Microclimatic features of *Carlia rubrigularis* habitats, a study at Lake Eacham

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Abstract

This study looked at the habitats and behavioural characteristics of the leaf litter rainbow-skink (*Carlia rubrigularis*) at Lake Eacham within the Australian Wet Tropics. The Australian Wet Tropics bioregion contains both complex ecosystems and a diverse range of habitats, and is therefore conducive for studying functional ecology. Here, we aimed to characterise the microclimates of lizard habitats in the forest interior and at the forest edge. We measured two aspects of the lizard microclimates: the leaf litter on the surface of the forest floor, and the topsoil covered by the leaf litter. In the end, we found that leaf litter and topsoil temperatures are similar in the forest interior but are more different at the forest edge. Moreover, leaf litter temperature was found to be more variable in forest-edge habitats. Secondly, basking behaviours in *C. rubrigularis* were only observed when the leaf litter temperatures were higher than the topsoil covered by the leaf litter. Together, these findings may help guiding the design and parameterisation of more accurate habitat prediction models for *C. rubrigularis* as well as other more endangered skink species to facilitate conservation in the face of climate change.

Running Title: Characterising *Carlia rubrigularis* habitat microclimate

Key Words: Scincidae, edge effects, habitat modelling, functional ecology, Australian Wet Tropics, Lake Eacham, conservation

Introduction

Skinks (Family: Scincidae) are principal parts of tropical ecosystems. The biodiversity of tropical skinks holds both intrinsic values and functional ones, helping to sustain the resilience and longevity of the ecosystems they inhabit (Chapple *et al.* 2021; Huey *et al.* 2009; Williams *et al.* 2016). On the other hand, anthropogenic climate change is projected to have rapid, large-scale impacts on all parts of tropical rainforest ecosystems, including the distribution, abundance and diversity of many skink species, especially those that dwell at high altitudes (Huey *et al.* 2009; Kearney *et al.* 2009). This introduction provides background regarding the study site, important physiological characteristics of ectotherms, and the relevance of microclimatic characteristics and edge effects on habitat modelling. The paper concludes with a discussion of the significance and hypotheses of this study.

Background

Australian tropical rainforests have one of the most biologically diverse tropical ectotherms (Williams *et al.* 2010). The Wet Tropics of Queensland are recognised by the United Nations Educational, Scientific and Cultural Organization (UNESCO) to be of Outstanding Universal Value and are listed as a UNESCO World Heritage Site (Williams *et al.* 2016). Due to its long-term stability over millions of years, the Australian Wet Tropics contains ancient lineages from more than 600 million years ago, back to the period of the Gondwana supercontinent, and has been able to preserve some of the most complete assemblages of ancient and evolutionarily distinct species in the world (Roberts *et al.* 2021). The Australian Wet Tropics supports 45% of Australian vertebrate species with high levels of endemism (Schneider *et al.* 1998): 120 species are considered rainforest specialists with 90 found nowhere else (Schneider and Moritz 1999). The Australian Wet Tropics therefore offers unique materials for the study of evolutionary history and historical ecological response to climate variations, as well as for potential use in predicting the effects of future anthropogenic climatic change (Weber *et al.* 2021).

Due to environmental specialisations, reproductive biology and dispersal abilities, different species exhibit different levels of resilience to future climatic change (Jiguet *et al.* 2007). For example, higher elevation habitats are often associated with higher extinction risks (Dirnböck *et al.* 2011), and rainforest specialists are considered to be more vulnerable than generalists (Isaac *et al.* 2009). The number of reptile species found in the Australian Wet Tropics currently stands at 860, with 131 being dependent on the rainforest habitat (Williams *et al.* 2016). Scincidae is a particularly diverse family of lizards that is also the largest lizard family in Australia, with more than 1,500 species found living under diverse environmental conditions. This wealth of biodiversity notwithstanding, some Australian skinks are classified as endangered or critically endangered due to restricted habitat ranges and changing climate conditions – for example, the Guthega skink (*Liopholis Guthega*) (Chapple *et al.* 2021).

Lizards such as skinks are ectotherms, meaning they lack the ability to regulate their body temperature (T_b) internally and are impressionable to environmental temperatures (du Plessis *et al.* 2012). Environmental heat sources influence ectotherms' T_b in several ways – namely, radiation, conduction, evaporation and convection (Friedman *et al.* 2019). Diurnal ectotherms are often found to regulate their T_b behaviourally, typically via basking under the sun or shading to avoid overheating (Mason *et al.* 2017). On the other hand, although basking can improve lizards' thermal performance, it can also increase predation risks by impairing crypsis; as such, basking can be considered a trade-off between superior thermal performance and higher predation risks (Carrascal *et al.* 2001). Furthermore, higher T_b also incurs higher metabolic rates and consequently restricts lizards' energy budget (Huey *et al.* 2009). Thermal physiology is one of the most important aspects of the study of lizard ecology, as lizards' sprinting speed, foraging ability and mating capability are all dependent on their T_b (Muñoz *et al.* 2016). A thermal performance curve can be constructed to describe the relationship between lizards' T_b and their thermal performance, the key values being critical minimum temperature (CT_{min}), critical maximum temperature (CT_{max}) and optimal body temperature (T_{opt}) (Figure 1). As Figure 1 shows, lizards' thermal performance drops rapidly after reaching T_{opt}; consequently, tropical lizards are typically found to live closely to their CT_{max}. However, this means they may be particularly susceptible to heat stress due to future climate change (Huey *et al.* 2009).

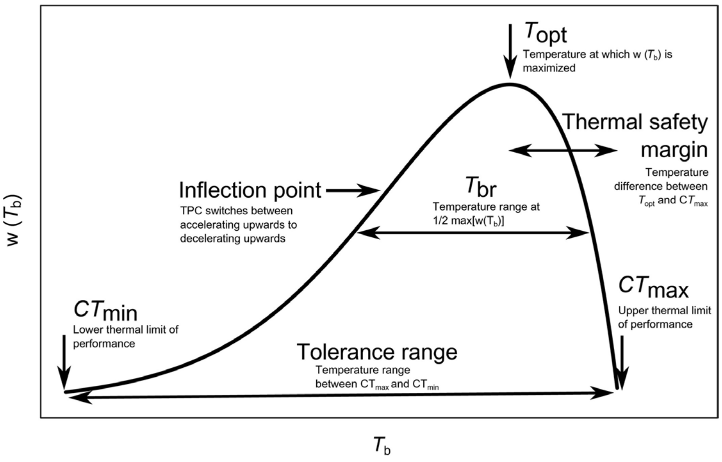
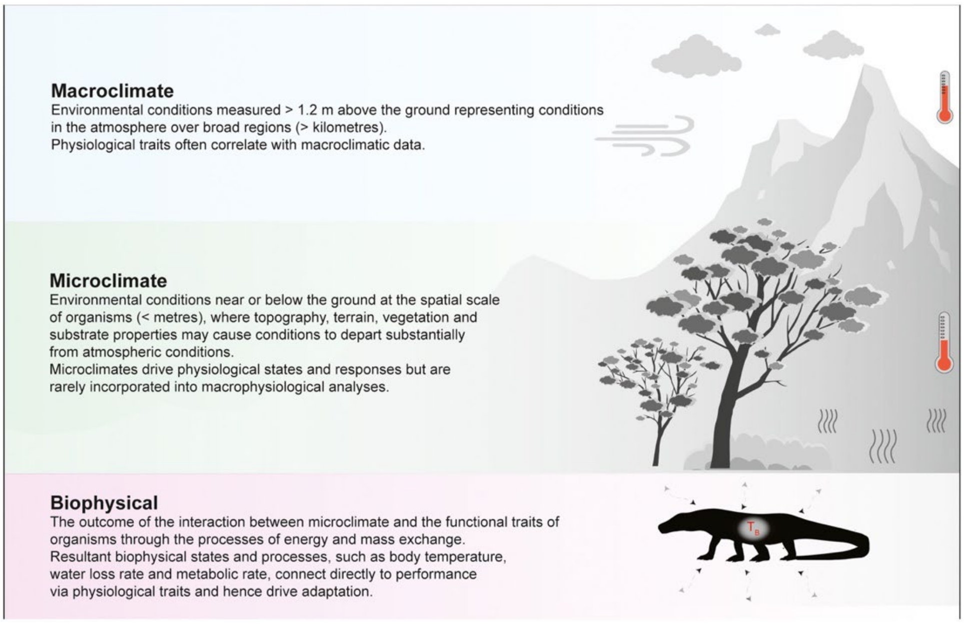


Figure 1: *Key values in the thermal performance curve of ectotherms, depicting the relationships between critical maximum temperature (CT_{max}), critical minimum temperature (CT_{min}) and optimal body temperature (T_{opt}). Source: Sinclair* et al. *(2016, p. 1374).*

Many of Australia's old-growth forests have been converted to agricultural land or cleared to make way for human settlements and infrastructure such as power lines and highways (Chen *et al.* 1995). Such clearing leads to habitat fragmentation and edge effects (Murcia 1995). Edge effects are often linked to microclimatic variables such as air temperature, humidity, soil moisture, light intensity, wind speed and vapour pressure deficit (VPD) (Murcia 1995). These environmental variables have been found to be more variable both daily and seasonally at the edges of forests (Pohlman *et al.* 2009). In regard to habitat fragmentation, studies of edge effects have found that the smaller the fragments, the greater the perimeter-to-area (P:A) ratio and the greater the aggregated effects of fragmentation (Jelbart *et al.* 2006). On the other hand, different types of leaf litter have been found to buffer edge effects, whereby the fluffier the leaf litter, the more it can buffer variation in soil moisture and topsoil temperature (Wang *et al.* 2010). Fluffy leaf litter may therefore play a significant role in buffering edge effects for forest-edge lizard species (Dixo and Martins 2008).

Habitat range is a crucial aspect of the living requirements of many species. The process of identifying and describing habitat range is called habitat modelling (Angelstam *et al.* 2004). Modern habitat modelling takes advantage of globally available climate data (Anderson *et al.* 2022). However, such macroclimatic data have been found to be inadequately representative of the microclimatic conditions that largely affect animals' physiology (Figure 2). Therefore, many efforts have been made to adjust global macroclimatic data by incorporating local and regional microclimatic data for more precise and accurate habitat modelling (Holt *et al.* 2009; Kearney *et al.* 2018; Kearney and Porter 2017). Coincidentally, the environmental variables used to adjust for macroclimatic data have a large overlap with the aforementioned environmental variables affected by edge effects (Murcia 1995). Therefore, a better understanding of the microclimatic conditions in which forest-edge species live is likely to benefit habitat modelling by informing the adjustments needed to be made to macroclimatic data (Borremans *et al.* 2019) Such modelling can usefully inform conservation management and monitoring for endangered or critically endangered forest-edge lizard species (Kearney and Porter 2017).



Macroclimate

Environmental conditions measured > 1.2 m above the ground representing conditions in the atmosphere over broad regions (> kilometres).

Physiological traits often correlate with macroclimatic data.

Microclimate

Environmental conditions near or below the ground at the spatial scale of organisms (< metres), where topography, terrain, vegetation and substrate properties may cause conditions to depart substantially from atmospheric conditions.

Microclimates drive physiological states and responses but are rarely incorporated into macrophysiological analyses.

Biophysical

The outcome of the interaction between microclimate and the functional traits of organisms through the processes of energy and mass exchange.

Resultant biophysical states and processes, such as body temperature, water loss rate and metabolic rate, connect directly to performance via physiological traits and hence drive adaptation.

Figure 2: *Macroclimatic conditions, microclimatic conditions and their biophysical effects on lizards. Source: Anderson* et al. *(2022, p. 334).*

Significance

This study's findings can help further knowledge and understanding of the microclimatic characteristics of *Carlia rubrigularis* in the Australian Wet Tropics. In addition, the field data and analyses can be used to inform certain aspects of high-elevation tropical lizard habitat modelling, thereby contributing to habitat modelling and conservation management decision-making for endangered or critically endangered skink species with restricted habitat ranges.

Study aims

This study has three main aims:

1. To measure and record the leaf litter and topsoil temperatures in-forest and forest-edge transects, and use this data to determine relations between topsoil and leaf litter temperatures and the associated necessity of lizard basking behaviours in different habitat types.

2. To observe occurrences of *Carlia rubrigularis* while measuring topsoil and leaf litter temperatures to determine if lizard basking behaviour can be predicted by substrate temperatures.

3. To characterise the responses of leaf litter and topsoil temperatures to abiotic factors such as wind speed and microclimatic conditions at different times of day in order to further distinguish in-forest and forest-edge lizard habitats.

Hypotheses and predictions

As basking in sunlit leaf litter can impair crypsis, I hypothesise that *C. rubrigularis* would bask only when the leaf litter is closer in temperature to the lizards' T_{opt} and is much warmer than the topsoil, and hence that leaf litter temperatures should be able to be used to predict numbers of basking lizards, following logistic regression. With regard to edge effects, I hypothesise that leaf litter and topsoil temperatures should be less correlated on forest-edge transects than on in-forest transects.

Glossary

Crypsis: Visual concealment of organisms to avoid predators, for example by developing body colours and patterns that blend in with the surrounding environment or by taking cover under physical objects.

Edge effect: Distinct change in community composition at the edges of habitats and ecosystems caused by acute shifts in abiotic and biotic conditions – for example, wind speed, temperature, moisture.

Methods

Species of interest

The genus *Carlia* is a group of small, diurnal, basking and active lizards in the family Scincidae (Hoskin and Couper 2012). *Carlia* typically inhabits leaf litter at the bases of trees and under stones and logs. It is found in Australia, New Guinea and the Indonesian archipelago. In the Australian Wet Tropics, 74 species of Scincidae and 8 *Carlia* species have been found (Williams *et al.* 2016).

Carlia rubrigularis (common name: red-throated rainbow-skink) is a medium-sized skink with an average snout–vent length (SVL) of 50 mm. *C. rubrigularis* is distributed in rainforests from south of Cooktown to Townsville, Queensland (Figure 3, left). *C. rubrigularis* is litter-dwelling and typically lives at the forest edge next to clearings and streams (Cogger 2014). *C. rubrigularis* is active year-round with a long reproductive period, between July and May (Goodman 2006).

Figure 3: *Carlia rubrigularis (right) and its distribution in Australia (left). Sources: Cogger (2014, p. 443).*

Study site

The field study was conducted on 27, 28 and 29 of June 2022 in the vicinity of Lake Eacham (17.2849° S, 145.6259° E), Northeast Queensland. Lake Eacham is a volcanic crater lake surrounded by cool rainforest and is one of the major features of the Crater Lakes National Park, which lies within the Wet Tropics of Queensland UNESCO World Heritage Site. The surrounding rainforests consist of mature simple notophyll vine forest, growing on tertiary basalt-flow-enriched fertile soils (Westman 1990), with a canopy height between 30 m and 35 m. The closest weather station (Malanda Queensland Weather Station, 17° 21' 06" S, 145° 35' 47" E, 735 m above sea level (ASL)) receives an average annual rainfall of 1,687.4 mm, an average daily maximum temperature of 25.6°C and an average daily minimum temperature of 15.3°C (Bureau of Meteorology 2022). The area experiences a wet season between December and March, and a dry season between June and October (Bureau of

Meteorology 2022). The region has an average altitude of 821 m due to its location on the Atherton Tableland (Westman 1990).

Field measurements

With the help of fellow students, I observed *C. rubrigularis* by eye and recorded their number. Ambiguity in species identification was resolved by consulting Professor Craig Moritz. Temperatures and numbers of observed lizards were collected from four transects around Lake Eacham, namely, (A) Winfield Road, (B) McLeish Road, (C) Lake Eacham Perimeter Walk and (D) Wrights Creek Road (Figure 4). The Lake Eacham Perimeter Walk transect (D) had the longest sampling distance (3 km), transects (B) and (D) both had a sampling distance of 1.5 km, and site (A) had a sampling distance of 1 km. The Lake Eacham Perimeter Walk is a footpath, whereas the other three transects are paved roads. Sites (A) and (B) are considered forest-edge transects, while sites (C) and (D) are considered in-forest transects (Figure 4). Temperatures were recorded every 2–5 minutes. Temperatures were not differentiated whether they were measured in sun or shade.

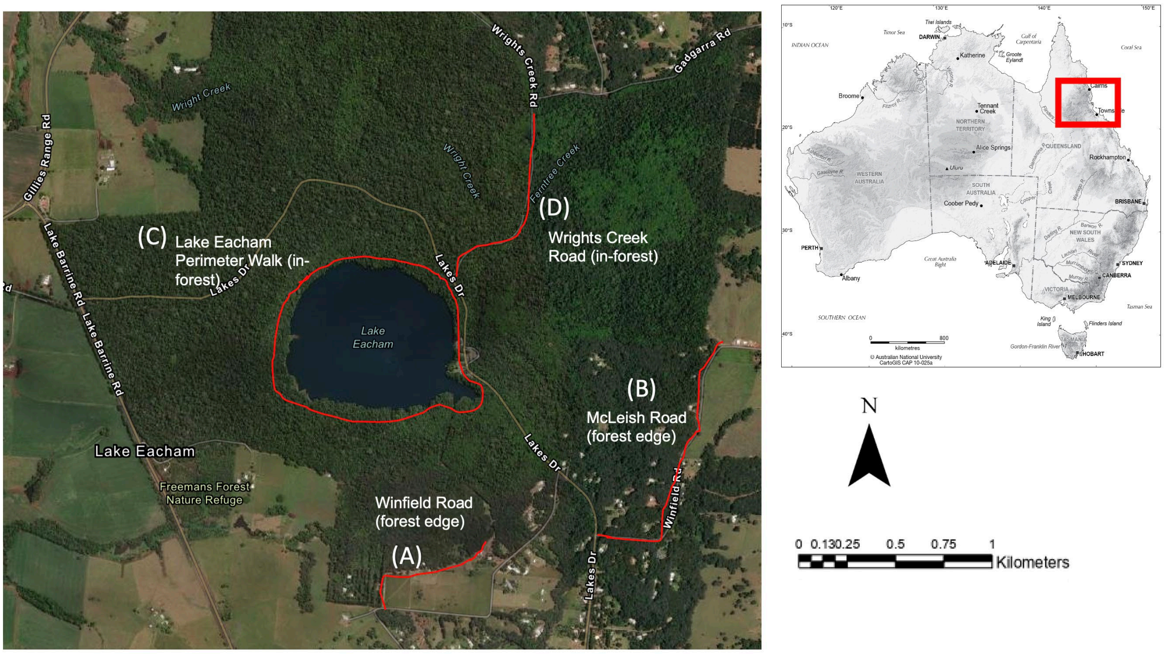


__Figure 4:__ The four transects of this study, (A) Winfield Road, (B) McLeish Road, (C) Lake Eacham Perimeter Walk and (D) Wrights Creek Road, of which sites (A) and (B) are at the forest edge, and sites (C) and (D) are within the forest.

The leaf litter and topsoil temperatures were measured using an infrared (IR) temperature gun for all four transects. Only afternoon data were collected for the temperature data. Rainy and cloudy weather was encountered during all three days of field data collection. The temperatures of the leaf litter were measured at a distance of 30–35 cm from the target, while the temperatures of the topsoil were measured 10–15 cm from the target. The IR guns used have a distance-to-spot ratio of 12:1 (Figure 5), so the diameters of the areas measured for the leaf litter were between 2.5 cm and 3 cm, while the diameters of the areas measured for topsoil were between 0.8 cm and 1.25 cm. For transect (A), 21 temperatures were sampled for both leaf litter and topsoil (21 for leaf litter and 21 for topsoil); for transect (B), 14 temperatures were sampled; for transect (C), 23 temperatures were sampled; and for transect (D), 29 temperatures were sampled.

To further characterise the microhabitat of *C. rubrigularis*, thermal images were taken for the leaf litter and topsoil at points where *C. rubrigularis* was spotted using FLIR ONE Pro thermal cameras, with an accuracy of ±3°C or ±5%, a measurement range between -20°C and 120°C, and a thermal resolution of 160 × 120 (FLIR 2022).

Figure 5: *(A) Leaf litter-covered ground, (B) topsoil exposed by kicking the leaf litter away and (C) the infrared temperature gun used to measure the leaf litter and topsoil temperatures with a distance-to-spot ratio of 12:1.*

Data analyses

Due to the small sample size (ranging from 14 to 29 temperature measurements for both leaf litter and topsoil along each transect) and the small number of observed lizards (seven), the findings of this study are mostly qualitative. Furthermore, it is likely the seven observed *C. rubrigularis* present a skewed distribution, as five out of the seven were observed at one site on one transect, and no lizards were observed on two of the transects. Therefore, it was not considered appropriate to conduct an analysis of variance (ANOVA) or a t-test to compare the numbers of observed lizards between transects. Logistic regression was conducted with the data from all transects and with the data from the transect where most lizards were observed (the McLeish Road transect) separately. The aim of conducting the logistic regression was to use leaf litter temperature to predict the number of observed lizards; therefore, the significance of the model-fitting was compared between all transects and McLeish Road only.

To explore the covariance of leaf litter and topsoil temperatures from different site types (in-forest and forest-edge), Pearson's Correlation Coefficients (Pearson's r) were calculated for the forest-edge and in-forest transects. An analysis-of-covariance (ANCOVA) test was performed on correlations between leaf litter and topsoil temperatures between in-forest and forest-edge transects.

The maximum temperature, 75% percentile temperature, mean temperature and standard deviation of temperature were displayed for topsoil and leaf litter along each transect. These values were used to see if more lizards were observed in transects with warmer environments. A range of temperature difference between topsoil and leaf litter for each transect was calculated by subtracting the leaf litter temperature from the topsoil temperature, with positive values indicating that the leaf litter was warmer than the topsoil and negative values indicating that the leaf litter was cooler than the topsoil. The range of temperature difference was calculated to see if a higher temperature difference between the topsoil and the leaf litter, with the leaf litter on top being warmer, would encourage lizards to bask on top and be seen.

Results

Overall, the temperatures of the topsoil were found to be more consistent than those of the leaf litter along the forest-edge transects, whereas on the in-forest transects the two temperatures were more similar. Figure 6 shows the temperatures of topsoil and leaf litter for the four transects, plotted in half-hour intervals. The temperatures of the topsoil and the leaf litter varied more independently in the forest-edge transects ((A) and (B) in Figure 6) than in the in-forest transects ((C) and (D)). Notably, the leaf litter temperatures were consistently lower than the topsoil temperatures in Winfield Road, suggesting that the windy and cloudy weather during the time of sampling reduced leaf litter temperatures considerably. In contrast, the leaf litter temperatures taken in McLeish Road between 2:00 pm and 2:30 pm peaked at 22°C, while the topsoil temperatures remained around 16°C, suggesting the potential for leaf litter to reach much higher temperatures than the topsoil in the absence of wind.

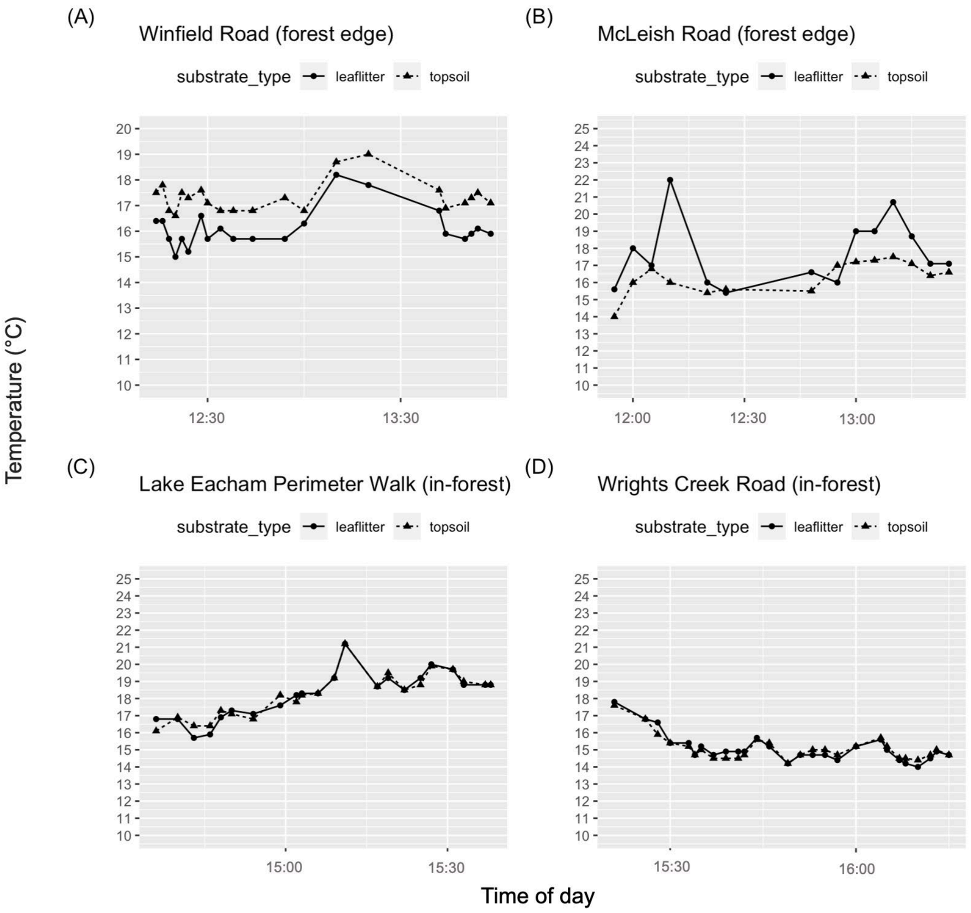


Figure 6: *Leaf litter and topsoil temperatures of the four transects – (A) Winfield Road, (B) McLeish Road, (C) Lake Eacham Perimeter Walk and (D) Wrights Creeks Road – presented over half-hour time blocks. All data were collected in the afternoon. Note that the topsoil temperatures were consistently higher than the leaf litter temperatures in Winfield Road.*

A positive correlation was present between topsoil and leaf litter temperature in both forest-edge and in-forest transects (Figure 7). However, the in-forest transects displayed a much stronger correlation ($r(47) = 0.988$, $p < 0.001$) when compared with the forest-edge transects ($r(33) = 0.138$, $p = 0.43$), suggesting that the in-forest microclimate created a more homogenous temperature gradient between topsoil and leaf litter. The ANCOVA test of the correlation yielded significant results ($F_{1,80} = 13.19$, $p < 0.001$).

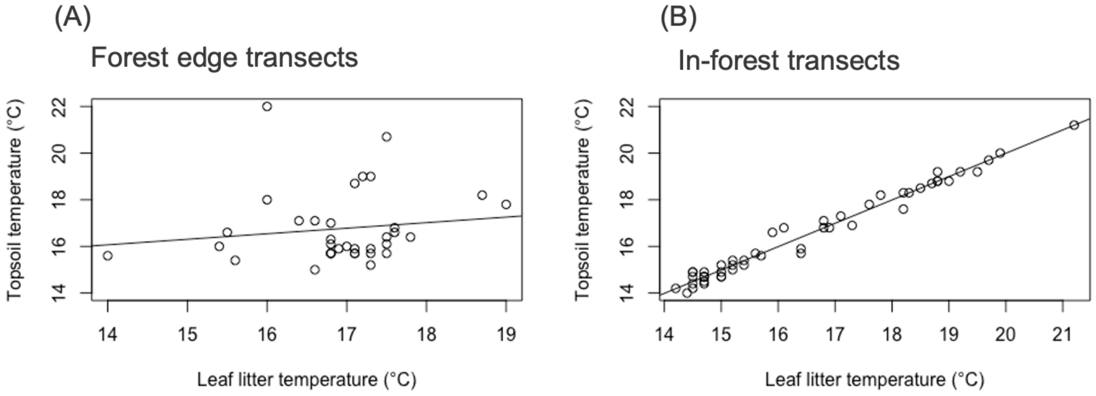


Figure 7: *The correlations between leaf litter and topsoil temperatures in (A) forest-edge transects (r(33) = 0.138, p = 0.43), and (B) in-forest transacts (r(47) = 0.988, p < 0.001).*

The images in Figure 8 were taken in the afternoon of 28 June on the Winfield Road (forest-edge) transect. They show that the leaf litter on top was evidently (by 9.1°C) cooler than the topsoil underneath under windy and cloudy conditions, suggesting that leaf litter may present a harsher environment than topsoil at the forest edge, especially in inclement weather.

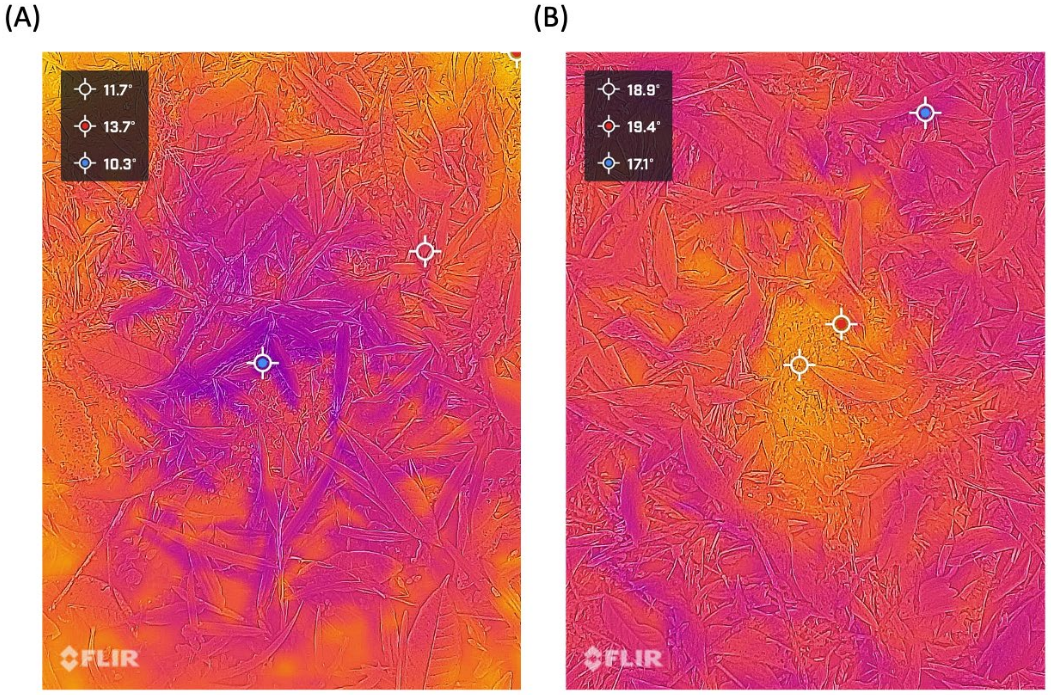


Figure 8: *Thermal imagery taken from the Winfield Road transect. The leaf litter on top (A) is shown to be 9.1°C cooler than the topsoil (B) underneath, suggesting insulating effects for leaf litter.*

Figure 9 presents the results of the logistic regression using leaf litter temperature to predict the number of observed *C. rubrigularis*. Due to the cloudy and windy weather during the time of sampling, few lizards were observed. Out of the four transects, five lizards were observed on McLeish Road and two lizards were observed on Winfield Road; all observed lizards were *C. rubrigularis*. The logistic regression model fitted badly (n = 157, p = 0.96) when all transects were included (Figure 9). The significance of regression improved when only the McLeish Road transect was included (n = 41, p = 0.058), although it was still statistically insignificant, suggesting that the observed environment temperatures did not reach the lizards' preferred temperatures.

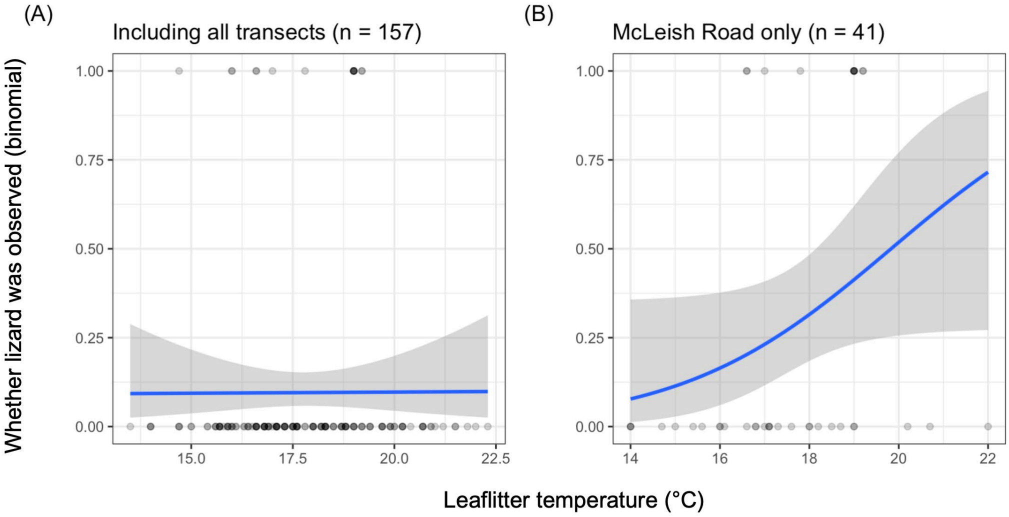


Figure 9: *Results of logistic regression using leaf litter temperature to predict whether* C. rubrigularis *would be observed for (A) all transects (n = 157, p = 0.96) and (B) the McLeish Road transect only (n = 41, p = 0.058).*

The highest maximum temperature was recorded in McLeish Road (22°C), where most of the lizards (5) were observed, closely followed by Lake Eacham Perimeter Walk (21.2°C), where no lizard was observed; McLeish Road also has the highest temperature difference between leaf litter and topsoil (-1°C and 6°C), in contrast with the relatively small temperature difference in Lake Eacham Perimeter Walk (-0.7°C and 0.7°C). Even though Lake Eacham Perimeter Walk had the highest 75% percentile temperature (19.1°C), no lizard was spotted in this transect, possibly because the lizards could use convection and conduction to raise their T_b, as opposed to radiation, thus avoiding crypsis impairment.

Table 1: Sample size (n), maximum temperature (T_{max}), 75% percentile, mean, standard deviation (Std.), and range of temperature differences between leaf litter and topsoil (Temp diff. range) of both leaf litter and topsoil temperatures on the four transects. Bold values are the largest in each column.

	Site type	n	T_{max} (°C)	75% percentile (°C)	Mean (°C)	Std.	Temp diff. range (°C)
Winfield Road (leaflitter)	Forest edge	21	18.2	16.4	16.12	0.76	-0.5 to 0.21
Winfield Road (topsoil)	Forest edge	21	19	17.5	17.32	0.61	
McLeish Road (leaflitter)	Forest edge	14	**22**	18.9	17.73	**2.00**	**-1 to 6**
McLeish Road (topsoil)	Forest edge	14	17.5	17.1	17.73	0.97	
Lake Eacham Perimeter Walk (leaflitter)	In-forest	22	21.1	**19.1**	18.23	1.35	-0.7 to 0.7
Lake Eacham Perimeter Walk (topsoil)	In-forest	22	21.2	18.9	**18.25**	1.30	
Wrights Creek Road (leaflitter)	In-forest	14	18.2	16.4	16.02	0.77	-0.5 to -2.1
Wrights Creek Road (topsoil)	In-forest	14	18.7	17.5	17.24	0.56	

Such behaviour can be predicted by both the temperatures of the sunlit leaf litter and the temperature difference between the shaded substrates. Most of the lizards observed in McLeish Road were found in one microhabitat. Figure 10 shows the temperature characteristics of said microhabitat, with a relatively high temperature for the sunlit leaf litter (20.1°C) and a relatively large temperature gradient between the sunlit leaf litter and the shaded substrate (2.5°C), suggesting that *C. rubrigularis* favours habitats with relatively large temperature difference that provide options for behavioural thermoregulation.

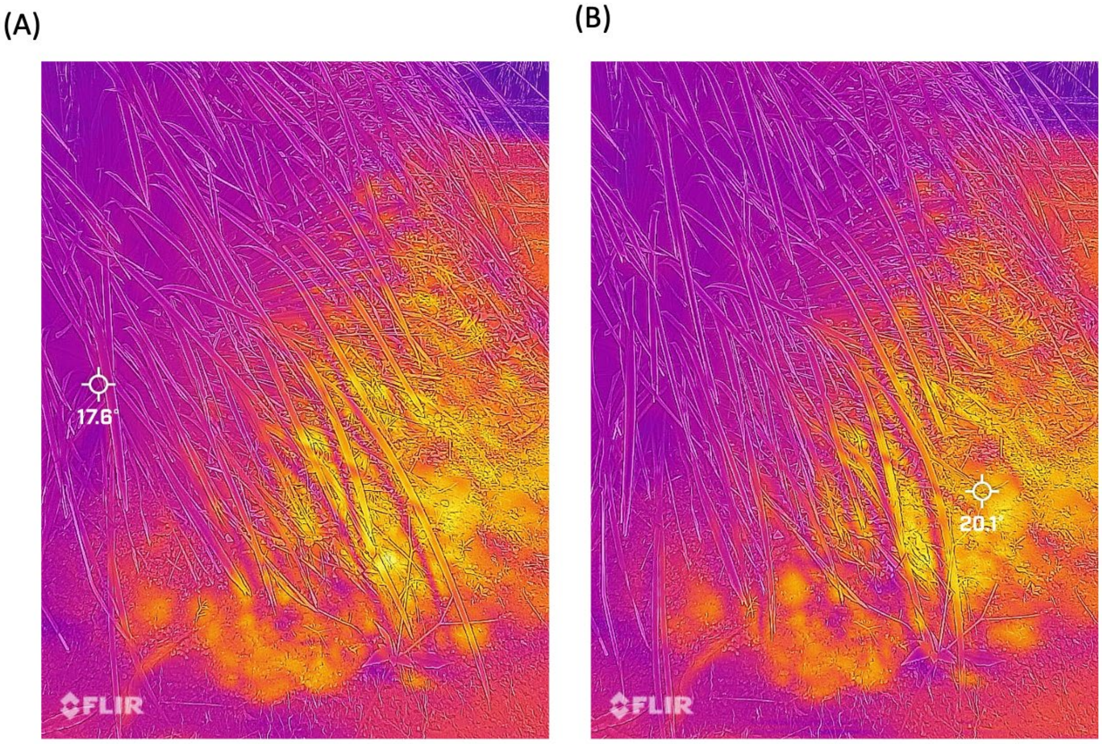


Figure 10: *Thermal imagery of the habitats where most of the* C. rubrigularis *were observed on the McLeish Road transect, showing the shaded areas (A) being much cooler than the exposed leaf litter (B).*

Discussion

The results of this study do not contradict the hypothesis that higher sunlit leaf litter temperatures motivate *C. rubrigularis* to bask at the risk of predation, as no lizard was observed when the leaf litter temperatures were cooler than the topsoil, nor when topsoil and leaf litter temperature were similar. The lack of observed lizards on Lake Eacham Perimeter Walk despite its high temperature suggest that basking behaviour is prompted not only by maximum temperature, but also by temperature difference between leaf litter and topsoil, with leaf litter being warmer than topsoil (Table 1). However, further inferences are difficult to make considering the small sample size. The logistic regression yielded insignificant results, which was likely because the maximum leaf litter temperature during field sampling (22°C) was much lower than the T_{opt} of *C. rubrigularis* (28.5°C) (Muñoz *et al.* 2016).

As suggested by Kearney *et al.* (2018), predicting lizards' response to future climate change mechanistically is difficult, although mechanistic niche models have been used to predict lizard distribution and potential response to future climate change (Holt *et al.* 2009; Jiménez-Valverde, Nakazawa, Lira-Noriega, & Peterson 2009; Kearney & Porter 2017). Kearney *et al.* (2018) suggested that daily temperature predicted desiccation level can better explain activity restriction of lizards. This conclusion supports the result of this study, as the variabilities in leaf litter and topsoil temperatures suggest that soil moisture, leaf litter water content and wind speed are likely to have more significant effects on microclimatic temperatures than macroclimatic air temperatures, especially for forest-edge habitats like those favoured by *C. rubrigularis*.

The edge effects manifested along the forest-edge transects were the most convincing results of this study, as they agreed with mounting evidence from previous studies (Delgado *et al.* 2007; Dixo and Martins 2008; Murcia 1995). Thus, greater leaf litter temperature variabilities were observed on forest-edge transects than on in-forest transects, although the full daily temperature variabilities of leaf litter and topsoil could not be confirmed as only afternoon temperatures were collected.

Limitations

Other than the small data set, measurements other than topsoil and leaf litter temperatures were not taken due to lack of equipment, short sampling timeframe and unfavourable weather conditions. Measurements commonly used in other studies such as relative humidity and wind speed (Chen *et al.* 1995; Pohlman *et al.* 2009; Wang *et al.* 2010) should be taken in future experiments to compare with similar studies.

Pohlman *et al.* (2009) found daily variabilities of maximum wind speed, air temperature and vapour pressure deficit, suggesting that collecting topsoil and leaf litter temperatures for whole days may make possible better characterisations of lizard microhabitat. That said, even though the Lake Eacham Perimeter Walk and Wrights Creek Road transects were referred as in-forest transects, strictly speaking they were not representative of the forest interior, as they are both human-constructed linear canopy openings within the rainforest and therefore display different microclimatic characteristics than the actual forest interior (Laurance *et al.* 2009). However, the thermal characteristics of those two transects – where the vertical temperature gradient between topsoil and leaf litter was smaller than on the forest-edge transects, and leaf litter and topsoil temperatures were more closely correlated with each other – were consistent with forest interior environments, supporting the hypothesis that old-growth tropical rainforests provide more stable and homogeneous microclimates (Chen *et al.* 1995).

Implications

Anderson *et al.* (2020), in their study of 369 lizard species, found that microclimatic variables of lizard habitats have greater explanatory power for lizard thermal performance and metabolic rates than macroclimatic variables. It would seem to follow then, that, the ability to translate globally available macroclimatic data into microclimatic data is crucially important for mapping the microhabitats of endangered lizard species.

On the other hand, Kearney *et al.* (2009) were able to resolve more than 70% of the diurnal lizard activities in their study using a thermodynamically grounded modelling framework, suggesting that consideration of the insulating properties of leaf litter could improve models of lizard diurnal activity in the future.

As mentioned in the introduction, *C. rubrigularis* typically inhabits the forest edge. As such, this known forest-edge species might benefit from habitat fragmentation. As forest-edge habitats are created through forest fragmentation, more habitats become available to *C. rubrigularis*. Consequently, *C. rubrigularis* could increase in abundance even as local rainforest ecosystems deteriorate.

Moreover, being a rainforest generalist, *C. rubrigularis* is likely to be able to adapt to future climatic change; it is therefore ranked as of least concern on the International Union for

Conservation of Nature (IUCN) Red List. However, other high-elevation rainforest skink species – such as *Spondylurus nitidus* in Puerto Rico (endangered, habitat = 750 m ASL), and *Nannoscincus rankini* (critically endangered, habitat > 900 m ASL), *Nannoscincus slevini* (endangered, habitat = 400–900 m ASL) and *Nannoscincus manautei* (critically endangered, habitat = 750–1,000 m ASL) in New Caledonia – may face greater challenges due to high levels of dependence on rainforest and restricted habitats (Sadlier *et al.* 2021). The results of this study are likely to be valid to a certain degree for niche modelling of those species, as they have similar habitat and share similar evolutionary lineages with *C. rubrigularis*.

Future research

The hypothesis that *C. rubrigularis* will bask on sunlit leaf litter only when leaf litter temperature is close to their T_{opt} should be tested under conditions where leaf litter temperature ranges from below to above its T_{opt}. Body size difference between adult and juvenile *C. rubrigularis* is likely to have an effect on their thermoregulatory behaviours, because juveniles have much larger surface-to-volume ratio, suggesting that they are more likely to face underheating stress than overheating stress (Sinclair *et al.* 2016; du Plessis *et al.* 2012). On the other hand, juveniles also have less mating pressure than adults, which should lead to less aggressive behaviours and hence superior T_b via basking (Chapple *et al.* 2021). Therefore, future research may focus on the thermal safety margin difference between adults and juveniles, the margin where lizards leave the sunspot before reaching their T_{opt} to prevent overheating.

On the other hand, the different levels of leaf litter and topsoil correlation exhibited on the in-forest and forest-edge transects suggest that further examination under different weather conditions is needed. It is relatively well-established that environmental variables such as soil and air temperature are less variable inside forests (Angelstam *et al.* 2004; Dirnböck *et al.* 2011). However, the relationships between the temperatures of leaf litter and of topsoil may change in response not only to the weather conditions on the day of measurement, but also to the weather conditions preceding the day of measurement. For example, the combination of wet leaf litter and windy weather for a few hours may cause leaf litter temperatures to drop much lower than topsoil temperatures, whereas if the weather is cloudy for consecutive days, the topsoil and leaf litter temperatures may become increasingly similar due to the lack of energy input from solar radiation (Wang *et al.* 2010).

Conclusions

Due to the small sample size, invariable weather conditions and lack of key microclimatic measurements other than temperatures, the results of this study are less than conclusive. However, this study's findings are consistent with the prediction that only when leaf litter temperatures are higher than topsoil temperatures and when leaf litter temperatures are relatively warm will *C. rubrigularis* bask on sunlit leaf litter. Furthermore, this study discovered an underexplored microclimatic characteristic of the forest-edge leaf litter habitat of *C. rubrigularis* and other *Carlia* species: leaf litter and topsoil temperatures are less correlated at the forest edge than inside the forest. Such information may be of use in future studies designed to generate more precise and accurate habitat modelling for monitoring and management of endangered skink species such as *N. manautei*, *N. selvini* and *N. rankini*.

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