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Predicting the occurrence of an endangered reptile based on habitat attributes

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Abstract. The endangered Blue Mountains water skink (*Eulamprus leuraensis*), a habitat specialist known from approximately 60 threatened highland peat swamps, is the sole endemic vertebrate of the Blue Mountains region, Australia. We quantified the species' habitat associations by surveying 10 such swamps annually for three years. We scored habitat features and trapped skinks, comparing habitat attributes of trap sites where skinks were and were not captured. The distribution of *E. leuraensis* was non-random: skinks were found at sites with high values for some variables (soil moisture, live vegetation, surface water, understorey density and numbers of burrows) and low values for others (dead vegetation, logs, rocks, bare ground, canopy cover, sunlight penetration and numbers of invertebrates), and were mostly found in sites that were close to surface water and far from trees and logs. *Eulamprus leuraensis* is widely distributed within swamps, with weak associations between microhabitat variation and skink presence. Skink abundance and mean body size were highest within swamp centres, decreasing towards the margins; larger skinks were found closer to water, gravid female skinks were found at wetter sites and juveniles occupied marginal habitat. Skinks were rarely recaptured $>$10 m from their original site, with adult males travelling further than adult females and juveniles. We developed a quick field detection method for managers to assess the likely presence of *E. leuraensis* using two habitat attributes (soil moisture and burrow abundance). We mapped the species' known and predicted habitat using GIS spatial layers, including locality records, associated vegetation communities and digital elevation models.

Additional keywords: conservation, field biology, freshwater ecosystems, habitat selection, herpetofauna, lizards, threatened species, wildlife management

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Introduction

To effectively manage an endangered species, we need to understand the habitats upon which it depends. In particular, understanding the role of habitat and microhabitat use allows us to determine the potential impacts of a changing environment on the species, and suggest relevant conservation measures (Smith and Ballinger 2001). As habitat fragmentation and loss are leading causes of species declines (Hibbitts *et al.* 2013), it is also critical to know where an endangered species occurs in order to identify and prioritise specific sites for management and conservation. Habitat changes will affect specialist species more than generalist species (Smith and Ballinger 2001), so the need for such information is especially great if the species in question is restricted to specific habitat types. Endangered species are often rare within their geographic distributions, and can be difficult to survey if activity is highly seasonal or weather-dependent (as is generally true for ectotherms: e.g. Webb and Shine 1997; Neilson 2002; Baird and Burgin 2013). Thus, managers need shorthand methods that will enable them to predict where a species is likely to occur – a logistically straightforward, pragmatic index of habitat suitability for management. Prior to management intervention, the validity of those predictions can be assessed with actual surveys, but an initial ecological triage approach enables managers to focus their efforts and prioritise funding. The information needed to link a species' occurrence to environmental attributes can be obtained by surveys, and the results of those surveys can then be used to develop species-occurrence prediction models.

One such imperilled species for which habitat-use patterns remain poorly known is the Blue Mountains water skink (*Eulamprus leuraensis*) (IUCN Red List: ARASG 1996; Cogger 2000). This endangered reptile is restricted to montane regions of south-eastern Australia, in the Blue Mountains and Newnes Plateau. It is endemic to a rare and endangered, isolated peat swamp habitat (TSSC 2005) and known from about 60 populations (because of low rates of gene flow among populations, each swamp is defined as a separate population: Dubey and Shine 2010*b*). *Eulamprus leuraensis* has been recorded within swamps across a range of elevations (~560–1140 m above sea level (asl)), and lizard abundances vary substantially among swamps (LeBreton 1996; Dubey and Shine 2010*a*; present study). Here we look for predictors of the species' occurrence, based on simultaneous surveys of skink distribution and habitat attributes. We conducted annual surveys over a three-year period to identify the habitats used by this little-known lizard.

Material and methods

Study area

The Blue Mountains (33.65°S, 150.44°E) and Newnes Plateau (33.34°S, 150.26°E) areas of south-eastern Australia (~100 km north-west of Sydney) have a temperate climate with a mean monthly temperature of 6.3–23.1°C (BOM 2015), and a mean annual rainfall of 464–1450 mm (Keith and Benson 1988; Whinam and Chilcott 2002; DEC 2006). The region experiences frequent fires (Hammill and Tasker 2010), has an underlying geology dominated by sedimentary (sandstones and metasedimentary rocks) and igneous (granite) rock (Pickett and Alder 1997), and supports the Temperate Highland Peat Swamps on Sandstone (THPSS) Endangered Ecological Community (EEC).

Study sites

The swamps sampled in this study include Blue Mountains Sedge Swamps and Newnes Plateau Shrub Swamps (Keith and Benson 1988; Benson and Keith 1990; Benson and Baird 2012). Islands within a matrix of sclerophyll woodland and open forest, these swamps are dominated by sedge, shrub and grass vegetation growing upon peaty soils (Fig. 1*a*) (Keith and Benson 1988; Benson and Keith 1990; TSSC 2005; Benson and Baird 2012). Each swamp contains one or more drainage lines (Benson and Baird 2012). Ten pristine swamps were selected for surveys, with mean elevations between ~680 and 1050 m asl, and ~0.90–26.60 ha in extent (Table 1) (Gorissen *et al.* 2015, Fig. 1). Three of the sites are on Newnes Plateau, within the state forest, and are at ~1000 m asl; four are in the Blue Mountains, in national parks, and are at ~900 m asl; and the remaining three are also in the Blue Mountains but are managed by the Blue Mountains City Council, and are at ~800 m asl. These 10 swamps encompass a diversity of elevations, sizes and fire histories (although none have been burnt by a major fire for at least 10 years), and they span the known distributional range of the sole endemic vertebrate, the Blue Mountains water skink.

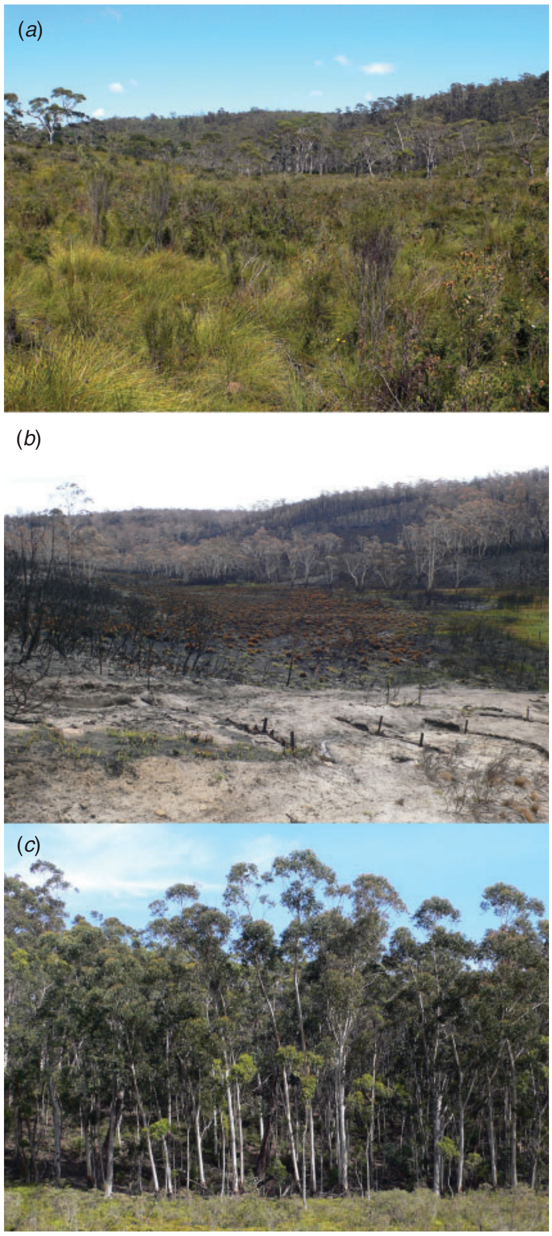

Fig. 1. Typical habitats within the swamp ecosystem: (*a*) pristine swamp habitat and (*b*) burnt swamp habitat (both inhabited by *Eulamprus leuraensis*), and (*c*) woodland habitat surrounding swamps (not inhabited by *E. leuraensis*). Photographs by S. Gorissen.

Focal species

Eulamprus leuraensis is listed as endangered under both state and federal legislation (NPWS 2001). Surveys suggest it is a swamp specialist (Gorissen *et al.* 2015, 2017*a*, 2017*b*; Gorissen 2016) restricted to groundwater-dependent swamps that are limited in extent (~3000–4000 ha in total: TSSC 2005; Hammill and Tasker 2010; Hensen and Mahony 2010; NSW OEH 2011; present study). These scincid lizards are short-lived (up to ~6 years), viviparous and reproduce annually (Dubey *et al.* 2013). They are medium-sized (snout–vent length (SVL) to 8.7 cm, mass to 14.8 g), and maturation occurs at a smaller size in males (adult SVL >5.2 cm) than in females (adult SVL >6.6 cm) (Dubey *et al.* 2013). These skinks are active on warm, sunny days and during the hotter months of the year (September to April/May). To escape predation, *E. leuraensis* takes shelter either in holes in the peat substrate or in dense sedgeland tussocks (Shea and Peterson 1985).

Quantifying faunal abundance

We conducted standardised mark–recapture surveys of three days' duration, in each of the 10 swamps, once per season

Table 1. Details of swamps surveyed

Locations and features of the 10 swamp sites we surveyed showing location, land tenure, elevation, extent and time-since-fire, and details of Blue Mountains water skinks trapped, such as abundance and size. Adapted from Gorissen *et al.* (2017*b*)

Swamp	Region	Land tenure	Latitude	Longitude	Mean elevation (m)	Area(ha)	Last major fire (year)	Total no. of skinks	Skink size (mean SVL, cm)
BH3	Blue Mountains	National Park	−33.606351	150.330455	967	1.26	1993/94	32	7.1
BH4	Blue Mountains	National Park	−33.610364	150.329987	955	2.72	1993/94	51	6.9
MH6	Blue Mountains	National Park	−33.641821	150.401938	800	8.94	2002/03	26	7.6
MH7	Blue Mountains	National Park	−33.651755	150.391787	808	6.00	2002/03	32	7.2
MRP1	Blue Mountains	Council	−33.717816	150.304642	955	0.89	Prior to 1967	24	7.5
NP4	Newnes Plateau	State Forest	−33.382006	150.227140	1050	26.61	Prior to 1967	60	6.8
PNP1	Newnes Plateau	State Forest	−33.340202	150.269538	991	14.65	2002/03	36	6.7
PNP4	Newnes Plateau	State Forest	−33.334320	150.289080	973	4.24	2002/03	20	6.5
SL	Blue Mountains	Council	−33.715367	150.427169	685	2.17	1977/78	34	7.4
WFL	Blue Mountains	Council	−33.706196	150.365407	878	10.57	Prior to 1967	13	7.2

(summertime) for three years (January 2013 to March 2015). We divided the swamp ecosystem into three survey zones – swamp, transition (swamp margin) and woodland (Gorissen *et al.* 2017*b*). To coincide with lizard activity, trapping was conducted only on days with a maximum temperature of 20–35°C and no rainfall (BOM 2015). At each zone in each swamp, we set 10 ground traps ~10 m apart. Pitfall traps (10-L buckets, 27 × 28 cm, without drift fences, one per zone) and unbaited funnel traps (18 × 18 × 75 cm, nine per zone) were used, and checked daily in the late afternoon. Captured herpetofauna were identified to species, and invertebrates to order. For all lizard species, body size (SVL and total length (cm)) was measured with a ruler, mass (g) by spring-scale, and sex by eversion of the hemipenes; tail (original/regrown), reproductive (gravid/non-gravid) and physical condition (i.e. scale and limb damage, and ectoparasites) were also recorded by visual estimation, and individuals were marked uniquely for later identification. Our index for population size of *E. leuraensis* was the number of individuals captured, excluding same-survey recaptures of individuals. Counts of recaptured lizards, however, included same-survey recaptures of individuals. Prior to surveying, our pilot studies established the presence of this species through trapping in all novel swamps (i.e. PNP4 and SL swamp sites): other records of presence were historical. Only live invertebrates were included, and we scored presence not abundance (i.e. as $n = 1$) if the trap also contained material that served as an attractant to insects.

Quantifying habitat characteristics

One author (SG) recorded a suite of habitat characteristics around each trap for all three zones and all 10 swamps, twice (once each in Years 2 and 3). Characteristics were visually estimated unless otherwise stated. Each plot was a circular area of 1 m radius, centred on the trap. Volumetric soil moisture content was calculated by taking the mean of three spatially randomised measurements from a Moisture Meter (MP406 Soil Moisture Instant Reading Kit, ICT International, Armidale; 6 cm probe). We also scored: (1) distance to nearest water (drainage line or pool ≥0.5 m diameter), tree (≥10 cm diameter, ≥5 m tall, alive), and log (≥10 cm diameter); (2) proportion of substrate covered by live vegetation, dead vegetation, log, surface water, rock, and bare ground (dirt or mud); (3) proportion of cover at the canopy (>5 m high) and understorey (0.5 m to 5 m high) levels, resulting in (4) sunlight penetration to ground level (the proportion of substrate exposed to direct sunlight at the sun's zenith). Distance measurements were made with a GPS device, and canopy approximated using a canopy cover estimation chart (Hnatiuk *et al.* 2009). Invertebrate burrows were counted when vegetation was sparse enough to evaluate total number of burrows in the entire quadrat (~<60% understorey in swamp). Burrows included those of the Sydney crayfish (*Euastacus australasiensis*) and the endangered giant dragonfly (*Petalura gigantea*) in swamps, and of spiders elsewhere. A soil moisture scale was established in order to rank moisture levels by sight alone. The scale was: 1 = dry, 2 = damp, 3 = wet, 4 = boggy, 5 = waterlogged/water, with 0.5 ratings used for intermediate levels.

Statistical analysis

We tested statistical assumptions and used regression (linear and logistic) and ANOVA (single-factor) to investigate the effects of habitat characteristics (independent variables) on skink abundances (dependent variables) (Table 2). We used mean annual values for each trap site as the unit for analyses for all variables. We used two measures of skink abundance: the number of *E. leuraensis* caught within all habitats combined, and within swamp habitat only (to avoid including sites with many zeroes, and to examine microhabitat preferences). When distributions deviated from normality, a standard $\log_{10}(x + 1)$ transformation was applied (Zar 1999). Our analyses on invertebrates included only species that are likely to be the prey of *E. leuraensis* (Veron 1969; Brown 1991; LeBreton 1992; S. Gorissen, G. Kosmala, M. Greenlees, R. Shine, unpubl. data 2014). We also quantified habitat differences between sites with and without *E. leuraensis* (using data for all trap sites) using linear Discriminant Function Analysis with stepwise variable selection using JMP Pro 11 (SAS Institute, Cary, NC).

Identifying predicted habitat

We define 'predicted habitat' as any area where *E. leuraensis* is not known to occur, but (from our mapping exercise) may be suitable for the species. Predicted habitat of the species was mapped using observations, field surveys (Baird 2012), existing locality records per swamp (ALA 2015; NSW OEH 2015),

Table 2. Results of statistical tests

Results of logistic regressions and contingency analyses comparing trap sites with and without *Eulamprus leuraensis* in terms of habitat characteristics for all habitats ($n = 300$), and swamp habitat only ($n = 100$). Asterisks indicate statistically significant results ($P < 0.05$); d.f. = 1 in all cases

E. leuraensis present (mean ± s.e.)	*E. leuraensis* not recorded (mean ± s.e.)	Variable	χ^2	*P*
All habitats				
78.90 ± 2.36	19.83 ± 1.35	Soil moisture content	219.89	<0.0001*
0.20 ± 0.14	0.01 ± 0.01	Burrows	6.99	0.0082*
12.54 ± 1.58	83.60 ± 4.19	Distance to water	196.17	<0.0001*
29.66 ± 1.69	5.43 ± 0.57	Distance to tree	166.40	<0.0001*
34.24 ± 1.81	6.37 ± 0.89	Distance to log	147.57	<0.0001*
65.00 ± 1.09	38.32 ± 1.32	Substrate, % live vegetation	138.38	<0.0001*
30.50 ± 1.02	43.78 ± 1.03	Substrate, % dead vegetation	63.42	<0.0001*
0.12 ± 0.08	12.36 ± 0.92	Substrate, % log	132.74	<0.0001*
2.55 ± 0.49	0.17 ± 0.08	Substrate, % water	40.65	<0.0001*
0.29 ± 0.13	2.50 ± 0.43	Substrate, % rock	26.65	<0.0001*
1.59 ± 0.38	2.88 ± 0.41	Substrate, % bare ground	4.84	0.0278*
0.96 ± 0.59	25.50 ± 1.61	Cover, % canopy	138.28	<0.0001*
71.51 ± 1.48	34.91 ± 1.59	Cover, % understorey	153.93	<0.0001*
28.89 ± 1.19	43.69 ± 1.32	Cover, % sunlight penetration	52.71	<0.0001*
0.65 ± 0.10	1.46 ± 0.13	Invertebrates (prey)	26.59	<0.0001*
Swamp habitat only				
86.21 ± 1.65	84.87 ± 4.36	Soil moisture content	0.07	0.789
0.30 ± 0.21	0.00 ± 0.00	Burrows	0.00	1.000
7.04 ± 0.72	6.36 ± 1.47	Distance to water	0.11	0.741
33.07 ± 1.66	27.50 ± 2.80	Distance to tree	1.40	0.236
37.98 ± 1.73	35.90 ± 4.31	Distance to log	0.17	0.683
65.45 ± 1.14	64.77 ± 2.97	Substrate, % live vegetation	0.04	0.841
29.89 ± 1.04	30.45 ± 3.03	Substrate, % dead vegetation	0.03	0.855
0.00 ± 0.00	0.00 ± 0.00	Substrate, % log	–	–
−2.98 ± 0.56	2.95 ± 1.21	Substrate, % water	0.00	0.987
0.06 ± 0.06	0.00 ± 0.00	Substrate, % rock	0.23	0.628
1.69 ± 0.42	1.82 ± 0.96	Substrate, % bare ground	0.01	0.916
0.03 ± 0.03	0.00 ± 0.00	Cover, % canopy	0.23	0.628
75.08 ± 1.10	80.68 ± 1.65	Cover, % understorey	3.93	0.0475*
27.28 ± 1.18	24.09 ± 1.18	Cover, % sunlight penetration	1.02	0.313
0.64 ± 0.12	0.61 ± 0.25	Invertebrates (prey)	0.01	0.914

and information on habitat preferences (LeBreton 1996; LeBreton and Fox 1997; Benson and Baird 2012; Gorissen *et al.* 2015, 2017*a*, 2017*b*; Gorissen 2016; present study). Candidate swamps:

(1) were restricted to the Blue Mountains region;
(2) had a peaty substrate with emergent groundwater (excluding swamps with total inundation);
(3) were reviewed using desktop analysis of the following vegetation mapping/classification exercises (Keith and Benson 1988; Benson and Keith 1990; Benson 1992; Fisher and Ryan 1994; Fisher *et al.* 1995; Benson *et al.* 1996; Ryan *et al.* 1996; Smith and Smith 1996; Bell 1998; NPWS 2003; Keith 2004; Tindall *et al.* 2004; DEC 2006; Tozer *et al.* 2010) and descriptions of potentially relevant threatened swamp ecological communities (NSWSC 2004, 2005, 2007, 2012; TSSC 2005; Department of the Environment 2015);
(4) were within the following vegetation communities – Temperate Highland Peat Swamps on Sandstone EEC and Montane Peatlands and Swamps EEC (those parts of both within the Blue Mountains region), Blue Mountains Sedge Swamps, Newnes Plateau Shrub Swamps EEC, Newnes Plateau Hanging Swamps, Coxs River Swamps, Boyd Plateau Bogs, Highland Peat Swamps, Blue Mountains Swamps (Vulnerable Ecological Community), Tableland Bogs, Tableland Swamp Meadows, Mountain Hollow Grassy Fen, Kurrajong Fault Swamps, Narrabeen Blue Mountains Sedgeland, Narrabeen Montane Plateau Shrub Swamps, and Blue Mountains-Shoalhaven Hanging Swamps (those parts within the Blue Mountains region) (these vegetation types are generally associated with peaty or organic-mineral sediments on poorly drained flats and hollows in the headwaters of streams, or in hanging swamps or slope mires, in catchments with sedimentary or igneous (granite) geology, and comprise a dense, open or sparse layer of shrubs with a generally sedgeland-dominated ground-layer: Keith 2004; Baird 2012);
(5) were classified as Coastal Heath Swamps and Montane Bogs and Fens (Keith 2004);
(6) did not include those in the northern Wollemi area (due to their isolation);

(7) were restricted to >520 m elevation, although field surveys identified some lower-elevation sites (e.g. 'Burralow Swamp', a Kurrajong Fault Swamp in the Bowen Mountain area); and
(8) were crosschecked with rainfall data (BOM 2015) and the above-listed vegetation publications, confirming that they are all within the indicative range for Montane Bogs and Fens (850–1500 mm per year) and almost all within the range for Coastal Heath Swamps (1000–1500 mm per year) vegetation classes (Keith 2004).

Mapping habitat

A digital map of predicted habitat was generated for the Blue Mountains water skink using GIS mapping tools. Spatial datasets of vegetation communities (of varying scales: Keith and Benson 1988; Benson 1992; ESP 2002; NSW OEH 2003, 2006; Tozer *et al.* 2010) were compiled into individual GIS layers. These spatial layers were then combined and analysed (both spatial and tabular) using ArcGIS mapping software (ArcMap 10.1, ESRI, Redlands, USA) to produce a draft spatial layer of predicted habitat. Anomalies with the line work were corrected using fine-scale remotely sensed data obtained from satellite imagery (SPOT 10 m: LPI 2014) and aerial photography (ADS40_SC 50 cm: LPI 2014). Thereafter, the data layer was objectively compared with field locality records to match it with the species' natural habitat and improve the accuracy of the model. Finally, 'ArcGIS Spatial Analyst' was used to analyse the Digital Elevation Model (30 m cell size: NSW OEH 2010) to identify and categorise the habitat polygons according to the specified elevation range. The resultant digital layer of the species' total habitat consisted of 1600 individual polygons (habitat patches) with an area of ~3495 ha. From this habitat, 'known habitat' (i.e. swamp habitat of this layer where the species was already recorded; 59 polygons, 8 of which were discovered during the current study; ~614 ha) was subtracted, leaving the remainder as predicted habitat (1541 polygons; ~2881 ha).

Results

Distribution of skinks

Within the highlands, *E. leuraensis* occurs almost exclusively in swamps, regardless of whether they are unburnt (last fire at least 45 years ago: Gorissen *et al.* 2015; Gorissen 2016) or have been burnt as recently as one month before the survey (Fig. 1*b*) (Gorissen *et al.* 2015; Gorissen 2016) although they were not found in hydrologically disturbed swamps (Gorissen *et al.* 2017*a*). These skinks were rarely found in swamp margins (Gorissen *et al.* 2015, 2017*b*), and our extensive surveys have never recorded this species in the woodland (Fig. 1*c*) (Gorissen *et al.* 2015, 2017*a*, 2017*b*; Gorissen 2016). Our analyses of presence/absence of this species across all habitat types revealed that skinks were found at sites with high soil moisture content (Fig. 2*a*), more burrows (Fig. 2*b*), a denser understorey (Fig. 3*a*) and more live vegetation (Fig. 3*b*). The strength of associations between skink presence and habitat features depended on whether analysis included all trap sites (i.e. at the level of the broader landscape) or was restricted to trap sites within the swamp only.

Although *E. leuraensis* was absent from drier areas within the broader landscape, not all areas with damp soil, dense understorey and live vegetation contained skinks (Fig. 4*a*–*c*, Table 2). For example, skinks were not recorded from sites with an understorey cover of ~40% and 80%, but were present at sites with ~70% understorey (Fig. 4*b*, Table 2). At a landscape level, sites without burrows lacked skinks, whereas sites with burrows often contained skinks; but if analysis was restricted to 'within-swamp' trap sites only, the association between skinks and burrows was much weaker (Fig. 4*d*, Table 2). In the broader spatial comparison, skinks were not recorded in areas far from water or close to trees. However, within swamps, distance from these habitat features did not influence skink occurrence (Fig. 4*e*, *f* respectively, Table 2).

At a landscape level, then, the distribution of *E. leuraensis* was highly non-random. These skinks were found in sites with a high soil moisture level and with many burrows; that were close to surface water and far from trees and logs; had substantial live vegetation and surface water, and lacked dead vegetation, logs, rocks and bare ground; with less canopy cover and sunlight penetration, and more understorey; and with few invertebrates (Table 2). Many of these characteristics consistently differ between the swamp habitat *per se*, versus the surrounding habitats (e.g. soil moisture content (%), number of burrows, etc.). If analysis is restricted to trap sites within the swamp habitat alone, most of these patterns disappear (Table 2). That is, skinks are widely distributed within the swamp, without strong effects of microhabitat variation (except, perhaps, preferring areas with a dense but not too dense understorey: Table 2).

Analyses using abundances of skinks (rather than presence/absence, as above) revealed the same general patterns, as well as some more subtle effects. These analyses were restricted to sites within the swamp itself. The number of skink captures was relatively unaffected by the trap site's proximity to water. However, numbers of skinks declined at the swamp margins (further from the drainage line etc.: Fig. 5*a*). The mean body size of skinks showed the same pattern, with larger skinks found closer to water (Fig. 5*b*). Gravid female skinks were recorded primarily from wetter sites (proportion versus percentage surface water: Fig. 5*c*). Almost all skinks appeared to be healthy (~94% with no overt injuries or ectoparasites).

Home range of skinks

There was no significant relationship for all recaptured skinks between the time since recapture (days) and distance travelled (m) from the original trap site ($n = 61$, $r^2 = 0.0001$, $P = 0.93$; for adult males only $n = 24$, $r^2 = 0.0008$, $P = 0.89$; for adult females only $n = 33$, $r^2 = 0.006$, $P = 0.66$). However, adult males tended to travel further (mean = 6.46 m) than did adult females (mean = 1.52 m), and juveniles not at all ($n = 4$, mean = 0 m; $F_{2,58} = 2.65$, $P = 0.079$). Noting that our traps were ~10 m apart, these small mean distances show that most recaptures occurred at the original trap site (48 of 61 cases, 79%; for adult males 16 of 24, 67%; for adult females 28 of 33, 85%; for juveniles 4 of 4, 100%: $\chi^2 = 8.04$, d.f. = 4, $P = 0.090$). If analysis is restricted to adult skinks only, males tended to travel further ($F_{1,55} = 4.40$, $P < 0.05$) and be less frequently recaptured at their original trap site ($\chi^2 = 6.05$, d.f. = 2, $P < 0.05$).

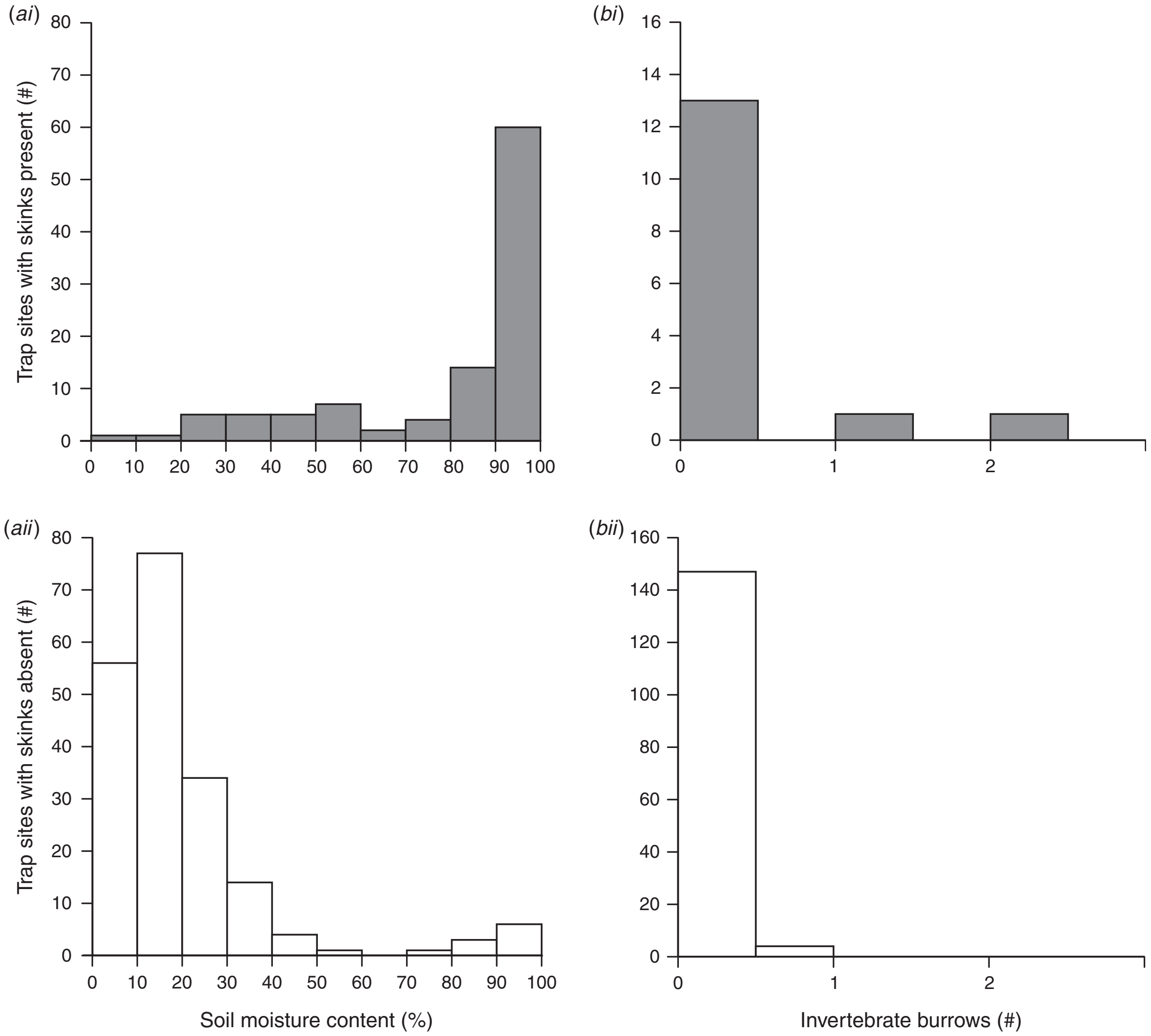

Fig. 2. Frequency distributions of the number of trap sites where *Eulamprus leuraensis* was either present (*i*: upper panels) or absent (*ii*: lower panels) as a function of (*a*) soil moisture content (% water, left panels) and (*b*) the number of invertebrate burrows (right panels; note: *y*-axis in (*bii*) is 10 times that of (*bi*)). Data are combined for all habitat types (swamp, transition, woodland).

Predicting skink occurrence

For predicting occurrence, managers need methods that are quick and simple to implement, and do not require expensive equipment. Encouragingly, our subjective soil moisture scale was highly correlated with measured soil moisture content (for all habitats combined, $n = 299$, $r^2 = 0.84$, $P < 0.0001$, with the soil moisture scale treated as a continuous variable). Thus, simply rating soil moisture subjectively may offer a robust indicator of skink presence (except during extreme dry periods or heavy rainfall). A Discriminant Function Analysis with stepwise comparisons revealed that ~25% of sites were misclassified (~22% *E. leuraensis* predicted to occur but do not; ~4% *E. leuraensis* not predicted to occur but do) using just the soil moisture scale, and only ~8% were misclassified after we added the number of invertebrate burrows as an additional variable (~4% error in each direction).

Habitat mapping

On the basis of the GIS analysis, the total area of known and predicted habitat for *E. leuraensis* is small (~3594 ha), of which just a fifth is known habitat (20%); the remaining ~2881 ha of predicted habitat is still largely unexplored (80%). Overlaying the mapped swamp polygons onto the satellite photo layer, however, reveals that these polygons overestimate the actual swamp area. Mapping predicts suitable habitat for the species in all cardinal directions beyond its known distributional limits. Known locality records coincide with the locations of swamps on the Newnes Plateau or surrounding townships in the Blue Mountains (Fig. 6). All existing records are in swamps described as Newnes Plateau Shrub Swamps, Newnes Plateau Hanging Swamps and Blue Mountains Sedge Swamps (Blue Mountains Swamps) (Keith and Benson 1988; Benson and Keith 1990; DEC 2006; NSWSC 2007), all of which form part of the

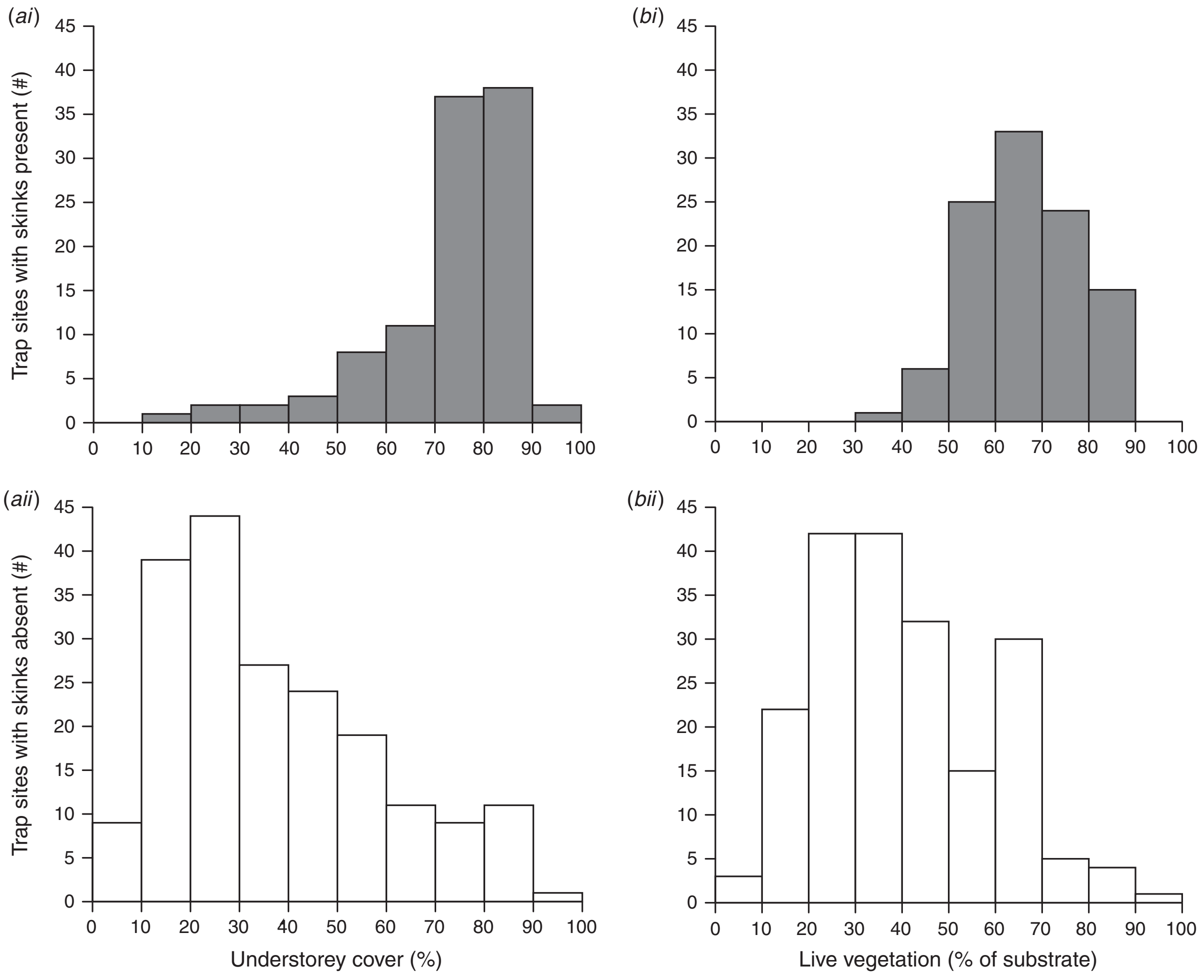

Fig. 3. Frequency distributions of the number of trap sites where *Eulamprus leuraensis* was either present (*i*: upper panels) or absent (*ii*: lower panels) as a function of (*a*) understorey cover (% shade, left panels) and (*b*) the percentage of the substrate covered by live vegetation (right panels). Data are combined for all habitat types (swamp, transition, woodland).

Temperate Highland Peat Swamps on Sandstone EEC. None of the existing records are in swamps included in the Montane Bogs and Fens vegetation class (Keith 2004) or the Montane Peatlands and Swamps EEC.

Discussion

The habitat attributes that drive the occurrence of *E. leuraensis* are strongly correlated with soil moisture content, and with the number of burrows constructed in wet soil by invertebrates. More broadly, the species occurs throughout suitable swamps as long as the soil is wet and/or surface water is present, the soil contains burrows, and the understorey is dense and dominated by live rather than dead vegetation. The connection between these lizards and water is consistent with our previous work (Gorissen *et al.* 2017*a*, 2017*b*), and with research on congeneric 'water skinks': *E. quoyii* is largely restricted to moist areas and creekside habitats (Heatwole and Veron 1977; Law and Bradley 1990), and *E. heatwolei* prefers damp areas of the swamp margins (Gorissen *et al.* 2017*a*, 2017*b*) and wet microhabitats (Cogger 2000). However, these widely distributed *Eulamprus* taxa are less closely associated with water than is *E. leuraensis*; it is common to find both *E. quoyii* and *E. heatwolei* in dense forest vegetation kilometres from water (Schwarzkopf 1998; Borges-Landáez and Shine 2003; Langkilde and Shine 2006).

Despite substantial heterogeneity in microhabitat characteristics within these swamps, our presence/absence data do not indicate any strong correlations between skink presence and local microhabitat features. Thus, *E. leuraensis* appears to be a habitat generalist at this level, requiring only the swamp macrohabitat. Previous studies on lizards have revealed non-random habitat choice at a range of spatial scales – for example, the gecko *Sphaerodactylus parthenopion* inhabits microhabitats that minimise desiccation (due to high rates of water loss: MacLean 1985), and *E. quoyii* prefers rocky, open creekside habitat in cool forests with thick vegetation (Law and Bradley 1990), whereas *Norops limifrons* selects its habitat based on landscape-scale characteristics (Heatwole 1977). The strict dependence of *E. leuraensis* on swamp habitat renders it totally reliant on these groundwater-dependent mires; but its broad

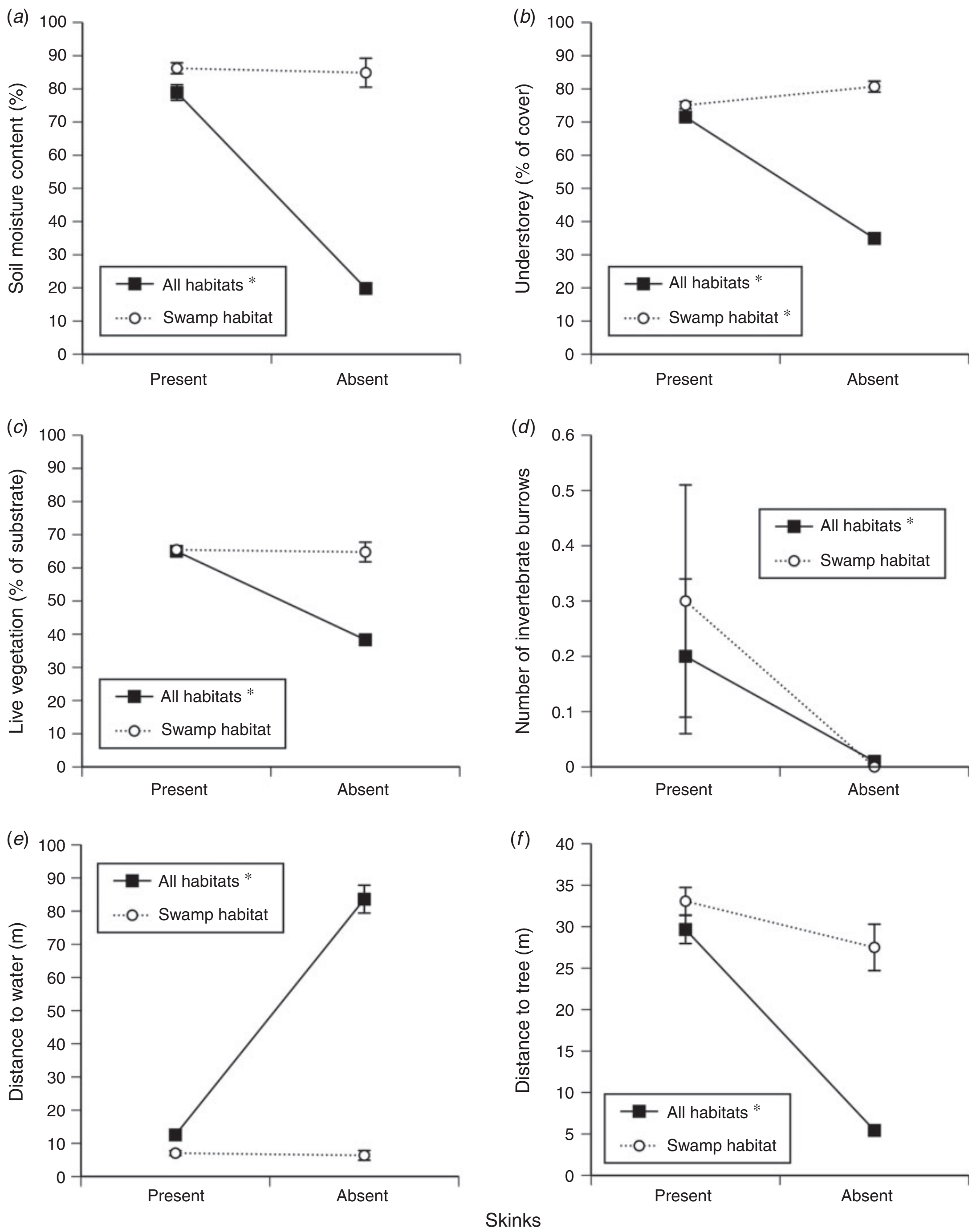

Fig. 4. The relationship between the presence of *Eulamprus leuraensis* and selected habitat characteristics. Data are shown for all habitat types combined (swamp, transition, woodland) and also for 'swamp habitat' only, in terms of (*a*) soil moisture content (%); (*b*) vegetation cover (% of understorey); (*c*) substrate composition (% of ground covered by live vegetation); (*d*) number of invertebrate burrows; and distances (m) to the habitat features (*e*) water, and (*f*) trees. Graphs depict mean annual values and associated standard errors. Asterisks denote statistically significant results ($P < 0.05$; also see Table 2).

microhabitat use within such a swamp is encouraging in terms of its conservation status. As long as the swamp macrohabitat is healthy (i.e. undisturbed: Gorissen *et al.* 2017*a*), it appears likely that *E. leuraensis* can persist.

Despite this species' ability to occur across a range of microhabitat types within a swamp, the numbers and sizes of skinks exhibit spatial heterogeneity at this scale. Within a swamp, *E. leuraensis* is concentrated centrally and close to

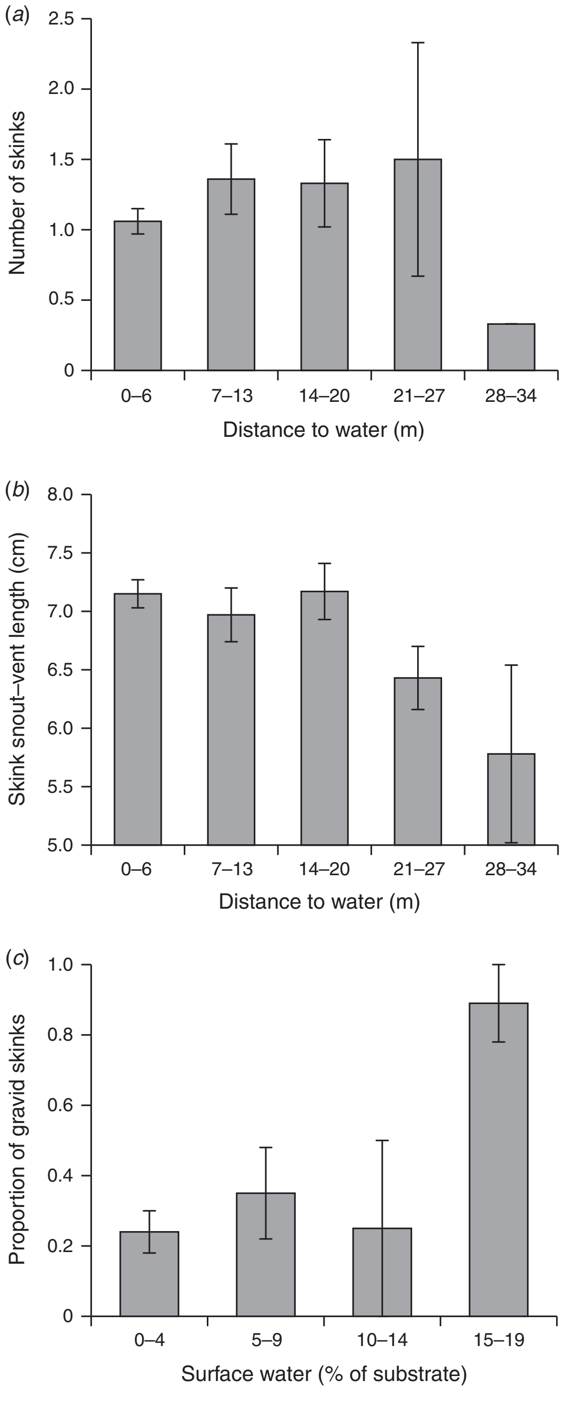

Fig. 5. The mean abundance, body size and demographic composition of *Eulamprus leuraensis* populations as a function of habitat characteristics easily assessed on site in the field within swamps: (*a*) abundance of skinks versus distance to water (m), (*b*) size of skinks (SVL, cm) versus distance to water (m), and (*c*) proportion of adult female skinks that were gravid versus the percentage of substrate as surface water (%).

water. Lower numbers at the periphery of the swamp may reflect an increase in predation risk on the fringe of the densely vegetated habitat. In the congeneric *E. tympanum*, predation by birds (kookaburras, *Dacelo novaeguineae*) is higher on subadult skinks than adults, plausibly because subadults are forced to marginal habitat where they are more vulnerable (Blomberg and Shine 2000). Many heliothermic reptiles are most abundant along the ecotone between dense and more open areas, reflecting the access to suitable thermoregulatory opportunities (e.g. Blouin-Demers and Weatherhead 2001), but *E. leuraensis* readily climbs onto tussock perches that receive full sun exposure (LeBreton 1992). Behavioural flexibility thus may enable the skink to achieve its preferred thermal conditions despite competing factors such as agonistic interactions and denser habitat (as in Langkilde *et al.* 2005).

Different sex and age classes of *E. leuraensis* inhabited different areas within the swamp, with average body size decreasing with distance from water. Adults occupied what is probably prime habitat, centralised and closer to water (0–20 m), whereas younger conspecifics occupied areas further from water (>20 m). The dependence on a specific type of swamp habitat was lowest then for smaller skinks, because they were more often found peripherally. Ontogenetic shifts in habitat use and movement ecology are common in squamate reptiles, and often driven by factors such as size-dependent shifts in diet, vulnerability to predators, and vulnerability to larger conspecifics (Bradshaw 1971; Stamps 1983; Taylor 1986; Law 1991). For example, subadult prickly forest skinks (*Gnypetoscincus queenslandiae*) move further per month than do conspecific adults (Sumner 2006), and juvenile *Amphibolurus ornatus* (Bradshaw 1971) and *E. quoyii* (Law 1991) may be ostracised to marginal habitats by intraspecific aggression (Done and Heatwole 1977). Gravid female *E. leuraensis* had the highest habitat specificity in our study, being found primarily at trap sites with more surface water, and that were central and close to drainage lines. That pattern suggests that pregnancy may induce these skinks to restrict their movements and remain within prime habitat, thereby reducing their exposure to predators (Dubey and Shine 2010*b*); alternatively, gravid females may be more aggressive, better securing this habitat. Adult male skinks have intermediate habitat specificity, found somewhat further away from water in more open habitat, probably moving between the swamp centre and areas further from water ‘nightclubbing’ for a mate, as in the polygynous *E. heatwolei* (Morrison *et al.* 2002).

Our recapture data suggest that *E. leuraensis* restricts its movements to a fixed home range of ~10 m in diameter. With most recaptures at the original trap site, this species also has high fidelity to these sites. Adult males travelled further than other age–sex classes, exhibiting larger home ranges and lower site fidelity. The same sex difference has been reported in *E. heatwolei* (Morrison *et al.* 2002), and adults of *E. tympanum* occupy fixed home ranges (Blomberg and Shine 2000). One important consequence of the fixed home range of *E. leuraensis* could be an inability to disperse. However, genetic studies have revealed that dispersal occurs, albeit rarely, and involves mostly males (Dubey and Shine 2010*b*). Fortuitously, we recorded this rare event in the field during our study. A large adult male *E. leuraensis* (marked in February 2013 at swamp NP4; SVL = 7.1 cm) was recaptured ~2.7 km away in a different swamp 10 months later (in December 2013 at swamp PNP9; SVL = 7.5 cm). Clearly, *E. leuraensis* sometimes moves through the woodland matrix, rather than remaining in its primary swamp habitat. As a result, effective conservation of

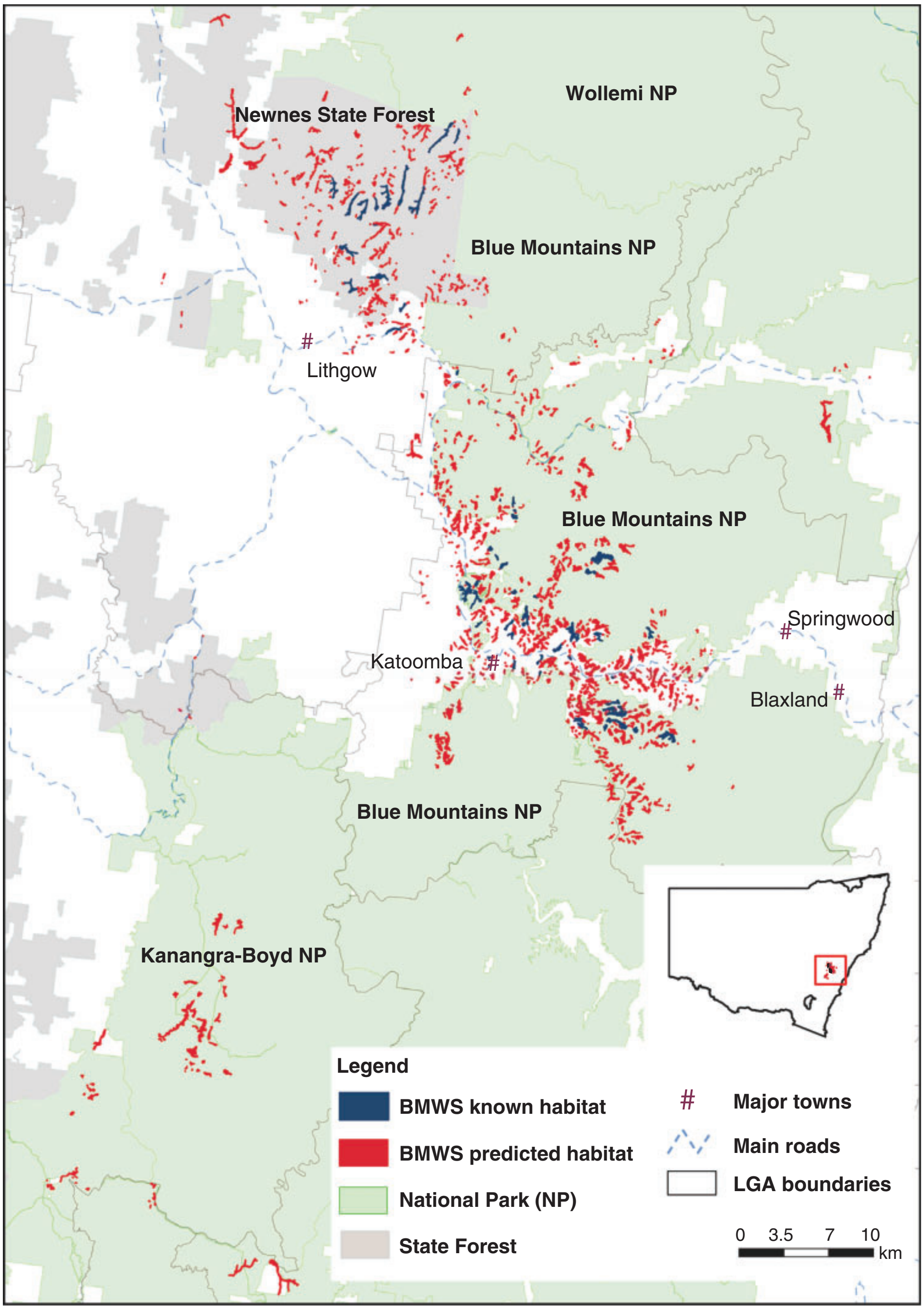

Fig. 6. Habitat map for the Blue Mountains water skink (BMWS) showing known swamp habitat (dark blue polygons) as well as predicted habitat (red polygons) all within the Blue Mountains region of south-eastern Australia. LGA, Local Government Area.

this species includes the need to maintain corridors between swamps to permit these rare but important dispersal events. For example, elimination of dispersal between habitat patches increased local extinction of the eastern collared lizard (*Crotaphytus collaris collaris*) due to human-induced fragmentation of the habitat matrix (Templeton *et al.* 2011). Dispersal is crucial to gene flow, alleviating inbreeding/genetic bottlenecks in populations and hence enhancing long-term viability of populations (Frankham 1998; Dubey and Shine 2010*b*).

Our attempt to predict the distribution of suitable habitat for *E. leuraensis* should be regarded as preliminary only. Mapping overestimated the actual swamp area, and revealed large areas of apparently suitable habitat outside the known distributional limits for the species (67 polygons, ~426 ha). These apparently suitable habitats are primarily to the south of the Coxs River in peat swamps of the Montane Bogs and Fens vegetation class (Keith 2004), either on granite or metasedimentary geology. They are typically either Tableland Bogs or Tableland Swamp Meadows (Tozer *et al.* 2010) in Jenolan State Forest, Kanangra Boyd National Park, and near Mt Werong and on the Loombah Plateau in the Blue Mountains National Park. In contrast, all known habitat is included within the Coastal Heath Swamps vegetation class (Blue Mountains Sedge Swamps, Newnes Plateau Shrub Swamps, and Newnes Plateau Hanging Swamps) on sandstone geology. Extensive surveys of flora and fauna (e.g. Keith and Benson 1988; Baird 2012) across the Blue Mountains over many years, including of Tableland Bogs and Tableland Swamp Meadows outside the known range of the species, have never resulted in sightings of *E. leuraensis*. This lack of records, despite intensive surveys, strongly suggests that the peat swamp types where the species has been recorded constitute its entire distribution.

Our field surveys have provided a straightforward way to predict the occurrence of this endangered species. The method is fast, reliable and simple, and does not require specialised equipment. Use of our moisture scale, coupled with invertebrate burrow counts, can enable managers to predict the likelihood of the species' occurrence with ~92% accuracy within its known range. Other information can add to the robustness of that prediction: for example, the species is more likely to be found in larger than smaller swamps, and in swamps close to other swamps that contain *E. leuraensis* (LeBreton 1996). The ability to rapidly assess habitat suitability for this endangered species (and thus, predict its occurrence) is particularly useful because that assessment can be conducted under weather conditions and times of year during which the skinks are inactive and hence not accessible for sampling.

Our results have significant implications for the conservation of this threatened taxon. Much of the mapped predicted habitat is protected within National Parks, encouragingly for the conservation of the species. However, the total habitat potentially available to *E. leuraensis* comprises a maximum of ~3600 ha. Coupled with high levels of genetic divergence among populations and limited dispersal, this means that conserving as much of the remaining habitat as practicable is paramount. The maintenance of corridors between adjacent swamps of pristine habitat within the woodland matrix would also facilitate dispersal events. Effective conservation of this endangered reptile species should focus on conserving habitat quality in swamps, rather than targeting the lizards themselves. If healthy swamps can be maintained, the lizards are unlikely to face extinction.

Conflicts of interest

The authors declare no conflicts of interest.

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