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Microhabitat Preferences, Climate Vulnerability and Conservation Status of the High-Elevation Orange-Speckled Forest Skink (*Tumbunascincus luteilateralis*)

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ABSTRACT

High-elevation species are particularly vulnerable to climate change due to their restricted distributions and reliance on stable, cool climates. *Tumbunascincus luteilateralis* (the orange-speckled forest skink), a high-elevation lizard endemic to the Eungella region in central Queensland, Australia, is currently listed as Data Deficient under the International Union of Conservation of Nature (IUCN) Red List of Threatened Species. Our study integrates field surveys, microhabitat analyses and ecological niche modelling to better understand the species' distribution, habitat preferences and conservation status. Field surveys detected *T. luteilateralis* at many new locations all within a highly restricted area on the Dalrymple Plateau. It occurred in a range of forest types above 800 m elevation, but very rarely occurred below 800 m, showing a strong ecological preference for high-elevation rainforests. Microhabitat analyses indicated that the species exhibits significant selection for warmer, refuge-rich sites characterised by higher log cover and larger logs, which likely support thermoregulation and predator avoidance. Ecological niche modelling highlighted that the species' current distribution is restricted to stable, cool climates typical of high-elevation rainforests, with no evidence of occurrence outside the Eungella region. Projections under future climate change indicate a severe reduction in suitable habitat, with complete loss predicted by the end of the century under a moderate warming scenario. These results show that *T. luteilateralis* meets the criteria for Endangered status under the IUCN Red List, with an extent of occurrence of 687 km^2 and area of occupancy of 169 km^2. Efforts that could help maintain or improve population resilience include protection of the rainforest habitat from bushfires, preservation of large log refugia and reducing the risk of predation from feral animals. This study underscores the need for conservation-oriented ecological studies on narrow-ranged, high-elevation species to understand their conservation status and inform conservation planning.

1 | Introduction

Biodiversity loss is a pressing global issue, with an alarming number of species under threat from anthropogenic pressures (Barnosky et al. 2011; Ceballos et al. 2017). Taking inventory of the species most at risk of extinction is an important component of conservation planning. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species is a regularly updated list of the extinction risk of species, providing a foundation for strategic conservation planning (Hoffmann et al. 2008; Cazalis et al. 2022; IUCN 2022). Amongst these Red List species, many are designated as 'Data Deficient' (DD)—a category given to species that are so poorly known that their extinction risk cannot be confidentially assessed (IUCN 2022). These species are often overlooked in conservation planning due to insufficient knowledge on their taxonomy, distribution, ecology, life history, threats, population status and trends, yet many may already meet the criteria for threatened status (Bland et al. 2017; Gumbs et al. 2020). These 'undiagnosed' species represent a hidden crisis in biodiversity conservation, as their obscurity often results in delayed recognition of their true imperilled status (Howard and Bickford 2014; Bland et al. 2015; Meiri et al. 2017; Gumbs et al. 2020; Borgelt et al. 2022; Caetano et al. 2022). Addressing the knowledge gaps surrounding DD species is essential to diagnosing their true conservation status and implementing timely conservation measures (Bland et al. 2017; Cazalis et al. 2022).

Field-based ecological research plays a pivotal role in resolving the uncertainties surrounding DD species (Bland et al. 2017; Hochkirch et al. 2021). By systematically investigating their distribution, habitat preferences and abundance, conservation ecologists can generate the critical data needed to accurately reassess their status and inform evidence-based conservation (Hochkirch et al. 2021). Amongst vertebrates, reptiles have considerably more DD species (1499) than amphibians (908), mammals (798) or birds (38), making them a priority group for further research (Cox et al. 2022; IUCN 2024). Recent conservation-oriented field research has been useful in uncovering the extinction status of DD Australian skinks (family Scincidae) (Graham et al. 2023; Farquhar, Carlesso, et al. 2023; Farquhar, Russell, et al. 2023; Scott et al. 2024; Bonifacio et al. 2024), a family with many DD species (Tingley et al. 2019; Chapple et al. 2019, 2021). Such research may be especially urgent for DD skink species occupying vulnerable habitats, such as montane ecosystems, where suitable environmental conditions are inherently restricted (Urban 2018) and are highly threatened by climate change.

Climate change poses an existential threat to many species, particularly montane fauna that have narrow elevational ranges and prefer cool and stable climates (Forero-Medina et al. 2011; Wiens 2016). Projections indicate that such species may face habitat contraction to shrinking climatic refugia, with some projected to lose all suitable habitat (Brereton et al. 1995; Hughes 2003; Williams et al. 2003; La Sorte and Jetz 2010). This phenomenon is referred to as the 'escalator to extinction' (Urban 2018) and underscores the acute vulnerability of mountain fauna to climate change and the need to understand (and where possible mitigate) these impacts. In Australia, high-elevation tropical rainforests, and their specialised fauna, are particularly at risk, with predictions of significant demographic and distributional loss in a range of taxa including skinks (Torkkola et al. 2022; Scott et al. 2024), frogs (Bolitho and Newell 2022), birds (Anderson et al. 2012; Williams and Fuente 2021) and plants (Shimizu-Kimura et al. 2017). For many species however, we simply do not have sufficient baseline data to detect whether changes are occurring.

Fine-scale habitat features can offer thermal refugia from extreme conditions; thus, microhabitat selection and availability may be critical to buffering climate change impacts (Scheffers et al. 2014; Neel et al. 2021). Some rainforest lizards are heliothermic, favouring openings in the canopy to bask on logs (e.g., Klingenböck et al. 2000), whilst others are shade-seeking thigmotherms (Scott et al. 2024) or thermoconformers (Rummery et al. 1995). Knowing the thermoregulatory behaviour of lizards is important for estimating climate change impacts because basking species have considerably higher heat tolerance than shade-seeking species (Muñoz et al. 2016). Consequently, population declines have been predicted to be more severe for thermoconforming, closed-habitat species with narrow thermal niches compared to heliothermic open-habitat species with broader thermal niches and which behaviourally compensate for changes in the thermal environment (Neel et al. 2021). Additionally, determining how time-of-day and weather variables influence rainforest lizard detections (and by inference, ideal conditions for surface activity) is of value because tropical ectotherms in general are specialised to a narrow thermal range (Deutsch et al. 2008; Tewksbury et al. 2008). Hence, their activity may be relegated to times of day when ambient air temperatures are within their thermal tolerance (e.g., cool mornings). Increases in environmental temperatures may threaten lizards by forcing individuals to spend more time in buffered microhabitats, thereby limiting the time available for reproduction and energy intake (Kearney et al. 2009; Sinervo et al. 2010; Logan et al. 2015). Periods of hot and dry weather may be particularly constraining for activity times and distribution, as demonstrated in numerous mesic-adapted ectotherms (e.g., Pintor et al. 2016; Hoffmann et al. 2021; Camacho et al. 2023).

Eungella National Park includes a region of high-elevation cloud rainforests in central Queensland, Australia, supporting exceptional biodiversity and endemism, including endemic lizards (*Saproscincus eungellensis, Tumbunascincus luteilateralis, Phyllurus nepthys*), frogs (*Rheobatrachus vitellinus*, *Taudactylus eungellensis* and *T. liemi*), a bird (*Bolemoreus hindwoodi*), a crustacean (*Euastacus eungella*), five plants and dozens of invertebrates (Hines et al. 2020; Kitching 2020). The region's biodiversity faces mounting pressures from climate change, fire, disease and invasive species (Meyer et al. 2020; Hines et al. 2020; Scott et al. 2024). Of the endemic vertebrates, only the orange-speckled forest-skink, *T. luteilateralis* (Covacevich and McDonald 1980), is considered DD. Although this species' existence has been acknowledged for 45 years, little is known about its ecology, current distribution, climate change vulnerability or other threats. Climate change has been posited as a significant threat to *T. luteilateralis* given it already appears restricted to the high elevations of Eungella National Park, with little capacity for elevational migration under climatic warming (Couper and Hoskin 2018).

To address ecological and conservation uncertainties for *T. luteilateralis*, our study aimed to: (1) investigate the distribution and abundance of the species, (2) assess its microhabitat preferences and activity patterns and (3) evaluate the potential impacts of climate change on its future distribution. By integrating distribution, abundance, microhabitat analyses and climate niche modelling, we reassess *T. luteilateralis* against IUCN Red List criteria. In doing so, we highlight the broader conservation challenges facing tropical mountain biodiversity in a warming world (Williams et al. 2003; Deutsch et al. 2008; Neel et al. 2021).

2 | Materials and Methods

2.1 | Surveys for *T. luteilateralis*

Most previous records of *T. luteilateralis* are from the Dalrymple Plateau, on the Clarke Range, 10–15 km north-east of Eungella township. Much of the plateau sits above 850 m in elevation and has been partially cleared for agriculture. Large portions of the plateau and adjoining high elevation areas of the Clarke Range fall within Eungella National Park. Observations from two separate surveys are combined in this study, one targeting *T. luteilateralis* (hereafter the Tl survey) and the other targeting a second skink endemic to the area, *Saproscincus eungellensis* (Eungella shadeskink) (Scott et al. 2024) (hereafter the Se survey). Although the Se surveys were focused on finding *S. eungellensis*, *T. luteilateralis* are very abundant in the same habitat; hence, we recorded every *T. luteilateralis* individual encountered at these sites, providing a systematic survey dataset for this species also.

For the Tl survey we conducted 36 surveys at 17 sites between 20th November and 2nd December 2023 (Figures 1C and 2A). These focused on accessible areas of the Dalrymple Plateau (mostly within the national park), with the aim of detecting *T. luteilateralis* at new sites whilst also measuring the species' microhabitat use (see '*Microhabitat Use*'). At each site two approximately parallel 200 m transects, spaced ~5 m apart, were surveyed (walked) by two observers for 40 min. We scanned the terrestrial habitat for the presence of *T. luteilateralis* and any other reptiles and recorded geospatial data for each using the EcoGIS iPhone application (MacDonald 2025). Most sites (16/17) were surveyed on at least two separate occasions/days. At the start and end of each survey we recorded air temperature (°C), relative humidity (RH %) and wind speed (km/h) using a hand-held weather meter (Kestrel 5000, Nielsen–Kellerman Company; ±0.5°C, ±3% RH). The weather meter was held ~1 m above the ground in the shade for 1 min before measurements were recorded.

The Se survey focused on streams and gullies and provided many additional observations of *T. luteilateralis* with associated data on time and temperature. Scott et al. (2024) conducted 60 min visual surveys ($n = 48$) along four 150 m long transects along two high-elevation tributaries of Cattle Creek (900–1000 m elevation); these transects were surveyed during four time windows (09:00–10:00, 11:00–12:00, 13:00–14:00, 15:00–16:00 h AEST). Each site was surveyed on three separate occasions for every time window (i.e., 12 surveys per site). In addition to weather data being recorded as per the Tl surveys, we also recorded solar radiation in the Se surveys using a solar radiation pyranometer (SR05-A1 solar meter, Hukseflux Inc.) and data logger (LI19 handheld data logger, Hukseflux Inc.) deployed in a standard position in every transect during each survey and set to record incident solar energy (W/m^2) for every minute of the survey. Data from these repeat surveys allow us to explore the effect of weather conditions and time-of-day on *T. luteilateralis* activity. Details of the Se survey sites and methods are provided in Scott et al. (2024).

Details of all observations of *T. luteilateralis* were summarised and provided to the Queensland Department of Environment, Science, Tourism and Innovation.

2.2 | Microhabitat Use

We performed microhabitat assessments for *T. luteilateralis* at multiple sites (Tl survey sites 2, 3, 4, 5, 12) to determine whether the species selected specific microhabitat attributes amongst those available in the rainforest. When an individual was sighted, we used a 1 m^2 quadrat (centred on the position the lizard was first observed) to measure habitat characteristics. We used an infrared thermometer (566 Thermal Gun Infrared & Contact Thermometer, Fluke Corporation; ±1°C) to record the warmest surface temperature found across all substrate types (e.g., rock, litter, log) within the quadrat. We then used a measuring tape to record the distance (cm) from the lizard's initial position to the nearest potential refuge site (i.e., any structure used by a lizard that could completely conceal the body from view) and to record the diameter (cm) of the thickest log within the quadrat. We recorded the type of nearest refuge to the lizard, which was either log, rock, dead epiphyte, dead palm frond or stick/litter pile). Within each quadrat we counted the number of plant stems (typically sapling rainforest trees) and visually estimated the ground cover percentage of the following features: logs, rocks, bare soil, vegetation foliage, large dead vegetation items (either palm fronds or decaying epiphytes that have fallen from trees), leaf litter and large tree bases. We did this for 30 lizard quadrats to capture the range of microhabitats utilised by *T. luteilateralis*. For each of these 30 quadrats, we replicated the sampling on a nearby randomly selected position to assess available microhabitat. We achieved this by choosing a random cardinal direction (N, E, S, W) and a short random distance of between 2 and 7 m as the rainforest ecosystems were structurally heterogenous at a very fine scale. If a random quadrat fell on a location where we had previously seen *T. luteilateralis*, we generated a new random position.

2.3 | Statistical Analysis

2.3.1 | Effect of Weather and Time-of-Day on Abundance

Using the repeat survey data from the Se surveys, we used a generalised additive model (GAM) with a Poisson distribution and log-link function to model the effect of weather variables on abundance (counts per survey) of *T. luteilateralis*. GAMs are

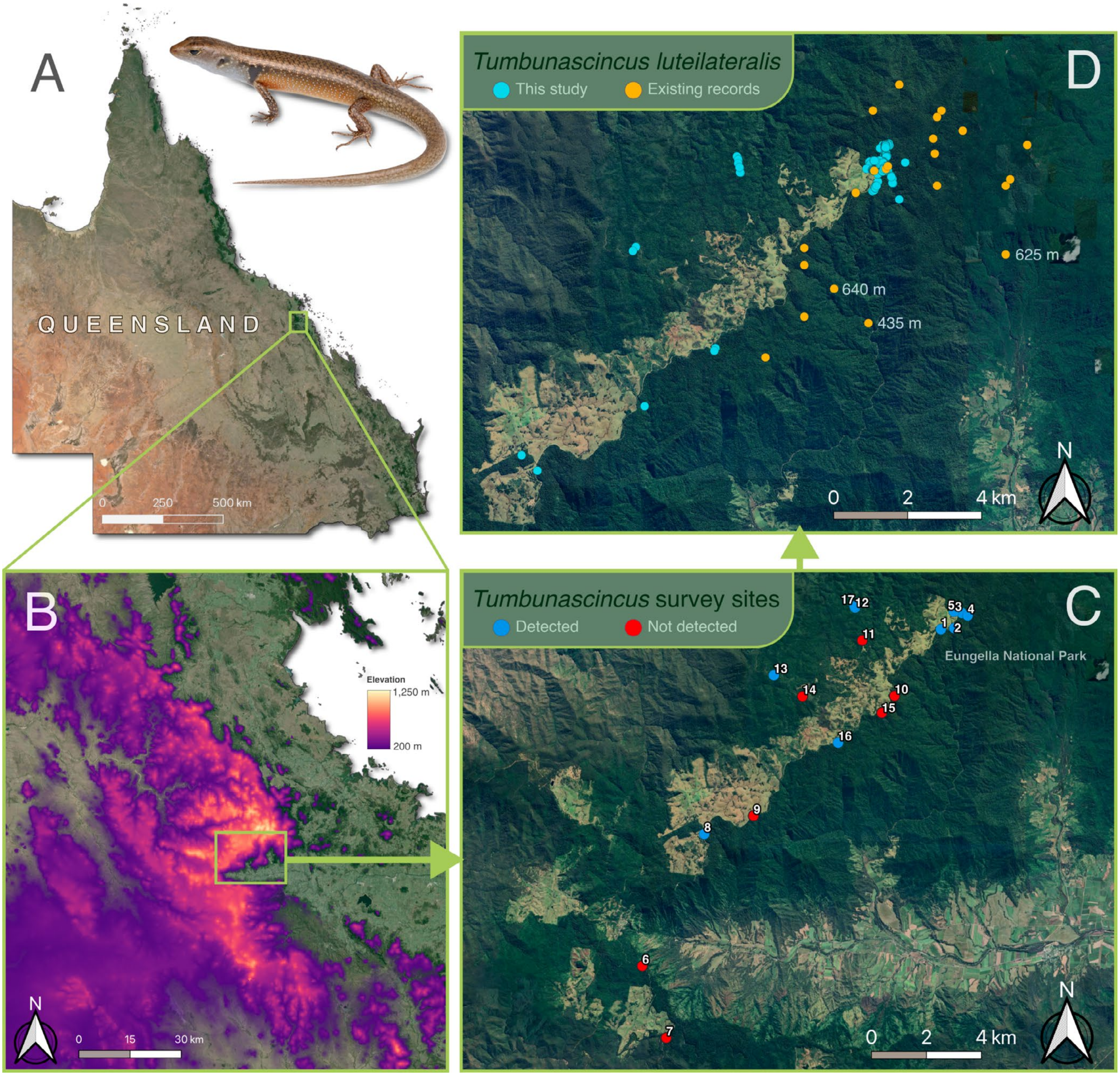

FIGURE 1 | (A) Map of the study region in Queensland, Australia, showing (B) elevated areas > 200 m of the Clarke-Connors Ranges, ~60 km west of Mackay. (C) Tl survey sites, showing a majority on the Dalrymple Plateau in the north, and two absence sites in the south in the Crediton area. (D) Records of *Tumbunascincus luteilateralis* annotated with elevation in metres for the three records below 800 m.

particularly well-suited for this type of analysis because they allow for flexible, non-linear relationships (Guisan et al. 2002; Wood 2017). For temperature and wind speed, we took the mean of the start and end survey values, and for solar radiation, we used the mean of all values recorded in the survey ($n = 60$). These values were used as continuous predictors with a smooth term allowed to vary flexibly with a basis dimension (k) set to 10, which balances the complexity of the model with the risk of overfitting. Time-of-day (four time windows: 0900–1000, 1100–1200, 1300–1400, 1500–1600 h AEST) was included as a categorical predictor to assess diurnal variation in lizard activity. The GAM was validated through the examination of model residuals and assessment of goodness of fit, including the explained deviance and adjusted R-squared values.

2.3.2 | Microhabitat Selection

From the Tl survey we used the Shapiro–Wilk test for normality and Levene's test for equal variances on the 11 continuous microhabitat variables. These tests revealed non-normality and heterogeneity of variances for most variables (Table S1). We therefore used the non-parametric Wilcoxon Signed-Rank Test to test for significant differences between microhabitats of quadrats selected by *T. luteilateralis* versus random quadrats. We created density plots of the 11 continuous variables to visualise differences between selected and random quadrats. To explore habitat selection in multivariate space, we used the '*adonis2()*' function of the *vegan* package (v2.6–5; Oksanen et al. 2020) to perform non-metric permutation multivariate

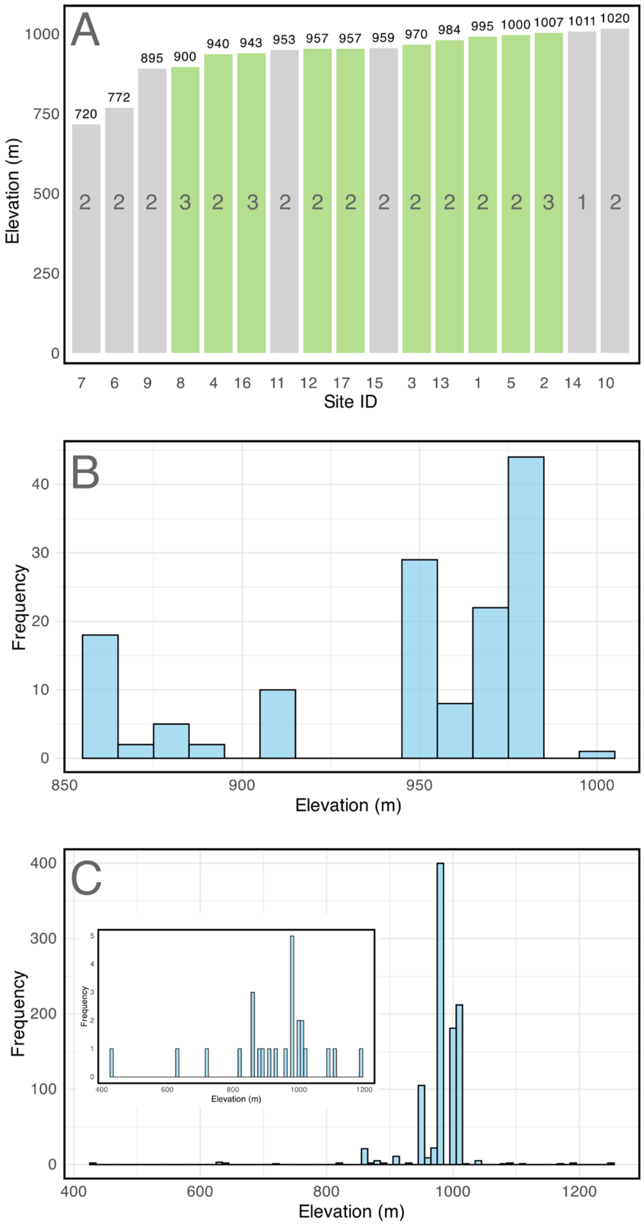

FIGURE 2 | (A) Elevation of the 17 TL survey sites with green bars denoting presence of *Tumbunascincus luteilateralis* within timed surveys. The number of times each site was surveyed is shown in the centre of each bar. (B) Frequency of observations of *T. luteilateralis* across elevation based on the Tl survey data and incidental encounter records outside of surveys. (C) Frequency of all known records ($n = 986$) of *T. luteilateralis* across elevation based on (i) the Tl survey ($n = 141$) and (ii) observations from the Se survey ($n = 822$) and vetted pre-existing records ($n = 23$). The inset graph for C shows elevational records of *T. luteilateralis* thinned to $1\,\text{km}^2$, to remove the effect of duplicate sampling at some sites.

analysis of variance (PERMANOVA) to determine whether the habitat attributes of selected quadrats differ from random. The PERMANOVA was based on the calculation of a Euclidean (dis)similarity matrix using 5000 permutations. We employed non-metric multidimensional scaling (MDS) using the '*metaMDS()*' function of the *vegan* package (v2.6–5; Oksanen et al. 2020) to visualise differences in multivariate space.

To evaluate whether the frequencies of refuge types within selected and random quadrats deviated from an expected equal distribution, we conducted chi-square goodness-of-fit tests. For each quadrat type, we compared observed frequencies of refuge types to the expected frequencies under the null hypothesis of equal distribution. A chi-square test of independence was used to assess differences in the frequencies of refuge types between the selected and random quadrats. The chi-square test statistic for independence was calculated to evaluate a null hypothesis that the distribution of refuge types was independent of quadrat type. A barplot was created to visualise counts of each nearest refuge item by quadrat type.

2.4 | Ecological Niche Modelling

2.4.1 | Occurrence Data

We combined all known records of *T. luteilateralis*, including those from the present study and pre-existing vetted records. The latter were obtained from the Atlas of Living Australia (ALA 2024) using the General Data Profile, excluding records with low scientific name quality (non-matching, incorrect or wrongly grouped names), records with high location uncertainty (>1 km), unresolved user annotations, fossil or eDNA records, absence records, duplicates and records collected pre-1700. We also included data from the Queensland Government's wildlife information system (WildNet 2022), the Australian Museum Collection and Queensland Museum collection. The full dataset contained 986 records but most were from a few independent sites. Hence, we reduced spatial clustering by thinning records such that no two points were less than 1 km distant from each other (and thus also matching the spatial resolution of our predictor variables) using the *thin* function of the R package *spThin* (Aiello-Lammens et al. 2015), resulting in 19 occurrence points.

2.4.2 | Defining the Modelling Domain

The 'domain' refers to the geographic area over which a spatial model is intended to make predictions, whereas the 'background' refers to the set of locations within the modelling domain that are used to represent available environmental conditions (i.e., background sampling). Given our aim was to map and model the climatic niche of a narrow-range species in a specific mountainous region, we defined the modelling domain as the extent of the Clarke-Connors Ranges subregion of the Central Mackay Coastal bioregion (Interim Biogeographic Regionalisation for Australia [IBRA] v7.0), a 300 km north–south montane area with extensive rainforest (Figure S1B). This is an ideal domain as it encompasses the wet forests contiguous with the Dalrymple Plateau and excludes more distant and biogeographically isolated rainforest areas (e.g., subregions of the Wet Tropics bioregion). The Clarke-Connors Ranges subregion encompasses the most likely potential range within which the species might realistically disperse or establish populations, considering historical, ecological and climate-related boundaries (Barve et al. 2011).

2.4.3 | Environmental Data

We selected variables that we considered to be important for the biology of *T. luteilateralis* (Fourcade et al. 2018). Climate variables likely drive this species' presence because it is an ectotherm and hence temperature and precipitation regimes are expected to predict the 'fundamental niche' of this montane rainforest lizard with reasonable accuracy. We used 15 of the 19 bioclimatic variables from WorldClim 2.0 (Fick and Hijmans 2017) at a 30 arc-seconds (~1 km grid cells) spatial resolution (Table S2). We excluded Bio8, Bio9, Bio18 and Bio19 as they are interactions of temperature and rainfall variables that are potentially more difficult to interpret biologically than the purely temperature or rainfall variables (Booth 2022). We used the '*resample*', '*mask*' and '*extract*' functions of the *raster* package (v3.6–26; Hijmans et al. 2013) to extract the values of these environmental variables from each *T. luteilateralis* occurrence point and background point (see background sampling details in 'Model Fitting and Validation'). To avoid including highly correlated variables in model fitting, we conducted a multicollinearity analysis by testing Pearson pairwise correlations and variance inflation factors (VIF), using the '*cor*' function of the *stats* package (v4.3.1; R Core Team 2023) and the '*vifstep*' function of the *usdm* package (Naimi et al. 2014), respectively. From this, we retained those predictors with Pearson's correlation coefficients of $< |0.7|$ and VIF of < 3: isothermality (Bio3), minimum temperature of the coldest month (Bio9), precipitation of the driest month (Bio14), precipitation seasonality (Bio15) (Figure S2). A general rule of thumb is that occurrence points should be at least 10 times the number of predictors (Harrell et al. 1996), which in our case would limit us to two covariates. However, we retained four predictors to preserve ecological relevance, then used fivefold cross-validation to confirm that this larger set did not lead to overfitting (see Section 3). This set of variables is relevant to *T. luteilateralis* because they describe extremes and variation in temperature and rainfall—tropical ectotherms often have narrow thermal ranges (Deutsch et al. 2008; Tewksbury et al. 2008) and are sensative to hot and dry weather (Camacho et al. 2023), which the above set of variables captures. Our final set of variables was therefore biologically meaningful and without multicollinearity issues. Definitions for key variables and how they were calculated are provided in the Data S1.

2.4.4 | Model Fitting and Validation

Ecological niche models were run using MaxEnt (Phillips et al. 2006; Phillips and Dudík 2008), because it outperforms other modelling algorithms for species known from a small number of sites (Wisz et al. 2008; Elith et al. 2011; Valavi et al. 2022). MaxEnt performs better when the proportion of background points is higher than the number of presences (Santini et al. 2021), hence we sampled 190 background points creating a 1:10 ratio for species presence to background points (Mancini et al. 2023). To account for uneven sampling effort across the study region, we sampled these 190 background points from a spatially weighted raster file ('bias file', Figure S1b), created by smoothing the occurrence data using a gaussian kernel density algorithm (bandwidth = 9 km). Therefore, selection of background points was concentrated on the more accessible Dalrymple Plateau area and was subjected to an approximately similar sampling bias as the occurrence data (Phillips and Dudík 2008; Kramer-Schadt et al. 2013).

MaxEnt model fine-tuning used the '*ENMevaluate*' function of the *ENMeval* package (v2.0.4; Muscarella et al. 2014; Kass et al. 2021) which runs MaxEnt models across multiple combinations of feature classes and values of the regularisation multiplier to allow comparisons of model performance. We then selected the MaxEnt setting combination that balanced model fit and predictive ability. We selected simple feature class combinations (linear, quadratic and linear + quadratic) and a sequence of regularisation multipliers (1, 2 and 3). To evaluate model performance, we used random fivefold cross-validation: the data were partitioned into five roughly equal subsets (folds), with each fold in turn serving as the test set (~20% of records), whilst the remaining four folds (~80%) were used for training; this process was repeated five times, and the model's performance metrics were averaged across all iterations. Models were evaluated using metrics AICc, AUC_{TEST}, AUC_{DIFF}, OR_{MTP}, OM_{10} and Boyce Index (BI) (see Table S3 for definitions and explanations of metrics). We considered the optimal model to be that which had the lowest AIC score (corrected for small sample sizes; AICc; Warren and Seifert 2011) and performed well against multiple other metrics of complexity and performance. To make predicted probabilities binary (presence or absence), we selected the probability threshold that maximised the true skill statistic (TSS) (Allouche et al. 2006). To explore relationships between variables and climatic suitability we visually inspected response curves using the clog-log transformation for each variable whilst keeping the rest at their mean value.

2.4.5 | Future Climate Projections

To model future climate change effects on the distribution of *T. luteilateralis* we projected the optimal MaxEnt model onto future climatic layers (for Bio3, Bio6, Bio14, Bio15) using the clog-log transformation for four future time periods (2021–2040, 2041–2060, 2061–2080 and 2081–2100). Future climate variables were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), a suite of models used to project climate changes under various future greenhouse gas scenarios (Eyring et al. 2016). We chose the Euro-Mediterranean Centre on Climate Change coupled climate model (CMCC-CM2; Cherchi et al. 2019) because it falls within the mean of the suite of climate models (Grose et al. 2023) and can realistically reproduce the main patterns of future temperature and precipitation regimes at a very high spatial resolution (Scoccimarro et al. 2021). We chose an intermediate shared socioeconomic pathway scenario (SSP2-4.5) to serve as a comparison against the baseline climate period (1971–2000). SSP2-4.5 is equivalent to the global targets set at the 2021 United Nations COP26 meetings in Glasgow and predicts a warming of 2.1°C–3.5°C towards the end of the century (2081–2100). We obtained the projected area (km^2) of potentially climatically suitable habitat for each time period (2021–2040, 2041–2060, 2061–2080 and 2081–2100) and used this to calculate the percentage of climate niche area decline over time.

3 | Results

3.1 | Individuals Observed

During the Tl survey we observed *T. luteilateralis* on 141 unique occasions, including 42 records incidentally outside of formal surveys. An additional 822 *T. luteilateralis* observations were made during the Se survey, with some of these likely repeat sightings of the same individuals on multiple surveys. The species was found in forest areas across the Dalrymple Plateau, including range extensions to the south and west, though we failed to detect the species at 7 out of 17 of the Tl survey sites (Figures 1 and 2A). We found the species in a wide range of rainforest habitats, from creeklines to ridges and in some areas that burnt in the 2018 bushfires. Based on all existing records of *T. luteilateralis*, the species occurs at elevations ranging from 435 to 1252 m. However, it has seldom ($n = 3$) been recorded below 800 m (Figures 1D and 2C), suggesting a preference for high elevations above 800 m. Lower elevation records below 800 m are from incised drainage lines with southerly aspects (Figure 1D).

Across the different sites where *T. luteilateralis* occurred in the Tl survey, numbers of detections were highly variable (Figures S3 and S4). For example, most surveys recorded 0–10 individuals, but site 5 yielded 25 and 31 individuals on the two surveys (see Section 4).

3.2 | Effect of Weather and Time-of-Day on Abundance

The GAM (Tables S4 and S5) indicated a significant effect of air temperature ($\chi^2 = 205.47$, edf = 2.259, $p < 0.0001$), wind speed ($\chi^2 = 51.09$, edf = 6.366, $p < 0.0001$) and solar radiation ($\chi^2 = 14.07$, edf = 5.939, $p = 0.0362$) on the number of *T. luteilateralis*, with greater detection numbers during surveys that are warmer, windier and with more solar radiation (but with a decrease under high solar radiation) (Figure S5). Compared to mornings (9–10 am), the mid-morning (11 am–noon) period showed no significant difference in detections ($\beta = -0.010$, $p = 0.951$), but the mid-afternoon (1–2 pm; $\beta = -0.319$, $p = 0.020$) and afternoon (3–4 pm; $\beta = -0.678$, $p = 0.0003$) were significantly lower in predicted detections compared to mornings, suggesting that *T. luteilateralis* is less detectable in afternoons. Overall, the GAM explained 81.1% of the deviance in lizard counts, with an adjusted *R*-squared value of 0.76, indicating a good fit.

3.3 | Microhabitat Selection

Compared to the available (random) microhabitats on the forest floor, *T. luteilateralis* selected microhabitats that were significantly warmer ($W = 585.5$, $p = 0.0105$), closer to refugia ($W = 85.5$, $p < 0.0001$) and with thicker logs ($W = 658.5$, $p = 0.0013$) and greater cover percentage of logs ($W = 673$, $p < 0.0001$) and litter ($W = 253$, $p = 0.0036$) (Figure 3). Similarly, from a multivariate perspective, PERMANOVA results show that there was a significant difference in the microhabitat variables between the selected and random quadrats ($F_{1,56} = 15.89$, $p = 0.001$, Table S6), visualised using multidimensional scaling in Figure 4.

The chi-square goodness-of-fit tests for each quadrat type showed significant differences between the observed and expected frequencies of nearest refuge type. Amongst quadrats selected by *T. luteilateralis*, logs were much more frequently (62% of cases) the nearest available refuge ($\chi^2 = 41.3$, df = 4, $p < 0.001$), indicating that this is likely the preferred refuge item (Figure 3). But this is also true of random quadrats; 57% of such quadrats had logs as the closest available refuge item, which was significantly more frequent than other refuge items ($\chi^2 = 25.6$, df = 4, $p < 0.001$). The chi-square test of independence indicated no significant association between quadrat type and nearest refuge type ($\chi^2 = 1.72$, df = 4, $p < 0.787$), suggesting that the frequency distribution of nearest refuge types is similar between random and selected quadrats (Figure 3, Table S7).

3.4 | Ecological Niche Modelling

The optimal MaxEnt model showed strong performance, with a test AUC of 0.83, indicating a high ability of the model to distinguish between potentially suitable and unsuitable habitats. BI for the training data was 0.81, further suggesting the model effectively captures the species' habitat preferences and accurately ranks areas based on predicted suitability. Model performance metrics of the candidate models are provided in Table S8.

Bio3 (isothermality) and Bio6 (minimum temperature of the coldest month) contributed 58% and 42% to the model, respectively. Suitability for the species was highest at low values of Bio3 and Bio6, implying that it is adapted to stable, cooler conditions typical of high-elevation areas. Bio14 (precipitation of the driest month) and Bio15 (precipitation seasonality) did not contribute to the model, indicating that precipitation patterns are potentially less relevant to the species' climatic niche. Response curves of the environmental variables from the optimal MaxEnt model are provided in Figure S6.

The resulting suitability maps (Figure 5) confirm that the species' current predicted climate niche is confined to high elevations on the Dalrymple Plateau, suggesting that the species is specialised to the plateau's unique climatic conditions. The model predicts low present-day suitability for other areas of the Clarke-Connors Ranges IBRA subregion further south, indicating that these areas are unlikely to climatically support the species. Whilst the current predicted climate niche of *T. luteilateralis* is 169 km^2, our future projections show that 100% of this climatically suitable area will be lost by the 2081–2100 time period (Figure 5B and Table 1).

4 | Discussion

Our study provides valuable insights into the distribution, habitat preferences and ecological niche of *T. luteilateralis*, contributing significantly to the understanding of this high-elevation rainforest skink species. By combining field surveys, microhabitat analyses and ecological niche modelling, we have identified key factors influencing its activity, occurrence and distribution, whilst highlighting conservation concerns under future climate scenarios. These data enable us to review the conservation status of this DD species under IUCN criteria

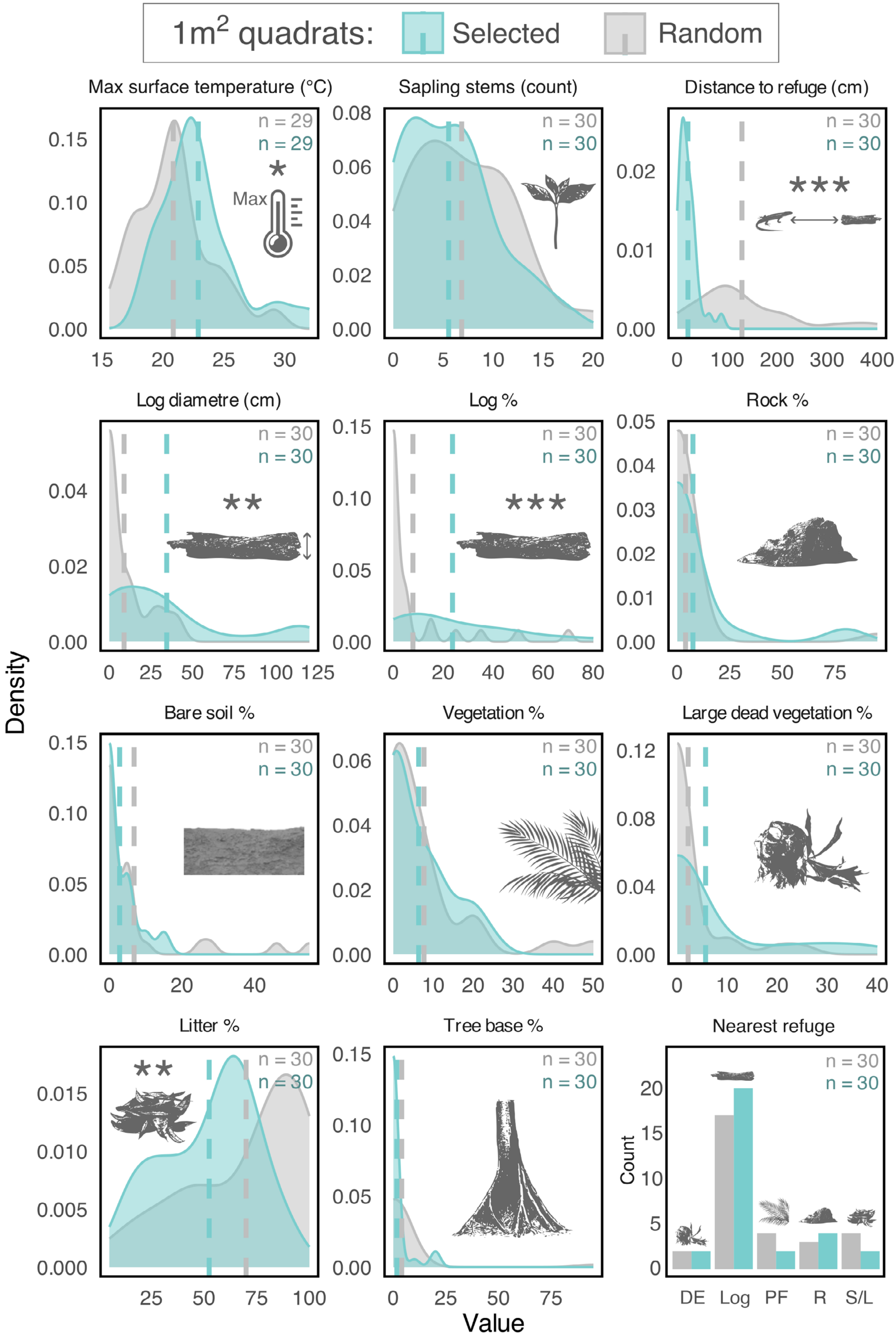

FIGURE 3 | Legend on next page.

FIGURE 3 | Microhabitat selection in *Tumbunascincus luteilateralis*. Density distributions illustrate differences in variation of habitat features between quadrats selected by *T. luteilateralis* (green) versus random quadrats (grey). Dashed vertical lines indicate the mean values for each quadrat type. The nearest refuge plot (bottom right) shows count of refugia types as follows: DE, dead epiphyte; Log, logs, including large fallen trees; PF, dead palm fronds on the forest floor; R, rock; S/L, piles of sticks and/or leaf litter. Significant *p*-value differences (base on Wilcoxon Signed-Rank Tests) are denoted by asterisks as follows: *< 0.05, **< 0.01 and ***< 0.001.

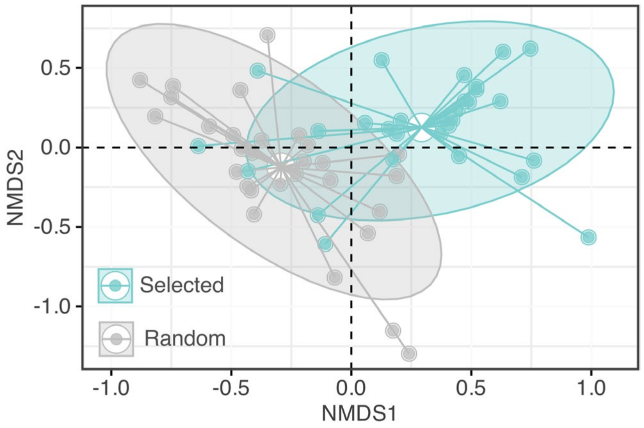

FIGURE 4 | Non-metric multidimensional scaling (NMDS) of 11 microhabitat variables. Quadrats (data points) ordinated closer to one another have more similar microhabitats than those further apart. Ellipses represent 95% confidence intervals for quadrats with *Tumbunascincus luteilateralis* (selected) and nearby random quadrats. Bray-Curtis dissimilarities, with a stable and robust configuration (stress value of 0.146), indicate a good representation of the original dissimilarities (Clarke 1993).

and provide novel insights into the species' microhabitat use and activity patterns.

4.1 | The Precarious Distribution and Climate Niche of *T. luteilateralis*

Collectively, the results of our surveys, earlier surveys and niche modelling confirm that the core area of the distribution of *T. luteilateralis* is upland rainforests of the mesic Dalrymple Plateau. Our field surveys show that *T. luteilateralis* is more widespread than previous records suggest. The species occurs in rainforest creek lines and gullies and upslope to ridgelines in a variety of forest types and landforms across the Dalrymple Plateau. In this regard, *T. luteilateralis* is more of a habitat generalist than *Saproscincus eungellensis*—another high elevation skink endemic to the Dalrymple Plateau, which is mostly restricted to rainforest creek lines (Scott et al. 2024). Nonetheless, there are few observations lower than 800 m ($n = 3$), indicating ecological intolerance of low elevation habitats and a strong preference for higher elevations. Further surveys are required in the difficult-to-access eastern fall of the plateau to clarify elevational limits, especially in creek lines which have elevated moisture and cold air drainage (Ashcroft et al. 2012). Considerable variation in the number of individuals detected between sites also suggests the species' abundance greatly varies across the plateau. Site-level factors such as habitat structure, elevation and climate are likely key factors.

Our climate niche modelling supports *T. luteilateralis* being confined to high elevation habitats: high climatic suitability for the species is characterised by stable, cooler conditions typical of high-elevation areas (i.e., low values of Bio3 and Bio6). Such conditions are not widely available outside of the Dalrymple Plateau, hence it is probable that the species is endemic to the plateau and does not occur elsewhere in the Clarke-Connors Ranges subregion. Concerningly, future climate niche projections indicate that the species is likely to go extinct due to climate change by the end of the century. Similar predictions have been made for the sympatric skink *S. eungellensis* (Scott et al. 2024) and two montane rainforest skinks (*Harrisoniascincus zia* and *Silvascincus tryoni*) in south-east Queensland (Torkkola et al. 2022). That multiple rainforest species are predicted to lose all available climatic habitat suggests that other narrow-ranged, high-elevation rainforest taxa are also likely to face significant range contraction and extinction under climate change (Deutsch et al. 2008; Bolitho and Newell 2022). Williams et al. (2003) predicted that many extinctions will occur in Queensland rainforest taxa, with losses increasing rapidly beyond an increase of 2°C. Our study supports this for the projected climate niche of *T. luteilateralis*—there is a rapid decline in suitable areas from the 2021–2040 period (~30% range decline) to the 2041–2060 period (~90% range decline). This rapid decline period roughly corresponds to when temperatures are expected to increase by 2°C under the SSP2-4.5 prediction (Deng et al. 2022). Even more concerningly, recent evidence for massive declines and the probable extinction of an Australian rainforest invertebrate (Monteith 2023) suggests that the disappearance of some mountain top relicts due to climate change may already be occurring.

4.2 | Microhabitat Selection in *T. luteilateralis* is Non-Random

We observed significant microhabitat selection by *T. luteilateralis*, favouring warmer, refuge-rich environments with thicker logs and greater cover of logs. These microhabitat features likely support thermoregulation, predator avoidance and foraging efficiency (Vitt et al. 2003; Blázquez and Rodríguez-Estrella 2007; Andersson et al. 2010; Farquhar, Carlesso, et al. 2023; Farquhar, Russell, et al. 2023). Whilst leaf litter cover was significantly lower at selected quadrats, we do not interpret this as avoidance of leaf litter; rather, *T. luteilateralis* is clearly selecting microhabitats with high log cover, which necessarily leaves less space for leaf litter cover. Whilst logs were the most frequently available and selected refuge type in both random and used quadrats, their ubiquitous presence in the habitat suggests that their importance lies in their abundance rather than selectivity by the species. The lack of significant differences in refuge type frequencies between random and selected quadrats may reflect the broader availability of suitable refuge types in the rainforest.

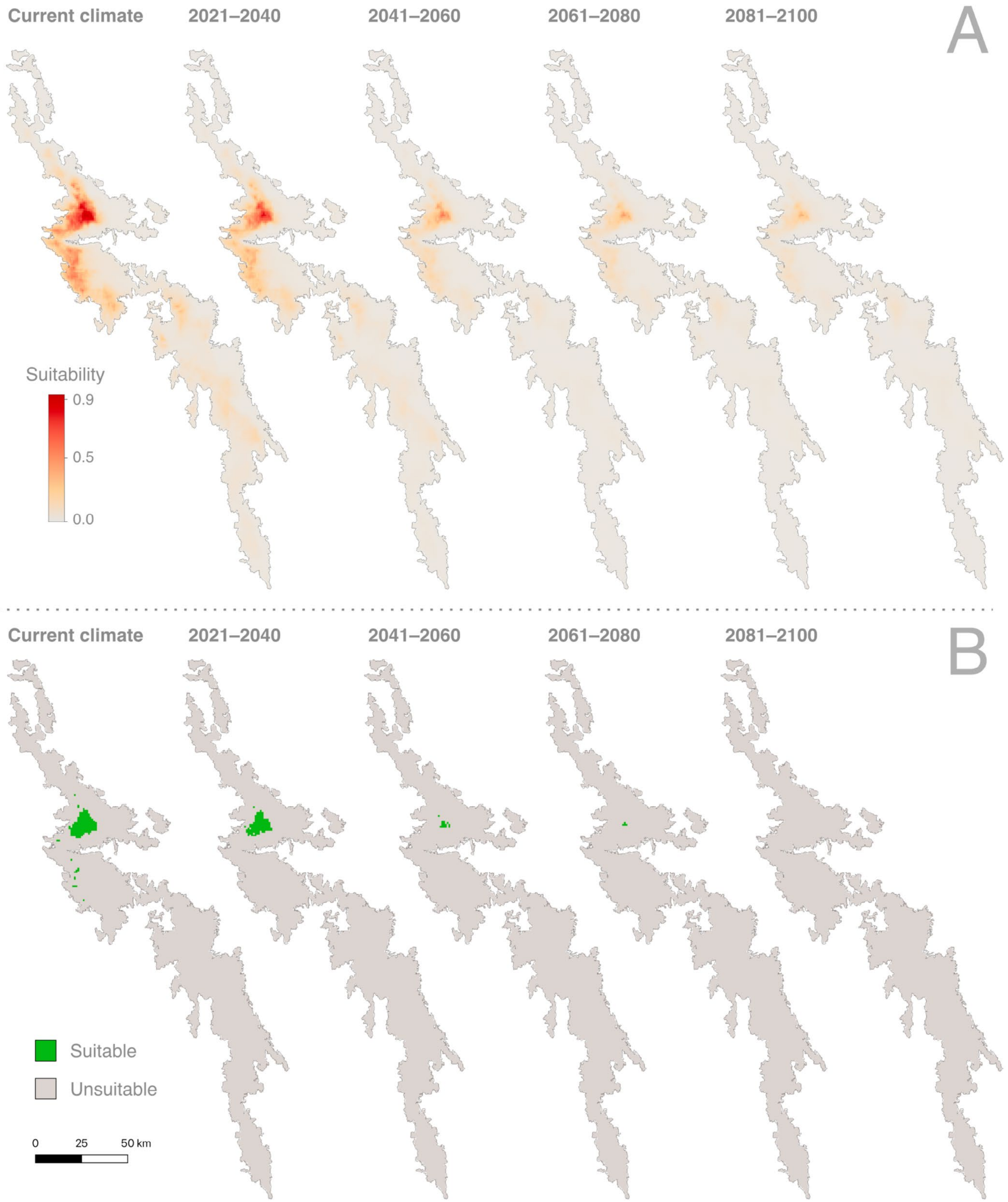

FIGURE 5 | MaxEnt model current predictions and future projections of climatically suitable areas for *Tumbunascincus luteilateralis* in the Clarke-Connors Ranges IBRA subregion. Maps show (A) continuous probability of suitability and (B) a binary prediction of habitat suitability based on a probability threshold that maximises TSS. Future climate projections are based on the SSP2-4.5 greenhouse gas emission scenario of the CMCC-CM2 global circulation model.

TABLE 1 | Area values of the extent of climatically suitable habitat for *Tumbunascincus luteilateralis*, based on binary MaxEnt model projections. Decline percentages are calculated relative to current.

Time period	Projected range size (km^2)	% of climatically suitable areas remaining	% decline of climatically suitable areas
Current	169	100.00	0.00
2021–2040	119	70.41	29.58
2041–2060	15	8.87	91.12
2061–2080	4	2.36	97.63
2081–2100	0	0.00	100.00

Non-random microhabitat use has been shown in a range of tropical skinks from Queensland (Klingenböck et al. 2000; Goodman 2007), emphasising that structural habitat features are key determinants of abundance, niche partitioning and site occupancy in tropical skinks. Microhabitat selection/use in *T. luteilateralis* is non-random; individuals are close to refugia, with logs being the primary refuge item, especially those proximal to warmer sunpatches. This association is demonstrated by the relatively high abundance of *T. luteilateralis* at site 5: this site was unique in that it possessed an abundance of large logs at the interface of rainforest and a large clearing. The clearing provided ample exposure to sunlight and hence higher basking temperatures, yet the elevated abundance of logs along the forest edge provided extensive cool refugia within the deep log cavities. However, this site is also at high elevation and near a deep gully with overall cool conditions; thus, despite ample sun exposure, the site likely does not get too hot, thereby enabling skinks to bask frequently.

These findings mirror those of Klingenböck et al. (2000), showing that the wet forest skink *Bellatorias major* is more abundant in areas with abundant logs and canopy openings that allow for basking opportunities. Thus, although *T. luteilateralis* is dependent on cool, shaded rainforest ecosystems, its microhabitat use is similar to that of other heliothermic rainforest skinks (Klingenböck et al. 2000; Goodman 2007). Potential refuges, particularly large logs, should be protected in the uplands of Eungella NP, as these features offer thermal refugia and may be critical to buffering impacts of climate change on *T. luteilateralis* (Scheffers et al. 2014). Feral pigs (*Sus scrofa*) are the principal threat to large logs and piles of accumulated forest litter at Eungella NP (Hines pers. obs.). Whilst the level of pig damage within *T. luteilateralis* habitat is currently low, observations of the long-term cumulative impacts of pigs on such microhabitat features in rainforests throughout Queensland (Hines pers. obs.) show potential significance over this threat in the near future.

4.3 | Weather and Diel-Dependent Activity Patterns

Tumbunascincus luteilateralis occurs in a high-elevation rainforest environment where overall thermal regimes are relatively cool compared to the surrounding regions. We surveyed at the hottest time of year, under the expectation that if the species is intolerant of warm air temperatures, this intolerance would be most evident in restricting activity. We found support for diel activity differences in *T. luteilateralis*, with significantly lower detections for the afternoons compared to mornings (independent of weather variables). The high-elevation rainforest skink *Techmarscincus jigurru*, which is only found above 1440 m elevation on Mount Bartle Frere in the Queensland Wet Tropics (Covacevich 1984) is also reported as more active in the mornings (Goodman 2007).

In our surveys, detections per survey were highest under warmer and windier conditions with moderate solar radiation. As expected in dense rainforest, our surveys were conducted under low wind speeds with limited range (all < 3 km/h) and similarly for solar radiation (most < 50 W/m^2). Lizard detections generally increased with solar radiation, but our few surveys above 125 W/m^2 indicate a decline at higher incident solar radiation. Although our results showed a positive correlation between abundance and air temperature, this should not necessarily be interpreted as a preference for very hot conditions; whilst our surveys were performed at the hottest time of year, Eungella NP is a relatively cold, often mist-shrouded montane area, so survey air temperatures did not exceed 26°C. Hence, we have no data under hot conditions (e.g., > 30°C). In this context, we still consider the species to be a cool-adapted rainforest specialist, albeit one that seeks warmer conditions (in both space and time) within an overall cool and mesic ecosystem.

This contrasts with some other high elevation skinks, such as *Gnypetoscincus* and *Saproscincus* of the Queensland Wet Tropics, which rarely bask (Muñoz et al. 2016). At Eungella, another endemic skink, *S. eungellensis*, occurs sympatrically with *T. luteilateralis* but differs in thermal ecology—it seldom basks in direct sunlight, with body temperatures reflecting rock surface temperatures rather than air temperature or solar radiation (Scott et al. 2024). Because basking skink species have considerably higher heat tolerance than shade skinks (Muñoz et al. 2016), it is possible that *T. luteilateralis* will be less impacted by climatic warming than *S. eungellensis*. Laboratory measurements of key physiological traits in both these species would enable more proximal predictions as to how climate change will differentially impact them (Kearney et al. 2008; Pirtle et al. 2019; Neel et al. 2021).

4.4 | Conservation Implications

The species is currently considered DD on the IUCN Red List. However, our surveys, modelling and assessment show that the species meets IUCN Red List criteria for Endangered (IUCN 2022; see Tables S9–S11 for full conservation assessment).

This is because the species' geographic distribution (Criterion B) is precarious for both extent of occurrence (EOO—calculated using a minimum convex hull around all modelled habitat) at 687 km^2 and area of occurrence (AOO—calculated using the area of modelled suitable habitat minus cleared farmland) at 169 km^2, its occurrence at only a single location in relation to the threat of climate change and the impact of the projected decline in the area of climatically suitable habitat on EOO and AOO. To ensure the species receives appropriate legislative protection, we recommend that *T. luteilateralis* be nominated as Endangered under both the Queensland *Nature Conservation Act 1992* and the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*.

4.5 | Future Surveys

Our climate niche modelling and survey results indicate that *T. luteilateralis* may indeed be endemic to the Dalrymple Plateau and occur almost exclusively within Eungella NP. Available data all suggest that *T. luteilateralis* does not occur far to the north, south or west of the records presented here. At least one researcher with experience with this species worked in the uplands of the Cathu area towards the northern extent of the Clarke Range rainforests (e.g., McDonald 1990) and did not encounter it. More recently, through helicopter access, surveys targeting frogs have occurred in the remote northern parts of the national park and the adjoining Macarthy State Forest in mid-elevation rainforests in the Urannah and Massey Creek catchments (Meyer et al. 2020; Hoskin and Hines unpublished data). These surveys spanned multiple days and numerous reptiles were recorded, but no *T. luteilateralis* were observed. Other high-elevation rainforests occur in the Crediton area to the south of Eungella township. Parts of this area (e.g., upper Broken River) are high visitation areas. These areas have been surveyed for herpetofauna multiple times (e.g., McDonald 1990; Meyer et al. 2020; Augusteyn 2004) without detecting *T. luteilateralis*, even though at least one of these surveys recorded 19 reptile species.

In contrast a large area of the Clarke Range to the immediate north of the known occurrence records for *T. luteilateralis* on Dalrymple Plateau (~240 km^2) is largely inaccessible and with limited survey effort and sits within the modelled range of the species. The scarcity of records of *T. luteilateralis* below 800 m in the immediate vicinity of Dalrymple Heights may also reflect difficulty of access. Dalrymple Road provides easy access to high elevations (> 800 m) on the plateau, but to the east the landscape drops precipitously. The species has not been recorded at frequently visited low elevation areas on these eastern slopes. Most notably, the Finch Hatton Gorge area in Eungella National Park is a popular tourist location, where the walking trail leading to the 'Wheel of Fire' reaches elevations up to 400 m. No *T. luteilateralis* have been recorded there, yet there are many records of *Concinnia amplus*, a skink of similar size that is seldom recorded at high elevations on the Dalrymple Plateau. Together these observations suggest that between 400 and 800 m elevation there is a transition over which range limits emerge for *T. luteilateralis*, due to shifts in either climate, habitat, competition with lower-elevation skink species or some combination of these factors (e.g., Jankowski et al. 2013; Senior et al. 2021; Farquhar, Carlesso, et al. 2023; Farquhar, Russell, et al. 2023). We recommend future surveys target areas to the north and east of where we worked in order to detect new populations and further understand the species' extent of occurrence. These surveys should also prioritise investigating the potential climate buffering effect of deep gullies on *T. luteilateralis*. Whilst our findings suggest that the species is likely to decline on the plateau, it remains possible that gullies provide microclimatic refugia. Data on comparative abundance and distributions in both gully and plateau habitats will be crucial for assessing whether the former are acting as refugia as the climate changes over coming decades.

Author Contributions

Jules E. Farquhar: conceptualization, methodology, investigation, writing – original draft, writing – review and editing, visualization, formal analysis, project administration, data curation. **Paul M. Oliver:** conceptualization, methodology, investigation, funding acquisition, writing – review and editing, project administration, data curation, resources. **Justin M. Wright:** investigation, writing – review and editing. **Nicholas A. Scott:** investigation, methodology, formal analysis, writing – review and editing, conceptualization, funding acquisition, data curation. **Jordan Mulder:** writing – review and editing, investigation. **Harry B. Hines:** writing – review and editing, investigation. **David G. Chapple:** conceptualization, writing – review and editing, funding acquisition, project administration, supervision, resources, investigation, methodology.

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Ethics Statement

This research was conducted in accordance with Queensland state wildlife research permits issued by the Department of Environment and Science (within protected areas: P-PTUKI-100483094, P-PTC-100483098 and P-SPP-100483101, and non-protected areas: WA0056270) and a Monash University Animal Ethics Committee approval (Approval number: 39971).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data associated with this study is available in Data S1.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.