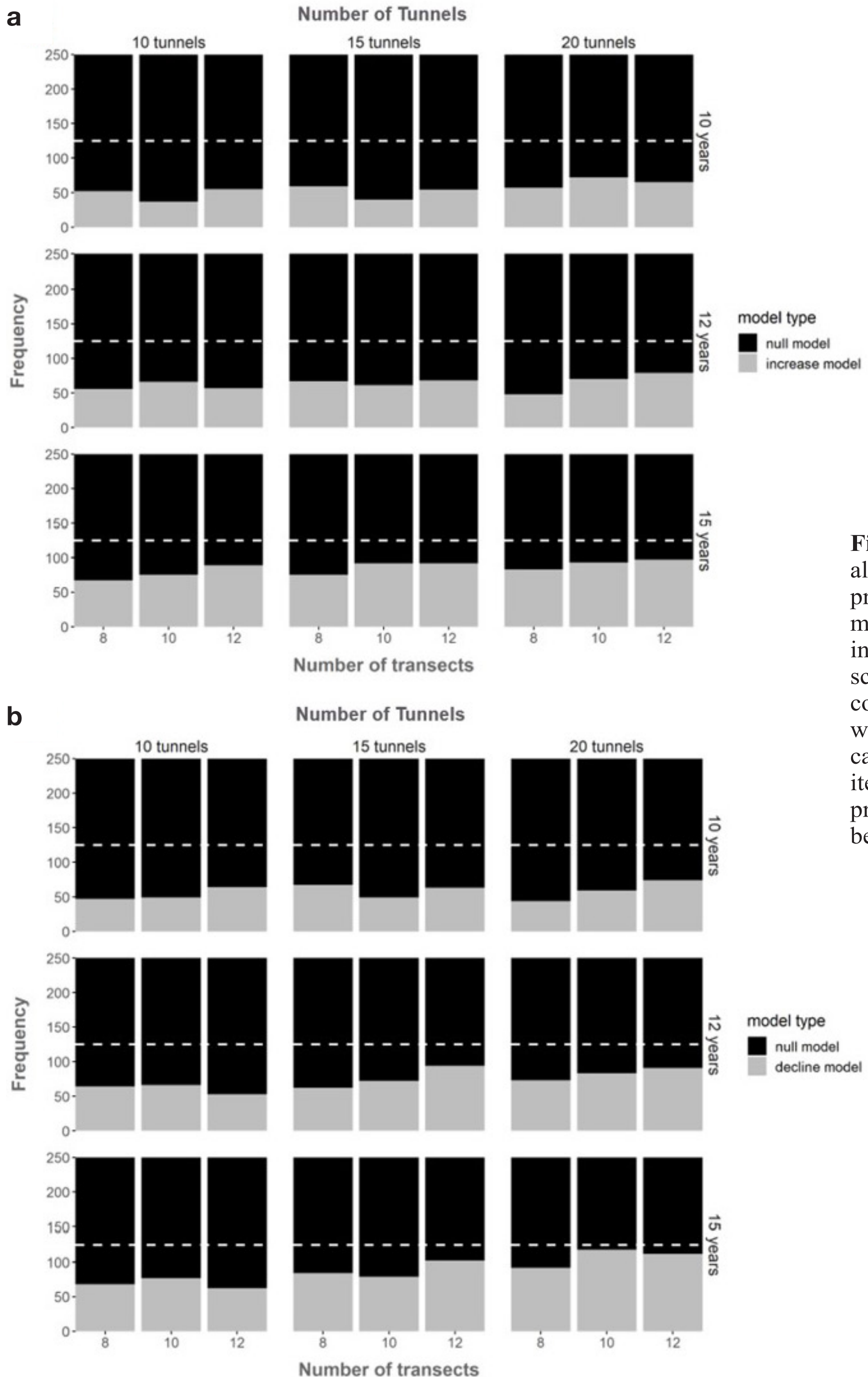

Figure 5. Simulation of frequency of the top-ranked alpine gecko model from a two-model selection process comprised of a null model and a 'true' model emulating a rate-of-change equivalent to 20% increase (a) or decline (b) over a 10-year period. 27 scenarios were considered consisting of different combinations of monitoring protocols associated with the number of years, transects, and tracking card tunnels. Each scenario was subject to 250 iterations. White dashed line = 50% threshold. Note: prior modelling suggested there was no difference between gecko species in terms of their detectability.

tunnels methods may be marginally more sensitive at detecting a population decrease than an increase (Figs. 3–5). In all cases, the probability of detecting the true model improved with increased monitoring effort and monitoring for a longer period. Hand searching by rock lifting utilising all the available rocks appeared to be the most sensitive method, and under some scenarios approached a 50% chance of detecting the true model. This compares relatively favourably compared to the 15 years required using footprint tracking to reach a similar threshold, and c. 30% correct detection rate for rock lifting scenarios involving only marked rocks (Figs. 3–5).

Discussion

While cascade and orange-spotted geckos were capable of being detected using both systematic hand searching via rock lifting and footprint tracking tunnels, systematic searching via rock lifting of all available rocks on strip transects appears to be the best method of the three methods for detecting population change. However, our modelling indicates that, given the observed detection rates, none of the methods would be capable of reliably detecting a 20% increase or decrease in population size over a 10-year monitoring period, regardless of species.

Unfortunately, increasing the number of transects is not possible due to the limited availability of habitat at each site. Although increasing the number of monitoring sessions is theoretically possible, it would require a proportional increase in funding for a guild of alpine species that have only very recently been elevated to threatened status (Hitchmough et al. 2026), despite their population trajectory not being determined.

This result highlights the conundrum of developing robust monitoring methods for detecting moderate changes in cryptic populations of data poor species in remote alpine ecosystems, particularly when they use sub-surface habitat for a high proportion of time. Collectively, our results suggest that alpine geckos need longer monitoring timeframes to detect meaningful population trends than their lowland counterparts, primarily due to their lower probability of detection, as previously identified for cascade geckos (Lettink et al. 2025). Such timeframes will need to be factored into the monitoring timelines of any management programmes targeting these gecko species.

Counts of cascade geckos obtained from by rock lifting were consistently higher than those of orange-spotted geckos. The higher number of detections of cascade geckos may be due to differences in habitat structure (e.g. boulder fields versus scree), which may influence ease of detectability, rather than reflecting a difference in true abundance or population density. The cascade gecko habitat consists of discrete boulder fields in a tussock matrix, where geckos are more likely to be detectable in accessible locations. In contrast, the orange-spotted geckos' habitat is more complex and consists of patches of scree where the rock is often numerous layers deep (Knox et al. 2019; Bertoia et al. 2021; Lettink et al. 2025; Fig. 1). In this habitat orange-spotted geckos may be able to retreat, or even bask, under numerous layers of rock, which logically reduces their detectability. They may also experience ground disturbance as the rocks are approached and have the opportunity to drop down into deeper retreats amongst the scree (CK, pers. obs.), whereas cascade geckos rarely have a similar option available in boulder habitat. Indeed, differences in habitat and refuge availability are known to impact the effectiveness of surveying methods for NZ lizards in other contexts (Lettink & Monks 2016; Knox et al. 2019; Lettink et al. 2022). Based on our observations we surmise that the ability to compare alpine gecko populations among sites is thus likely to be strongly influenced by lithology, which influences both detectability and population density.

Our simulations indicate that hand searching of all suitable rocks, as opposed to the more constrained version involving marked rocks, maximises the chances of detecting population trends over time. However, such an approach risks negatively impacting alpine lizard populations via repeated disturbance (e.g. Pike et al. 2010), and this may also result in reduced capture rates over time if geckos avoid previously disturbed sites. Hand surveying by rock lifting over a large area, while improving sample size, could lead to significant microhabitat disturbance (Díaz et al. 2006). Even subtle microhabitat disturbance through rock lifting has been correlated with reduced lizard abundance in other rock-dwelling species at lower elevations (Díaz et al. 2006; Pike et al. 2010). Hand surveying by rock lifting has historically been the most effective technique in surveying alpine gecko distributions (Tocher & Marshall 2001; Hitchmough et al. 2016; Lettink & Monks 2016; Knox et al. 2019) and will inevitably remain the most effective technique for inventory. However, despite our results, we recognise the potential deleterious impact of repeated microhabitat disturbance caused by rock lifting as a monitoring method (Díaz et al. 2006).

Hand searching of selected, marked rocks would enable us to substantially mitigate against microhabitat disturbance. Marked rocks were chosen to represent ideal daytime refuges for alpine geckos, based on previous studies of orange-spotted geckos (Knox et al. 2019; Bertoia et al. 2021; Lettink et al. 2025). Gecko counts under marked rocks were 2.5–6.3 times higher than those of unmarked rocks. Such a result confirms the ability of experienced observers to identify preferred gecko habitat and that most rocks in the environment represent lower quality refuges. While restricting the number of rocks searched makes sense in terms of minimising habitat disturbance, removing unmarked rocks (averaging 83 and 222 per transect for cascade and orange-spotted geckos, respectively) from the simulation analyses reduced the overall number of gecko encounters. However, even when unmarked rocks were included in the simulation the technique was still insufficient to reliably identity a 20% change in gecko counts or detection rates within a 10-year time frame.

Results from tracking tunnels in this study were relatively unpatterned, limiting utility in deriving trend data. Recent research has demonstrated that combining eDNA sampling with tracking tunnel methods can boost detection rates (Reeves et al. 2025), and thus may improve the probability of detecting lizard population trends in a management-relevant timeframe. However, eDNA methods for terrestrial species including lizards are still in the development stage and false absences have limited effectiveness of the technique in other situations, including via soil sampling for Critically Endangered Arnhem rock skinks (*Bellatorias obiri*), in Australia (Hoffmann et al. 2024).

One alternate monitoring option is to explore the use of artificial retreats as a field technique, which may be particularly apt in alpine settings where natural, superficial rocks are limited. This technique has been piloted on a small scale in orange-spotted gecko habitat where natural superficial rocks were abundant, with limited success (Knox et al. 2019), but has not yet been tried in cascade gecko habitat where surface rocks are a limited resource. Similar methods have been used elsewhere. For example, artificial rocks placed in sandstone outcrops in Australia increased the detection rate and juvenile survival rate of lizards (Croak et al. 2013). Given the relatively high encounter rate of cascade geckos under selected, marked rocks, we hypothesise that artificial rocks placed in the alpine zone might form the basis for a successful monitoring technique in habitat where suitable natural rocks are limited. Artificial rocks that provide an ideal thermal refugia may have high levels of occupancy in the field, particularly in rocky tor habitat where surface rocks are limited (Croak et al. 2013). However, potential biases of artificial retreats, especially the possibility of yielding inflated counts as the placement period increases, must be acknowledged (Table 1; Batson et al. 2015).

We also recognise the possibility that an occupancy method (sensu MacKenzie et al. 2017) could be a monitoring option in this setting. Occupancy methods are an estimator approach in which the probability of a site being occupied is monitored over time. In the case of our alpine sites such a method would likely involve gridding up the area into numerous discrete spatial subunits. Within each monitoring season each spatial unit would be visited multiple times. Occupancy approaches have various advantages over individual (count) approaches in that they explicitly incorporate variation in detection probability and can robustly monitor colonisation/extinction dynamics in user-defined habitat units (MacKenzie et al. 2017). The technique is also being increasingly used for the monitoring of cryptic and threatened lizards (e.g. Hartley et al. 2023; Turner et al. 2023). For alpine geckos, an occupancy methodology could potentially be built around a marked rock system in which a random sample of marked rocks is lifted within each spatial unit but the sampling stops as soon as one individual is detected, thereby reducing overall habitat disturbance. Occupancy methods lend themselves to spatial representation which might be particularly apt for alpine geckos which are spatially constrained and likely to be affected by climate change or changes in rodent invasion dynamics (O'Donnell et al. 2017; Knox et al. 2019; Walker et al. 2019; Macinnis-Ng et al. 2021). Whether such a system would be any more sensitive than the current rock lifting method is unclear, but we suspect it could provide certain advantages in terms of reducing habitat disturbance and providing a better understanding of the spatial population dynamics. It is important to recognise that these metrics, whether counts, presence-absence detection rates, or occupancy rates, may not correspond proportionally to changes in real-world gecko abundance and density, rather they are envisaged as a benchmark for future managers to determine whether conservation interventions involving these alpine species are required or, once deployed, working.

Our study suggests that neither rock lifting nor footprint tracking are currently fit for the purpose of monitoring population trends in alpine gecko species within an ecologically meaningful timeframe. Simulations using data obtained by our methods showed all were incapable of reliably detecting a rate of change equivalent to a 20% increase or decline within ten years, even if sampling effort was reasonably increased. Our results highlight the difficulties in developing monitoring methods for data poor or cryptic species with limited ecological information. From this we conclude that alpine geckos, using existing monitoring methods, will require longer monitoring timeframes than their lowland counterparts due to their slow life histories and cryptic nature. We are cognisant that funding agencies may be reluctant to back conservation interventions for alpine geckos if there is little ability to measure project effectiveness within a reasonable time frame. For this reason, we feel it is imperative that the trialling and development of new field methodologies continue. We suggest trialling artificial retreats at sites where surface rocks are a limiting resource and the use of occupancy modelling as potential next steps. We also note the potential of eDNA as a monitoring tool for alpine geckos, but recommend method development at more accessible sites prior to deployment in the alpine zone.

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Additional information and declarations

Author contributions: JM, ML and CK conceptualised the research. ML and CK led data collection in the field. NW analysed the data. JM, HM and NW wrote the original draft of this manuscript. All authors contributed to review and revision of the manuscript.

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Data and code availability: All data and R code can be found at https://osf.io/gqf6c/. No GPS locations of gecko captures are provided to reduce the risk of poaching.

Ethics: Our research was undertaken as part of DOC's Alpine Research Programme, and as such a Wildlife Act Authorisation was not required. Geckos were captured as part of routine management of lizards under the Conservation Act 1987 (as accommodated by section 3 of the Animal Welfare Act 1999).

Conflicts of interest: The authors declare no conflicts of interest.

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