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RESEARCH

Habitat use of obligate alpine geckos from southern New Zealand

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Abstract: Animals that inhabit the alpine zone often persist in isolated and fragmented populations and possess a range of behaviours and adaptations that enable them to survive in these harsh environments. These characteristics can make them particularly susceptible to escalating anthropogenic threats, including climate change. New Zealand has a diverse lizard fauna, of which approximately 25% of species inhabit the alpine zone. The cryptic nature of many alpine lizards makes them difficult to find and study, limiting effective conservation management. We investigated the habitat use of the orange-spotted gecko (*Mokopirirakau* "Roys Peak"), a cryptic species found between 1150 and 1800 m a.s.l. in central and western Otago. We measured attributes of 30 plots based on gecko sightings and shed skins and 30 plots that we randomly allocated across the searched area. We evaluated gecko habitat use relative to availability by recording rock size, rock thickness, slope, percent cover of rock and shrubs, and plant community composition at both locations where geckos or skin were observed and random sites in the search area. We also trialled a novel method of tracking movements of these animals using fluorescent powder for understanding microhabitat use. We found that orange-spotted geckos select habitats with larger rocks and a greater proportion of rock cover. We did not identify a difference in the use of various vegetation types or communities, which likely reflects the greater importance of rock characteristics in determining gecko habitat selection. Tracking gecko movements using fluorescent powder offered new information about the habitat use of this species, including evidence of geckos using novel microhabitats such as small subterranean holes and tunnels. Our findings revealed key characteristics of habitats selected by orange-spotted geckos, extending our understanding of their ecology and contributing towards addressing the deficiency of knowledge about alpine lizard species that we hope will ultimately lead to improved conservation management.

Keywords: Animal tracking, fluorescent powder, habitat selection, lizard, *Mokopirirakau*

Introduction

The world's mountainous regions are characterised by high biodiversity and endemism (Myers et al. 2000), with around 87% of amphibians, birds and mammals found within the 25% of mountainous global land mass (Rahbek et al. 2019). Complex topography brings vastly different climates together over short distances, contributing to the evolution of numerous species with isolated populations and small ranges (Beniston 2003). Above the altitudinal limit of forests and between the permanent snowline in these mountainous areas is the alpine zone (Mark 2021). Characterised by harsh climates with low temperatures and extreme fluctuations (Körner 2021), the life that flourishes in these severe places is often highly specialised to survive these conditions. The nature of these severe environments, combined with naturally small and fragmented populations (Atkins et al. 2020) make alpine ecosystems sensitive to change.

Alpine New Zealand covers a considerable proportion of total land area (c. 11%; O'Donnell et al. 2017) including over 30% of public conservation land (Ministry for the Environment 2010). With mountain landscapes overrepresented in protected areas, many alpine ecosystems remain intact and relatively undisturbed by humans. Despite this, human influences including the introduction of a suite of invasive species such as mammalian predators have been implicated in declines in native fauna (O'Donnell et al. 2017; Norbury et al. 2022). The alpine zone is home to a diverse lizard fauna of at least 30 of New Zealand's 124 endemic species (O'Donnell et al. 2017; Hitchmough et al. 2021). Some of these species are found at lower altitudes while others are alpine obligates that occupy various habitat types including alpine shrubland, grassland, rocky boulder fields and sheer cliffs (Bell & Patterson 2008; Patterson & Bell 2009; van Winkel et al. 2018). Our understanding of these species is still undeveloped and growing, and while some may be obligate alpine species, others may represent relict populations limited to alpine refugia (Knox et al. 2019). Invasive mammalian predators pose the primary threat to lizards in New Zealand's alpine zone (O'Donnell et al. 2017), a threat which is likely to be more pronounced with climate change as the alpine climate becomes more thermally suitable to a greater diversity and abundance of invasive mammals (Walker et al. 2019; Macinnis-Ng et al. 2021).

Unfortunately, a lack of detailed knowledge about our lizards is a severe barrier to effective and targeted conservation

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management (Böhm et al. 2013; Hitchmough et al. 2016; Cox et al. 2022). The ecology and distribution of New Zealand's lizard species are poorly understood, with 72 of 124 known species currently listed as data poor (Hitchmough et al. 2021). Much of this lack of data is driven by the difficulty of surveying and monitoring some lizard species due to cryptic behaviour (Hitchmough et al. 2016; Lettink & Monks 2016; Monks et al. 2022). Lettink and Monks (2016) reviewed common survey techniques, including systematic searches, pitfall trapping, funnel trapping, and artificial retreats. These methods are limited in their application by species and habitat type, and currently we lack effective methods for detecting lizards that occur at low densities. Tools for tracking the movement of lizards is similarly limited, with use of common methods such as radio-telemetry proving difficult and unreliable for species that reside in rocky alpine habitat, such as Sinbad skinks (*Oligosoma pikitanga*; JMM, unpubl. data) and orange-spotted geckos (Bertoia 2020).

An alternative method with the potential for tracking lizards is fluorescent powder. Previously used to track small mammals (Nicolas & Colyn 2007), insects (Johansson 1959; Buxton et al. 2022), amphibians (Roe & Grayson 2008; Ramírez et al. 2017) and other reptiles (Furman et al. 2011), these powders offer the opportunity to provide insight into animal movements without some of the human bias associated with other methods. Safety of powder application has been tested in amphibians (Rittenhouse et al. 2006) and mammals (Stapp et al. 1994). While there are concerns of this technique making animals more visible to predators (Rittenhouse et al. 2006), application to the ventral areas only can minimise any increase in visibility.

Arguably, our best studied and understood alpine lizard species is currently the orange-spotted gecko (*Mokopirirakau* "Roys Peak") found in the mountains of central and western Otago (Knox et al. 2019). Despite this, even this species is still considered data poor on population trend according to the latest update to conservation status of New Zealand's reptiles (Hitchmough et al. 2021). Secretive and saxicolous, orange-spotted geckos are known from sparse populations between 1150 and 1800 m a.s.l. (Purdie 2022). Surveys by Knox et al. (2019) suggested that the species primarily uses scree, boulder fields and rock jumbles rather than other rocky habitat types such as tor or bluffs. While the species has not been found in shrubland and forests, Knox et al. (2019) have theorised that these habitats may have once connected today's fragmented populations.

Previous research by Knox et al. (2019) and Bertoia et al. (2021) has greatly improved our understanding of the ecology and physiology of orange-spotted geckos. While considered primarily nocturnal, individuals have been observed to cryptically thermoregulate and bask during the day (Bertoia et al. 2021) and observations of the reproductive cycle of orange-spotted geckos suggest that they may last for two or more years (Knox et al. 2019), longer than that recorded in any other lizard worldwide (Cree & Hare 2016). Previous surveys have predominantly located orange-spotted geckos by systematic daytime searching including lifting rocks by hand. Attempts to monitor these geckos using artificial retreats have not been successful, and temperatures are not consistently warm enough for spotlighting at night (Knox et al. 2019). Bertoia et al. (2021) made several attempts to monitor body temperature using bio-loggers, but they were unsuccessful in relocating individuals using very high frequency radio transmitters. Often the devices fell off and geckos could not be relocated despite the aid of the transmitters. We know little about how predators impact this species and have a limited understanding of their habitat preferences (Knox et al. 2019). Lacking a comprehensive understanding of habitat use limits our understanding of a species' status and the threats it faces, hindering adequate management of their populations. Understanding habitat use can enhance detection probability, enabling mark-recapture studies vital for obtaining population estimates, survival and reproduction information, which contribute to basic ecological understanding that can inform improved conservation management.

We aimed to improve ecological knowledge of orange-spotted geckos to help inform best practice monitoring and targeted conservation interventions. Firstly, we evaluated habitat selection of orange-spotted geckos. Based on our current knowledge of their ecology (Knox et al. 2019; Bertoia et al. 2021) and that of other New Zealand gecko species (Chukwuka et al. 2021), we predicted that orange-spotted geckos would select habitat with larger rocks and a higher proportion of rock and shrub cover relative to the availability of these habitat types in the landscape. Secondly, we examined whether fluorescent powder is effective for studying microhabitat use in alpine geckos. We defined success as the powder leaving visible trails that provided novel information about gecko habitat use not available from other viable methods.

Methods

This research was conducted in the Queenstown-Lakes district at a site known as QL-A (Knox et al. 2019). Actual site name and details are withheld due to concerns of poaching risks. The QL-A site consists of mostly scree slopes, with some boulder fields, rocky bluffs, and tors (Bertoia et al. 2021). The altitudes in the surveyed area ranged from approximately 1400 to 1600 metres above sea level. Common vegetation included *Chionochloa rigida*, *Dracophyllum rosmarinifolium*, *Aciphylla squarrosa*, *Pimelea oreophila*, *Leucopogon fraseri*, *Raoulia subsericea*, *Gaultheria depressa* and *Lycopodium fastigiatum*. The site also has very abundant non-native *Hieracium lepidulum*.

Gecko surveys

Daytime searches were conducted for orange-spotted geckos in March and April 2022. Three surveying trips took place: (1) 12–13 March, (2) 25–27 March, and (3) 8–9 April. Searches involved systematic searching by lifting rocks between 9 a.m. and 5 p.m., targeting weather windows previously found to be optimal for searching for geckos (fine weather with light or no wind and air temperatures between 10 and 20°C; Bertoia 2020). All large rocks encountered (at least approximately 30 by 30 cm) that could be lifted without excessive disturbance were turned. Due to the potential for this method to disturb gecko habitat (Pike et al. 2010; Lettink & Monks 2016), we took appropriate care to carefully restore rocks to their original locations. We chose systematic daytime searching by rock lifting because alternative monitoring techniques, such as artificial retreats (Lettink & Monks 2016), were ineffective for this species (Knox et al. 2019). We did not conduct night-time spotlighting searches due to a lack of warm (> 9°C) nights considered to be most suitable for night-time searches (Knox et al. 2019).

Geckos caught were measured and painted with fluorescent powder. We determined the snout-to-vent length (SVL), vent-to-tail length and sex of each gecko (where possible, geckos smaller than 58 mm are too small for identifying sex; Knox et al. 2019). We used a fluorescent powder obtained from Day-Glo Colour Corp (Ohio, USA) in the colours saturn yellow and corona magenta. After capture and morphometric measurements were made, we gently applied yellow or magenta fluorescent powder to each gecko's ventral surface and feet using a small, soft-bristled paintbrush (Fig. 1). We avoided the head and vent areas to minimise exposure of sensitive areas to powder (Stapp et al. 1994). To minimise the dispersal of powder into the environment we applied the powder to geckos away from the release location and inside a small, empty ice-cream container. Once powder was applied, we released geckos carefully at the entrance to the rock under which they were originally found.

We revisited and searched release sites with an ultra-violet flashlight approximately two to three hours before dawn on the morning after capture. We measured trails using a soft, 150 cm long measuring tape and described the microhabitat location every 30 cm along the trail. Descriptions included the presence and size of rocks, vegetation, whether the gecko was under cover or the distance to nearest cover. Cover was defined as locations where a gecko would not be visible without moving objects (i.e. vegetation or rocks). Trails ended when no more powder could be found, or the trail could not be followed (i.e. the gecko moved under large surface rocks).

We recorded capture global positioning system location, date and time, capture method (systematic daytime searching or incidental discoveries) and retreat rock size for each individual. We measured habitat in 60 plots across the site. This included 20 plots located where geckos were caught or sighted and the locations of 10 shed gecko skins (collectively, 'habitat use' plots). The remaining 30 plots were allocated randomly across the surveyed area spaced at least 30 metres apart ('habitat availability' plots). At each plot, we described the habitat within a circular two metre radius estimated using a peg and two metre string. Specifically, we recorded the sizes in centimetres (width × height × depth) of three rocks selected at random (using a randomly generated bearing and distance from centre) within each plot, as well as percent cover of rock, vegetation (sub-categorised as shrub, tussock, non-native and other) and bare ground within the plot. In addition, we recorded the slope, and a list of all plants present within each plot. A list of variables measured and justification for their inclusion can be found in Table 1.

Statistical analysis

We completed all analyses in R version 1.46.0 (R Core Team 2022), and all plots were created using the ggplot2 package (Wickham 2016). We used a principal components analysis (PCA) to compare habitat use by geckos with habitat availability to assess habitat use of orange-spotted geckos at the QL-A site using the *prcomp* function in R. We defined habitat use as presence, and availability was equated to absence. The predictor variables rock area, rock thickness, rock cover % and slope were included in this analysis. We $\log_{10}$ transformed all variables to reduce differences in scale.

We also explored key differences in habitat used versus habitat available using an information-theoretic approach. We constructed a set of candidate generalised linear models (GLMs) using the R *glm* function. We used four hypothesised predictors of gecko habitat use: rock area, rock cover %, shrub cover % and slope. We tested for multicollinearity among predictor variables and included variables with a variance inflation factor (VIF) less than 1.5 in our models. A common threshold for VIF is less than 10 (Chatterjee & Hadi 2006) and our variables fell well under this threshold. The binomial response variable was gecko present (1) or absent (0). Due to the limited previous knowledge of habitat use of orange-spotted geckos and strong hypotheses existing for all variables and all possible combinations (Symonds & Moussalli 2011), we

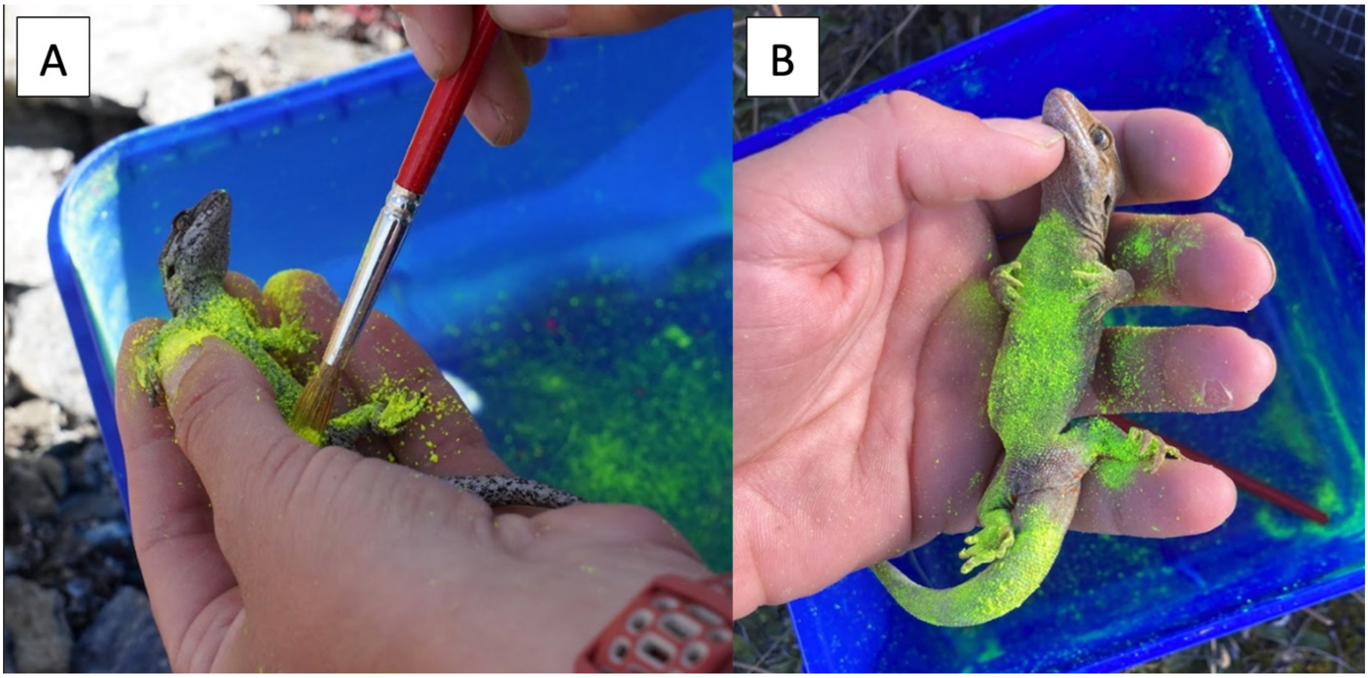

Figure 1. Photos of fluorescent powder method showing (a) application of fluorescent powder to the ventral surface of orange-spotted geckos (*Mokopirirakau* "Roys Peak") and (b) the amount and location of fluorescent powder coverage.

Table 1. Descriptions of predictor variables used in models for characterising habitat use of orange-spotted geckos (*Mokopirirakau* "Roys Peak") and habitat availability at an alpine site between 1400 to 1600 m a.s.l. within the Queenstown-Lakes District.

Variable	Description	Justification
Rock area (cm^2)	Mean estimated area (length × width) of three rocks selected at random from the habitat plot.	Large rocks are more likely to offer adequate space for a gecko. Larger rocks can also provide greater thermal heterogeneity, thus can remain useful shelters in a wide range of weather conditions (Chukwuka et al. 2021). Other saxicolous New Zealand gecko species have been shown to select larger rocks as retreats (Chukwuka 2021).
Rock thickness (cm^2)	The average thickness of the above three rocks within the habitat plot.	Rock thickness influences the rate at which rocks heat up (Huey et al. 1989). Thinner rocks can expose geckos to heat stress (Chukwuka et al. 2021). Thus, we hypothesised that geckos would select thicker rocks.
Rock cover %	Percent rock cover within the habitat plot.	As orange-spotted geckos use rocks as retreats, habitats with a higher proportion of available rocks were expected to be selected.
Shrub cover %	Percent shrub (defined as woody vegetation > 5 cm tall) cover within the habitat plot.	The diet of orange-spotted geckos is expected to include plant materials (e.g. berries) and insects (van Winkel 2018) associated with shrubs. They may also provide a source of shelter.
Slope (°)	Slope of habitat plot from lowest to highest point.	Orange-spotted geckos are absent from locations with frequent erosion (Knox et al. 2019), and steeper slope are expected to be related to less stability and greater disturbance to scree.

constructed the full suite of possible competing models using the *dredge* function of the MuMIn package (Barton 2022). We excluded interactions between variables due to the small sample size. We used Akaike's information criteria (AIC) to rank models by parsimony, with AIC values being corrected for the small sample size (AICc). Several models competed strongly for the best model (Burnham & Anderson 2002), so we used a multi-model inference and model averaging approach to explore the relative importance of all variables that we expected to influence gecko habitat use (Synomds & Moussalli 2011). We performed model averaging using the *model.avg* function in the MuMIn package (Barton 2022) on the models making up the 95% confidence interval of model weights.

To explore whether plant communities differed between used and available habitat, we conducted a non-metric multidimensional scaling analysis using the *metaMDS* function in the vegan package (Oksanen et al. 2022). This analysis used presence and absence data of plant genera in each of the 30 habitat use and 30 habitat availability plots to determine Jaccard distances (a measure of dissimilarity) between plots. We then used a permutational multivariate analysis of variance (PERMANOVA) to assess the difference between the used and available habitat plots, using the *adonis2* function in the vegan package (Oksanen et al. 2022).

Results

We observed 20 orange-spotted geckos in the 106 person hours of searching conducted throughout these surveys. Twelve individuals were adults (defined as > 70 mm SVL, the smallest size at which females were observed to be gravid by Knox et al. (2019), six were sub-adult size and two were juveniles. Five geckos were male, seven were female, and eight were too young to be accurately sexed. We also included locations and habitat descriptions of 10 shed orange-spotted gecko skins as evidence of gecko habitat use. The average dimensions of rocks lifted with geckos or gecko skins found underneath were 52.7 × 33.8 × 5.8 cm (length × width × depth).

Habitat use versus available habitat

The mean area and average thickness of rocks were both higher in the used habitat compared to the available habitat (Table 2). Similarly, the percentage of rock cover across plots was greater in used (56%) than available (31%) habitat, and used habitat had a minimum rock cover of 20% (compared with 0% for available habitat plots). Means for vegetation, shrub and tussock cover were higher for available habitat (66.5, 7.9 and 34.0% respectively) than for used habitat (43.0, 4.5 and 20.0% respectively), however the ranges for these groups were similar.

The PCA summarised the variation in habitat characteristics (Fig. 2), with the first two principle component (PC) axes representing 87% of total variance in the data. As the remaining PC axes each explained less than 9% of the variation, our subsequent analyses were based exclusively on the first two axes. Loadings of variables showed that PC1 was driven primarily by rock area (−0.91) and PC2 by rock cover % (−0.94) (shown by the direction and length of arrows in Fig. 2). Thus, positive scores on PC1 largely represents habitats with lower average rock area and positive scores on PC2 primarily represent habitats with less rock cover. Other variables less important in determining PC axes are shown in Table 3. Using GLMs, we found significant differences between available and used habitat for PC1 ($p < 0.001$, pseudo $r^2 = 0.73$), but not for PC2 ($p = 0.409$, pseudo $r^2 < 0.01$).

The highest ranked model included rock area and percent cover (Table 3). We excluded the variable rock thickness due to a high collinearity score (0.89) with rock area, and the greater importance of rock area as shown in the PCA. The Akaike weight of 0.32 suggests that no single model was best for predicting gecko habitat use. Models within six ΔAICc of the best model all included rock area, signalling that this variable was of particular importance. Slope and shrub cover appeared less important for predicting habitat use, with models including

Table 2. Mean and range of habitat characteristics for orange-spotted gecko (*Mokopirirakau* "Roys Peak") habitat use plots (where geckos or shed gecko skins were found) and habitat availability plots (randomly allocated across the surveyed area) at an alpine site between 1400 to 1600 m a.s.l. within the Queenstown-Lakes District.

Variable	Habitat use (n = 30)	Habitat availability (n = 30)
Rock area (cm^2)	486.5 (71.1–2412.4)	60.6 (0–341.8)
Rock thickness (cm^2)	3.6 (1.3–14.7)	1.4 (0–3.5)
Slope	25 (1–40)	28 (5–42)
Rock cover (%)	56 (20–90)	31 (0–90)
Vegetation cover (%)	43 (15–95)	66.5 (15–100)
Shrub cover (%)	4.5 (0–35)	7.9 (0–35)
Tussock cover (%)	20 (0–65)	34 (0–70)

slope and/or shrub cover percentage performing similarly to the null model (Table 3).

We estimated relative importance of variables by adding Akaike weights across the models where the variable occurred, reflecting the importance of each variable relative to all others (Burnham & Anderson 2002). Model averaging suggested that rock area was the variable of greatest relative importance (1.0), and was included in all models within the 95% confidence set of models (Table 4). Rock cover percentage had a variable importance of 0.83, while shrub cover percentage and slope had much lower values. The coefficient estimates for rock size and rock cover suggested positive relationships with gecko use. The 95% confidence interval range for all other variables included zero. We found no significant difference in the vegetation community between used and available plots (PERMANOVA; p = 0.435, r^2 = 0.016; Fig. 3).

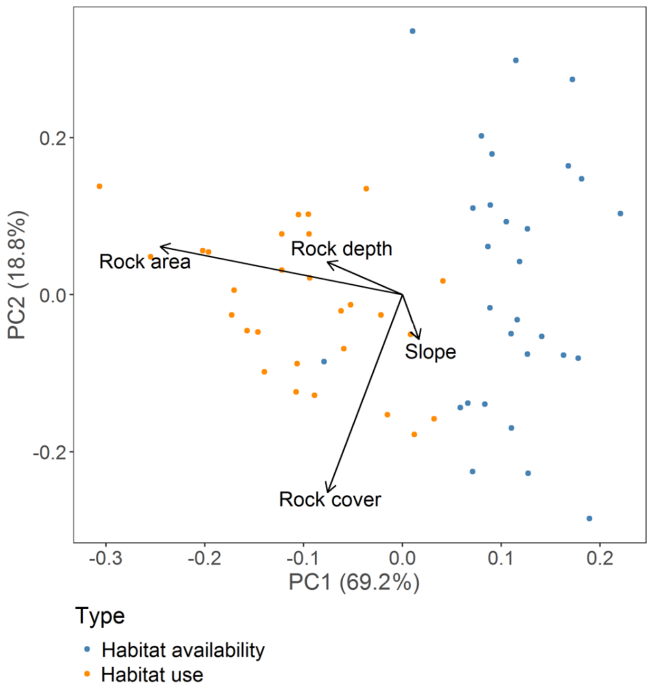

Figure 2. Principal components analysis (PCA) plot showing orange-spotted gecko (*Mokopirirakau* "Roys Peak") habitat use plots (determined by gecko sightings or sign) in relation to habitat availability (randomly generated plots across the surveyed area) at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District. Arrows represent the direction and magnitude of the habitat variables' contribution to the variation.

Fluorescent trails

We tracked 16 orange-spotted geckos at the QL-A site using fluorescent powder (see summary of trails in Table 5). We used yellow powder on 14 geckos and magenta on the remaining two geckos found within approximately 20 m of another gecko. Weather conditions were very similar for all trips (as trips were planned around ideal searching conditions), and thus these variables were not of interest for this study. However, no variation in weather conditions (i.e. light dew or frost) experienced in this study appeared to affect the visibility of trails.

The average trail length was 309 cm, with trails ranging from 30 cm to 790 cm in length (see Table 5 for summary of trails). Using a linear model, we did not detect a relationship between SVL and trail length (p = 0.308, r^2 = 0.078). We recorded geckos on or under rock for 63% of observations (n=159). Geckos were on vegetation for 31% of observations, including in tussock (15%), *Hieracium lepidulum* (6%), *Dracophyllum* spp. shrubs (4%), and *Gaultheria depressa* (4%). We observed geckos on bare ground in 5% of observations.

Trail locations were under cover (not visible from above without moving rocks or vegetation) for 48% of observations. Where gecko trail observation locations were not in cover, the average distance to nearest cover was 20.5 cm, with a maximum observed distance of 71.0 cm from cover. Trails were frequently located in areas that would not have been searched for geckos (did not contain rocks large enough for systematic rock lifting) or could not have been searched (underneath very large rocks or unstable scree). This included trails being observed moving through the middle of very dense tussocks with excellent cover. The smallest rock that trails were observed underneath was 10 × 10 × 2 cm. Geckos tended to move in relatively straight lines across open space or bare ground, and followed curves or zig zags following vegetation where it was available along paths.

We checked eight trails on consecutive nights, but powder trails appeared to be left for less than one night as no additional trail segments were found during observations after the second night. Trails were all well-defined on the first night of observation (see Fig. 4) and were easy to follow even when powder became sparse. We were only able to relocate one gecko (QLA15) while following trails. Geckos often left large patches of powder underneath large rocks, suggesting thermoregulatory behaviour (Fig. 4).

Table 3. Generalised linear models explaining the habitat use of orange-spotted geckos (*Mokopirirakau* "Roys Peak") at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District. Candidate models ranked by AICc score including the null model highlighted in grey for comparison.

Model	d.f.	AICC	ΔAICC	Weight	r^2	Cumulative weight
Rock area + Rock cover (%)	3	36.54	0	0.34	0.58	0.34
Rock area + Slope + Rock cover (%)	4	37.86	1.32	0.18	0.59	0.52
Rock area + Rock cover (%) + Shrub cover (%)	4	38.10	1.56	0.16	0.58	0.68
Rock area	2	38.40	1.86	0.13	0.55	0.81
Rock area + Slope + Rock cover (%) + Shrub cover (%)	5	39.45	2.91	0.08	0.59	0.89
Rock area + Slope	3	40.44	3.90	0.05	0.55	0.94
Rock area + Shrub cover (%)	3	40.62	4.08	0.04	0.55	0.98
Rock area + Slope + Shrub cover (%)	4	42.75	6.21	0.01	0.55	0.99
Slope + Rock cover (%)	3	68.84	32.30	< 0.01	0.28	0.99
Slope + Rock cover (%) + Shrub cover (%)	4	71.00	34.46	< 0.01	0.28	0.99
Rock cover (%)	2	72.23	35.69	< 0.01	0.21	0.99
Shrub cover (%) + Rock cover (%)	3	74.45	37.91	< 0.01	0.21	0.99
Slope	2	83.57	47.03	< 0.01	0.04	0.99
Null	1	83.85	47.30	< 0.01	0	0.99
Shrub cover (%)	3	84.56	48.02	< 0.01	0.06	0.99
Slope + Shrub cover (%)	2	84.68	48.14	< 0.01	0.02	1

Table 4. Model-averaged estimates of coefficients and relative variable importance of predictor variables explaining orange-spotted gecko (*Mokopirirakau* "Roys Peak") habitat use at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District. Importance of predictor variables was determined by model averaging of those within the 95% confidence set of models. The table shows averaged coefficients ± 95% confidence interval for each variable and the relative variable importance for each variable.

Variables	Coefficient	Relative importance
Rock area (cm^2)	17.02 ± 10.83	1.0
Rock cover (%)	1.69 ± 2.42	0.83
Shrub cover (%)	0.83 ± 2.47	0.29
Slope	−0.41 ± 3.31	0.36

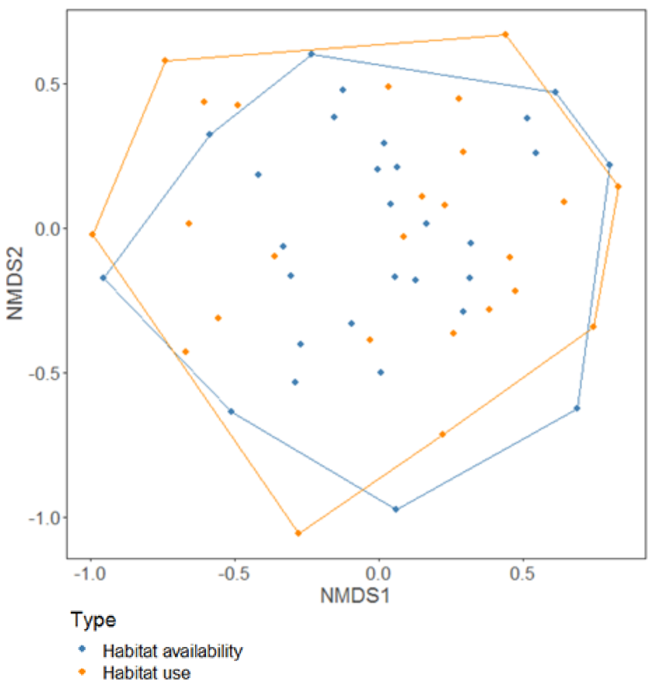

Figure 3. Non-metric multidimensional scaling (NMDS) plot showing plant community composition similarity among orange-spotted gecko (*Mokopirirakau* "Roys Peak") habitat use sites (determined by gecko sightings or sign) and habitat availability sites (randomly generated plots across the surveyed area) at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District.

Table 5. Demographics and fluorescent trail details for each of the 16 orange-spotted geckos (*Mokopirirakau* "Roys Peak") tracked using fluorescent powder at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District. Time and temperature were recorded at the time of capture. Trail length was measured from the release site to where no more powder could be found, or the trail could not be followed.

ID	Life-stage	SVL (mm)	Time	T (°C)	Colour	Trail length (cm)	Notes
QLA1	Adult	80	14:00	16.5	Yellow	30	Trail does not leave original rock. Large patch under this retreat, showing movement in all available spaces under this rock.
QLA2	Adult	71	14:45	20.4	Yellow	240	Large patch of powder under initial rock, then travels to thick *Dracophyllum rosmarinifolium* and disappears into subterranean hole.
QLA4	Adult	79	16:55	20.4	Yellow	60	Patches concentrated underneath original rock, then trail across small tussocks to another rock jumble.
QLA5	Juvenile	36	17:05	21.9	Pink	100	Trail appears to only show fleeing movement after release.
QLA6	Sub-adult	61	13:20	17.2	Yellow	275	Trail moving between rocks on tussocks and *G. depressa*, then cannot be followed into small subterranean hole.
QLA9	Adult	78	16:25	14.6	Yellow	370	Trail moves through scree, sometimes above the surface. Trail enters very loose scree and could not be followed without severe disturbance.
QLA10	Adult	83	16:45	14.6	Pink	120	Large patch under original rock, then travels over rock to second large retreat.
QLA11	Adult	79	12:35	21.7	Yellow	495	Travels from original rock across rocks and various vegetation types, mostly out of cover.
QLA12	Adult	79	13:25	17.9	Yellow	295	Trail goes deep into loose scree, cannot follow without severe disturbance.
QLA13	Juvenile	39	15:00	18	Yellow	285	Large patch at original rock, meandering trail within relatively small scree rocks. Trail moves too deep into this scree to be followed.
QLA14	Adult	81	13:20	15.7	Yellow	380	Trail moves from original rock to a very large tor, moving over rock, bare ground, and vegetation.
QLA15	Adult	78	09:35	15.4	Yellow	275	Moves over rocks from original rock to large rock that cannot be lifted without excessive disturbance.
QLA16	Sub-adult	68	10:20	18.1	Yellow	300	Very large patch of powder under original rock, showing lots of movement here. Then moves through scree, ending back at original location.
QLA17	Adult	75	12:25	19.9	Yellow	570	A large patch under original rock then moves in zig zag (mostly near vegetation) to large unliftable rock.
QLA19	Adult	89	13:10	13.3	Yellow	790	Trail moves from original rock and spends lots of time deep within large *Chionochloa rigida*. Trail fades at end.
QLA20	Sub-adult	51	14:15	16	Yellow	365	Moves from original rock to a large subterranean hole (some rocks inside).

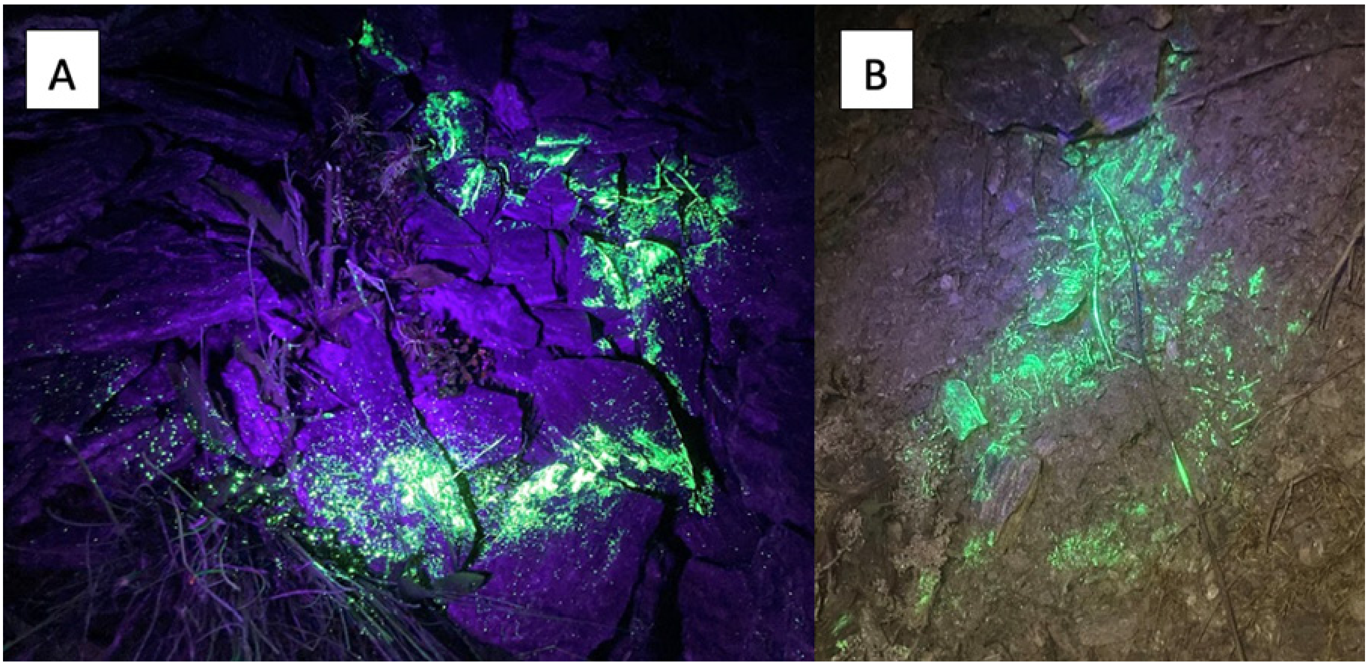

Figure 4. Photos of (a) a well-defined fluorescent powder trail and (b) a large patch from orange-spotted geckos (*Mokopirirakau* "Roys Peak") in scree rock habitat at an alpine site between 1400 and 1600 m a.s.l. within the Queenstown-Lakes District. Both photos show trails from single animals observed on the first night after application.

Discussion

Habitat use

We found evidence of key factors that may influence habitat suitability for orange-spotted geckos. The most important appeared to be the average size of rocks available in the habitat. The average size of retreat rocks where geckos were found in thus study were large (estimated area of 1781.3 cm^2), as were the average rock size in gecko presence plots (estimated area of 486.5 cm^2). Orange-spotted geckos have been previously found under rocks as small as 17 × 18 × 1.5 cm (Carey Knox, Southern Scales, unpublished data), and the smallest rock where a gecko was found in this study was 20 × 21 × 4 cm. In addition, gecko fluorescent trails were observed underneath rocks as small as 10 × 10 × 2 cm. In comparison, most of the available habitat contained very fine rocks smaller than the body size of the geckos. Rocks of a larger size can offer retreats that warm up slowly, with more stable temperatures in the space underneath (Huey et al. 1989). Chukwuka et al. (2021) also found that larger, thicker rock slabs often had greater thermal heterogeneity, offering geckos greater breadth of opportunities for thermoregulation without leaving the relative safety of a single retreat. Our finding is also consistent with the selection of larger retreats (rocks) found in a similar species, kōrero geckos (*Woodworthia* "Otago/Southland"), in a study near Macraes in Eastern Otago (Chukwuka et al. 2021). The rock measurements recorded in this study can guide future search efforts for orange-spotted geckos in the alpine zone.

Our hypothesis that geckos would select habitats with a greater proportion of shrubs was not supported. Furthermore, we found no evidence of geckos selecting habitat for the presence of any plant species. This is despite expectations that the diet of orange-spotted geckos would include plant materials and plant-dwelling insects as in other *Mokopirirakau* species, as well as observations of geckos using vegetation in this study and others (Knox et al. 2019). This lack of detectable selection for vegetation characteristics may reflect the significantly greater importance of rocks. It may also be an artefact of the way plant characteristics were measured in this study. The two metre radius habitat plots tended to include most of the dominant plants at the site, meaning the data collected was quite broad in scale. In contrast, Chukwuka et al. (2021) investigated the importance of plants by measuring the distance from suitable retreats to nearest vegetation, finding that geckos chose retreats closer to vegetation. Given the clear importance of rocks for a saxicolous gecko, further investigation of the selection of vegetation characteristics by orange-spotted geckos may be more effective if measurements relate vegetation to the rocky features of the habitat.

Effectiveness of fluorescent powder method

Our study demonstrated the promise of fluorescent powder as a more suitable tool than radio telemetry (which has been previously trialled for this species without success; Bertoia 2020) for tracking the fine scale movements and habitat use of orange-spotted geckos. This method may also hold potential for monitoring other alpine lizard taxa. The method revealed the use of several microhabitat types previously undocumented (Knox et al. 2019), that would not have been seen or easily located by spotlighting or hand searching. These microhabitats included within thick tussock grass and shrubs, underneath multiple layers of rock, in small holes or crevices and underneath smaller rocks than has been previously observed. These insights provide more nuanced guidance on locating these animals and the characteristics of areas that may require protection.

The apparent use of small holes or tunnels by orange-spotted geckos is notable and warrants further investigation.

Use of similar retreats has also been observed in Otago green skinks (*Oligosoma aff. chloronoton* "Eastern Otago") during post-translocation monitoring at Orokonui Ecosanctuary (Carey Knox, Southern Scales, pers. comm.). Several lizard species utilise subterranean retreats (Fenner et al. 2012; Moore et al. 2018; Ridley et al. 2018), including those created by other animals (Fellows et al. 2009). For example, the pygmy bluetongue lizard (*Tiliqua adelaidensis*) is known to exclusively occupy the burrows of spiders (Fellows et al. 2009). This information allowed conservation managers to consider the interaction between species, and how factors impacting spider populations (such as livestock grazing) could indirectly influence lizards (Clayton & Bull 2015). While the origin of the holes used by orange-spotted geckos is currently unknown, further investigation may reveal similarly important factors indirectly influencing habitat suitability.

Application of fluorescent powder was a simple, fast and low cost method. However, trails deposited revealed only part of a night's activity for each gecko tracked, limiting its usefulness for generating longer-term microhabitat use data. This limitation has been noted by other trials of fluorescent powder use on reptiles and amphibians (Dodd 1992; Stark & Fox 2000; Ramírez et al. 2017), and a comparison with other tracking methods found that fluorescent powder trails represented the shortest paths of all tracking methods trialled (Rittenhouse et al. 2006). Despite this, these studies also concluded that fluorescent powder tracking could provide useful, precise information about fine-scale movements that is not currently attainable using other tracking methods, such as radio telemetry. Fluorescent powder studies have been useful in determining ecological information including differences in daily movements between sexes of lizards (Stark et al. 2009) foraging distance of bats (Medellin et al. 2018) and the exact plants fed upon by nocturnal rodents (Lemen & Freeman 1985). Overall, fluorescent powder remains a valuable tracking method for tracking the fine-scale movements of many smaller animals including the cryptic lizard fauna of New Zealand.

Conclusion

Designing effective monitoring and management of cryptic alpine species requires a detailed understanding of their ecology and habitat use. A standardised monitoring method to improve searching success of orange-spotted geckos can be created by combining knowledge of selected rock sizes (this study) and optimal weather conditions outlined by Bertoia et al. (2021), maximising search effectiveness in a challenging environment. The fluorescent powder method revealed novel information about their microhabitat use, providing insight into reasons for low detection probability. Studying and protecting cryptic alpine species is challenging. The methods used in this study (and others, e.g. drones, Monks et al. 2022; Davidge et al. 2024) fill important knowledge gaps that can inform population trend monitoring and effective conservation management in challenging environments.

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Additional information and declarations

Author contributions: JR and JM conceptualised the project and developed the methods; JR conducted data collection and wrote the original draft; JR, JM and AB worked on the analysis and reviewed the final manuscript.

Data and code availability: Data and code are available from the corresponding author upon reasonable request, but exact location information won't be shared.

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