

## The impact of wildfire on an endangered reptile (*Eulamprus leuraensis*) in Australian montane swamps

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**Abstract.** Intense fire is a key threatening process for the endangered Blue Mountains water skink, *Eulamprus leuraensis*. This species is restricted to isolated, densely vegetated and waterlogged peat swamps in montane south-eastern Australia. We surveyed 11 swamps (5 unburnt, 6 burnt) over 2 years, before and after the intense spring bushfires of 2013, to quantify the fires' impacts on these skinks, other lizards and the habitat upon which they depend. Trapping revealed no direct effect of fire on *E. leuraensis* populations, with skinks persisting in all burnt swamps. Fire modified ground vegetation, virtually eliminating live plants and the dense understorey. Despite the conflagration, vegetation regrowth was rapid with swamp habitat largely recovering in just over 1 year post-fire. Fire thus had only a transitory effect on lizard habitat and a non-significant impact on *E. leuraensis* numbers. Nonetheless, broader-scale analyses suggest a different story: skinks were more abundant in swamps that had experienced a longer time since major fire. Although the ability of this endangered reptile to survive even intense wildfires is encouraging, fire during prolonged dry periods or an intensified fire regime might imperil skink populations.

**Additional keywords:** biodiversity, ecosystems: temperate, fire frequency, fire regimes.

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### Introduction

Famously, Australia is a land of fire. Over much of the continent, wildfires move through forested areas with obvious effects (Braithwaite *et al.* 1984; Bradstock 2010). In the post-fire landscape, it appears as though most species have not survived – but in general, the impacts of fire on natural ecosystems are less damaging for fire-adapted landscapes than it may seem (Means and Campbell 1981; Braithwaite 1987; Woinarski *et al.* 2004). Historically, to survive such conflagrations, native plants and animals may have adapted to frequent fires in the Australian landscape (Williams 2003; Woinarski *et al.* 2004; Keith *et al.* 2006). Indeed, some species tolerate or benefit from frequent fires (Braithwaite 1987; Woinarski *et al.* 2004) and some ecosystems are resilient and exhibit adaptations to intense fires (Woinarski *et al.* 2004). Nonetheless, fires may have major impacts on some types of habitats, under some types of conditions (Caughley 1985; Lunney *et al.* 1991; Benson and Baird 2012). For example, an endangered faunal species restricted to isolated patches of wet and densely vegetated habitat may be at particular risk (Kearney *et al.* 2009). Such a habitat specialist may be unable to survive in the surrounding landscape, and hence be imperilled by the sudden disappearance of its usual shelter and moist environment (Lindenmayer *et al.* 2008).

One such species is the Blue Mountains water skink (*Eulamprus leuraensis* Wells & Wellington, 1984), known from fewer than 70 isolated sites within the montane regions of south-eastern Australia (Blue Mountains and Newnes Plateau: IUCN

Red List ARASG 1996; NPWS 2001; Gorissen 2016; Gorissen *et al.* 2018). It is endemic to a rare and unique peat-swamp habitat, Temperate Highland Peat Swamps on Sandstone, which is also nationally endangered (TSSC 2005). In these regions, climate change is expected to cause hotter and drier weather conditions, resulting in increased fire frequency and reduced water availability (CSIRO 2007; IPCC 2013). An increase in prescribed burning may also intensify fire regimes, and altered fire regimes are a driver of biodiversity decline in general (Driscoll *et al.* 2012). More precisely, high-frequency fire was listed as a key threatening process to threatened species state-wide (Penn *et al.* 2003), and to *E. leuraensis* specifically (NPWS 2001). Understanding the disturbance ecology of this endangered reptile, notably its vulnerability to fire, is thus essential for framing conservation initiatives.

In previous work, we showed that the abundance of *E. leuraensis* was lower in swamps that had a higher frequency of major fires over the preceding 45 years, but we did not detect any relationship between skink abundance and time since fire (based on all recorded fires, regardless of their extent, Gorissen *et al.* 2015). Partway through our ecological research project on the swamp ecosystem and its herpetofauna, intense wildfires swept through the study area in October 2013. Some of our study sites were burnt, and others were not. We utilised this opportunity to investigate the short-term effect of fire on lizards (especially the endangered *E. leuraensis*) and habitat attributes, and to monitor the course and timeline of post-fire recovery.

## Materials and methods

### Study area

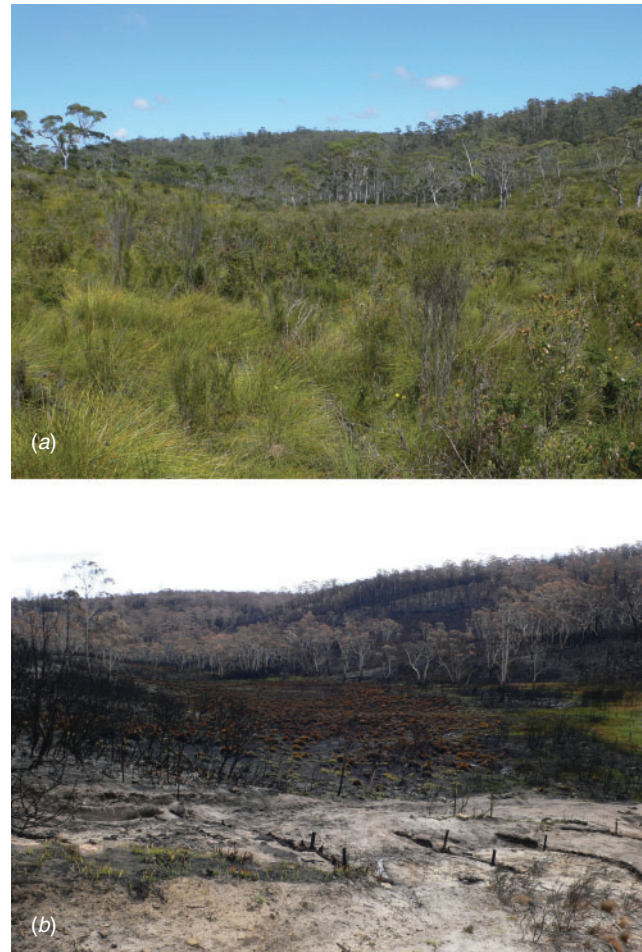
The montane areas of the Blue Mountains (33.65°S, 150.44°E) and Newnes Plateau (33.34°S, 150.26°E) in south-eastern Australia (~100 km north-west of Sydney) have a mean annual rainfall of 464–1450 mm (Keith and Benson 1988; Whinam and Chilcott 2002; DEC 2006) and an underlying sandstone geology (Benson and Keith 1990). The region has a temperate climate (mean monthly temperature 6.3–23.1°C; <http://www.bom.gov.au/climate/data/>), experiences a variety of fire regimes (Hammill and Tasker 2010), and contains the endangered ecological community of Temperate Highland Peat Swamps on Sandstone (THPSS; TSSC 2005). Guidelines on ecologically sustainable fire frequencies for major vegetation formations recommend a fire interval of 6 to 35 years for ‘freshwater wetlands’ (Kenny *et al.* 2004) and a minimum fire interval of 8 to 11 years for THPSS (Keith 2010).

### Study sites

These swamps are habitat islands within a matrix of open forest and sclerophyll woodland, and are dominated by sedge, shrub and grass vegetation growing on peaty soils (Fig. 1; Keith and Benson 1988; Benson and Keith 1990; Benson and Baird 2012). Each swamp contains one or more drainage lines (Benson and Baird 2012). Eleven such swamps were selected to survey, with mean elevations between ~680 and 1100 m ASL, and areas between ~1.75 to 26.65 ha (Table 1). Five swamps were unburnt (control sites; Fig. 1a) and six swamps had been burnt (treatment sites; Fig. 1b). Most of the burnt sites were the result of bushfires in October 2013, but one site (NL) had been burnt by a prescribed burn in August 2013. The swamps were further categorised as ‘urban’ or ‘bush’ based upon proximity to urban areas – from the nearest town centre, bush swamps were >5 km, whereas urban swamps were <2 km. These 11 swamps encompass a diversity of sizes, elevations and fire histories (although none had been burnt by a major fire for at least 5 years before the present study); and, span the known distribution of the sole endemic vertebrate in this region, *E. leuraensis* (Table 1; see fig. 1 in Gorissen *et al.* 2015, 2017a and fig. 6 in Gorissen *et al.* 2018).

### Focal species

Surveys suggest *E. leuraensis* is a swamp specialist, restricted to isolated, groundwater-dependent montane swamps of the region (Gorissen *et al.* 2015, 2017a, 2017b, 2018), which are limited in extent (~4000 ha in total: Hammill and Tasker 2010; Hensen and Mahony 2010; NSW OEH 2011; Gorissen *et al.* 2018). This skink is short-lived (up to ~6 years), viviparous and reproduces annually (Dubey *et al.* 2013). Specimens collected in Spring (male: September and October; female: October) were reproductively active (Shea and Peterson 1985), inferring mating during these months. Young are born with a snout–vent length (SVL) of ~30 mm (Dubey *et al.* 2013) and a mass of ~0.7 g (Dubey and Shine 2011) in late December (LeBreton 1996). The species is medium-sized (SVL to 87 mm, mass to 14.8 g); and maturation occurs earlier in males (adult SVL >52 mm) than in females (adult SVL >66 mm; Dubey *et al.* 2013). This scincid lizard is active on warm days during the hotter months of the



**Fig. 1.** Photographs of a swamp pre- and post-fire. (a) A typical ‘bush’ swamp at Newnes Plateau (XFC1), photographed 10 months before (December 2012), and (b) 2 weeks following (November 2013) the bushfires (October 2013).

year (September to April–May; S. Gorissen, pers. obs.). To escape predation, *E. leuraensis* takes shelter either in dense sedgeland tussocks or in holes in the peat substrate (Shea and Peterson 1985; S. Gorissen, pers. obs.).

### Quantifying habitat characteristics

Habitat surveys were conducted ~8 months before, and 1, 3 and 15 months post-fire over 3 years (i.e. seasons: January 2013 to March 2015). We divided the swamp ecosystem into three survey zones – swamp, transition (swamp margin) and woodland (Gorissen *et al.* 2017b, 2018). One researcher (S. Gorissen) recorded a suite of habitat characteristics at each trap site in all three zones of all 11 swamps, three times (once per post-fire survey). Characteristics were visually estimated unless otherwise stated. Each plot was a circular area of 1-m radius, centred on the trap. We scored: (i) distance to nearest surface water (drainage line or pool  $\geq 0.5$ -m diameter); (ii) proportion of substrate covered by live vegetation, dead vegetation, log, surface water, rock and bare ground (dirt or mud); (iii) proportion of cover at the canopy (>5 m high) and understorey (0.5–5 m high)

**Table 1. Locations and features of unburnt and burnt swamp sites**

Includes: total number of Blue Mountains water skinks (*Eulamprus leuraensis*) caught in swamps during the study, and years since the last major fire (before the fires of 2013). Swamp ID refers to the terminology of LeBreton (1996), Baird (2012) and Gorissen *et al.* (2015, 2017a, 2017b, 2018). Adapted from Gorissen *et al.* (2015)

| Swamp ID | Class | Region         | Mean elevation (m) | Area (ha) | Surveys (months post-fire) | Skinks in swamps (total <i>n</i> ) | Swamp type | Last major fire (year) | Time since major fire (years) |
|----------|-------|----------------|--------------------|-----------|----------------------------|------------------------------------|------------|------------------------|-------------------------------|
| BH2      | Bush  | Blue Mountains | 937                | 2.83      | 1, 3, 15                   | 37                                 | Burnt      | 2006–2007              | 5                             |
| BH3      | Bush  | Blue Mountains | 967                | 2.02      | –8, 1, 3, 15               | 31                                 | Unburnt    | 1993–1994              | 18                            |
| BS       | Urban | Newnes Plateau | 1100               | 10.82     | 1, 3, 15                   | 2                                  | Burnt      | before 1967            | >45                           |
| NL       | Urban | Blue Mountains | 687                | 1.75      | –8, 1, 3, 15               | 8                                  | Burnt      | 1977–1978              | 34                            |
| NP4      | Bush  | Newnes Plateau | 1050               | 26.61     | –8, 1, 3, 15               | 65                                 | Unburnt    | before 1967            | >45                           |
| NP5      | Bush  | Newnes Plateau | 1087               | 12.97     | 1, 3, 15                   | 24                                 | Burnt      | before 1967            | >45                           |
| PNP1     | Bush  | Newnes Plateau | 991                | 14.65     | –8, 1, 3, 15               | 43                                 | Unburnt    | 2002–2003              | 9                             |
| PNP8     | Bush  | Newnes Plateau | 1080               | 4.56      | 1, 3, 15                   | 13                                 | Burnt      | before 1967            | >45                           |
| PNP9     | Bush  | Newnes Plateau | 1085               | 11.11     | 1, 3                       | 19                                 | Unburnt    | before 1967            | >45                           |
| SL       | Urban | Blue Mountains | 685                | 2.17      | –8, 1, 3, 15               | 33                                 | Unburnt    | before 1967            | >45                           |
| XFC1     | Bush  | Newnes Plateau | 1075               | 11.90     | –8, 1, 3, 15               | 32                                 | Burnt      | 1997–1998              | 14                            |

levels, resulting in (iv) the proportion of sunlight penetration to ground level (i.e. the proportion of substrate exposed to direct sunlight at the sun's zenith). 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, NSW, Australia; 6-cm probe) during the 15-month post-fire survey only. Distance measurements were made with a global positioning system (GPS; Garmin GPSMap62, Garmin Australasia, Eastern Creek, NSW, Australia) device, and canopy approximated using a canopy cover estimation chart (Hnatiuk *et al.* 2009).

Invertebrate burrows were counted within three burnt swamps (NL, NP5 and XFC1) at 3 months post-fire along a 45-m transect every 5 m, at a distance of 1, 5 and 10 m from the drainage line (water). Burrows included those of the Sydney crayfish (*Euastacus australasiensis*) and the endangered giant dragonfly (*Petalura gigantea*).

#### Quantifying faunal abundance

We surveyed the 11 swamp sites for fauna by mark–recapture over 3 days, once or twice per season timed as above. Within each zone of each swamp we set 10 ground-traps ~10 m apart. Unbaited funnel traps (18 × 18 × 75 cm, 9 per swamp) and pitfall traps (10-L buckets: 27 × 28 cm, without drift fences, 1 per swamp) were checked daily from late afternoon onwards. Reptiles and amphibians were identified to species, and invertebrates to order. For all captured lizards, size (SVL and total length, cm) was measured by ruler, mass (g) by spring-scale, and sex by eversion of the hemipenes; reproductive status (gravid or non-gravid) and tail condition (original or regrown) were also recorded by visual estimation; and individuals were uniquely marked for later identification. Our index for population size of *E. leuraensis* was the number of individuals captured, excluding individuals that were recaptured during the same survey. We estimated 'minimum number alive' (MNA) as the actual number of individuals caught during a survey at time *t* plus those caught in surveys both before and after that time (excluding recaptures) and, hence (based on the lizard's low vagility, Dubey *et al.*

2013), known to be present but not captured at time *t* (Krebs 1966). Recapture rates were too low for us to use the alternative capture–mark–recapture estimates of lizard population sizes. Prior to surveying, our pilot studies established the presence of this species through trapping in all novel swamps (BS, NL, PNP8 and SL); other records of presence were historical. Only counts of live invertebrates were included in the analyses, and we scored presence not abundance if the trap also contained material that served as an attractant to insects. To coincide with lizard activity, this trapping was conducted only on summer days with a maximum temperature of 20–35°C and no rainfall (all climate data were accessed from <http://www.bom.gov.au/climate/data/>).

#### Quantifying fires

Time since major fire was calculated as in Gorissen *et al.* (2015). In brief, in the present paper we define major fires as those that had burnt >75% of a swamp's area. Fire history data during the period January 1967 to January 2013 were used to calculate time since fire based on major fires affecting swamps in this study.

#### Statistical analysis

We evaluated statistical assumptions (normality, homogeneity of variance) of all tests used. For statistical tests that require normal distributions we applied an arcsine transformation ( $p' = \arcsin\sqrt{p}$ ) to proportion data, a square root transformation ( $x' = x + \sqrt{0.5}$ ; Zar 1999) to count data, and a standard transformation ( $\ln$  or  $\log_{10}(x+1)$ ) to other data.

We used Generalised Linear Mixed Models (GLMMs) to investigate the effects of swamp type (unburnt or burnt: the main effect) on habitat characteristics (raw values per trap site per survey, with swamp site as the random factor) within swamps over time (1, 3 and 15 months post-fire; Table 2). With this design, significant interactions between the main effect and time should reveal impacts of burning. We used GLMMs (normal distribution, identity-link function for percentage live vegetation, percentage understorey and percentage sunlight penetration), GLMM (Poisson distribution, log-link function for



**Table 2. Impacts of time since fire on habitat attributes of swamps**

We report outcomes of statistical analyses on the habitat attributes of swamps. Statistically significant results ( $P < 0.05$ ) shown in bold. For effect sizes, see the figures referred to in the table below. ANOVA, Analysis of Variance; B, burnt; GLMM, Generalised Linear Mixed Model; MPF, months post-fire; TSF, time since fire; U, unburnt; U/B, unburnt v. burnt (the main effect)

| Figure | Category | Response variable               | Independent variable(s) | Source variable | Test  | d.f.  | Statistic | Value | <i>P</i> -value   | Trend      |
|--------|----------|---------------------------------|-------------------------|-----------------|-------|-------|-----------|-------|-------------------|------------|
| 2a     | Habitat  | Percentage live vegetation      | U/B; TSF                | U/B             | GLMM  | 1, 9  | <i>F</i>  | 84.66 | <b>&lt;0.0001</b> | U > B      |
| 2a     | Habitat  | Percentage live vegetation      | U/B; TSF                | TSF             | GLMM  | 1, 8  | <i>F</i>  | 86.55 | <b>&lt;0.0001</b> | 1 < 3 < 15 |
| 2a     | Habitat  | Percentage live vegetation      | U/B; TSF                | U/B × TSF       | GLMM  | 1, 8  | <i>F</i>  | 86.27 | <b>&lt;0.0001</b> | U/B × TSF  |
| 2a     | Habitat  | Percentage live vegetation      | U/B                     | 15 MPF          | ANOVA | 1, 98 | <i>F</i>  | 0.077 | 0.783             |            |
| 2b     | Habitat  | Percentage surface water        | U/B; TSF                | U/B             | GLMM  | 1, 7  | <i>F</i>  | 0.630 | 0.453             |            |
| 2b     | Habitat  | Percentage surface water        | U/B; TSF                | TSF             | GLMM  | 1, 6  | <i>F</i>  | 0.470 | 0.517             |            |
| 2b     | Habitat  | Percentage surface water        | U/B; TSF                | U/B × TSF       | GLMM  | 1, 6  | <i>F</i>  | 1.000 | 0.356             |            |
| 2c     | Habitat  | Percentage understorey          | U/B; TSF                | U/B             | GLMM  | 1, 9  | <i>F</i>  | 381.0 | <b>&lt;0.0001</b> | U > B      |
| 2c     | Habitat  | Percentage understorey          | U/B; TSF                | TSF             | GLMM  | 1, 8  | <i>F</i>  | 84.04 | <b>&lt;0.0001</b> | 1 < 3 < 15 |
| 2c     | Habitat  | Percentage understorey          | U/B; TSF                | U/B × TSF       | GLMM  | 1, 8  | <i>F</i>  | 67.88 | <b>&lt;0.0001</b> | U/B × TSF  |
| 2c     | Habitat  | Percentage understorey          | U/B                     | 15 MPF          | ANOVA | 1, 98 | <i>F</i>  | 75.96 | <b>&lt;0.0001</b> | U > B      |
| 2d     | Habitat  | Percentage sunlight penetration | U/B; TSF                | U/B             | GLMM  | 1, 10 | <i>F</i>  | 310.4 | <b>&lt;0.0001</b> | U < B      |
| 2d     | Habitat  | Percentage sunlight penetration | U/B; TSF                | TSF             | GLMM  | 1, 9  | <i>F</i>  | 116.3 | <b>&lt;0.0001</b> | 1 > 3 > 15 |
| 2d     | Habitat  | Percentage sunlight penetration | U/B; TSF                | U/B × TSF       | GLMM  | 1, 9  | <i>F</i>  | 89.95 | <b>&lt;0.0001</b> | U/B × TSF  |
| 2d     | Habitat  | Percentage sunlight penetration | U/B                     | 15 MPF          | ANOVA | 1, 98 | <i>F</i>  | 57.29 | <b>&lt;0.0001</b> | U < B      |
|        | Habitat  | Soil moisture content           | U/B                     | 15 MPF          | ANOVA | 1, 98 | <i>F</i>  | 3.82  | 0.054             |            |

percentage surface water) and Analysis of Variance (ANOVA) to tease out the effects.

We also used GLMM (Poisson distribution, log-link function) to examine the effects of fire on the abundance of *E. leuraensis* (total number per trap site per survey, with swamp site as the random factor) over time (−8, 1, 3 and 15 months post-fire; Table 3).

We used Analysis of Covariance (ANCOVA) to explore the effects of distance to water and the number of invertebrate burrows on skink abundance of burnt swamps 3 months post-fire. We also used ANCOVA to examine the relationships between time since fire (−8, 1, 3 and 15 months post-fire) and swamp type (unburnt or burnt) on skink body condition (residual scores from regressing ln mass/ln SVL), on relative tail length (residual scores from regressing ln tail length/ln SVL, including data on both regrown and original tails) and on skink morphometrics (SVL; sex ratio, juveniles; proportion of adult females that were gravid; Table 3). We used the raw values from each individual skink (body condition; relative tail length) or mean value per survey (SVL; sex ratio, juveniles; proportion of gravid females) as the unit for analyses for morphometric variables.

We defined a category of lizards other than the focal species, 'wet-zone lizards', as those that usually inhabit the wetter habitats (i.e. primarily the transitional zone, but also the swamp; Gorissen *et al.* 2017b). Our definition of 'prey' included only invertebrate species that are likely to be the prey of *E. leuraensis* (Veron 1969; Brown 1991; LeBreton 1992, 1996; S. Gorissen *et al.* unpubl. data). We used Generalised Linear Model (GLM; Poisson distribution, log-link function) to investigate fire effects over time on 'wet-zone lizards' and *Saproscincus mustelinus* (southern weasel skink; using raw values per swamp per survey) and 'prey' (using raw values per trap site per survey; Table 3). We also used GLM (Poisson distribution, log-link function) with our geographic information system (GIS) data to explore

the impact of time since major fire (years) on skink abundance (mean number of *E. leuraensis* per swamp per survey in season one; Table 3).

## Results

### Impacts of fire on habitat characteristics

Intense wildfire transformed the swamp habitat (typified by a dense, live understorey, with little dead vegetation, much shade and virtually no bare ground; Fig. 1a: pre-fire) into one that was open with a sparse understorey, permitting sunlight through and exposing bare ground, with little live vegetation and shade (Fig. 1b: post-fire). Overall, fire reduced the amount of live vegetation and understorey in swamps; and increased the amount of sunlight penetration (Fig. 2a, c, d, Table 2). However, the proportion of the ground surface covered by water remained stable (Fig. 2b, Table 2). These impacts were most apparent shortly after fire (1 month), but lessened through time to 3 months, and were relatively minor (in terms of understorey density and sunlight penetration) within 15 months (Fig. 2, Table 2). At 15-months post-fire the ground-cover of live vegetation was similar to that recorded in the pre-fire surveys (Fig. 2a, Table 2); and, soil moisture content was similar between unburnt and burnt swamps (Table 2).

### Impacts of fire on the Blue Mountains water skink

Fire did not affect lizard abundances differently in unburnt v. burnt swamps over time (i.e. there was no significant interaction between unburnt or burnt and time since fire: Fig. 3, Table 3). In both swamp types, skinks were present pre-fire, reduced in numbers before and immediately after the period when fires occurred, but then increased over time to numbers higher than pre-fire abundances (Fig. 3). From recaptured individuals, we verified that skinks survive fires: three individuals were

**Table 3. Impacts of time since fire on populations of lizards within swamps**

We report outcomes of statistical analyses on lizard abundances. 'Wet-zone lizards' are taxa that are characteristic of the wetter zones within the broader swamp ecosystem. Statistically significant results ( $P < 0.05$ ) shown in bold. For effect sizes, see the figures referred to in the table below. ANCOVA, Analysis of Covariance; B, burnt; DTW, distance to water; *E. l.*, *Eulamprus leuraensis*; GLM, Generalised Linear Model; GLMM, Generalised Linear Mixed Model; *S. m.*, *Saprosincus mustelinus*; TSF, time since fire; U, unburnt; U/B, unburnt v. burnt (the main effect)

| Figure | Category         | Response variable              | Independent variable(s) | Source variable | Test   | d.f.   | Statistic | Value | P-value           | Trend           |
|--------|------------------|--------------------------------|-------------------------|-----------------|--------|--------|-----------|-------|-------------------|-----------------|
| 3      | <i>E. l.</i>     | Abundance per trap             | U/B; TSF                | U/B             | GLMM   | 1, 7   | <i>F</i>  | 4.800 | 0.065             |                 |
| 3      | <i>E. l.</i>     | Abundance per trap             | U/B; TSF                | TSF             | GLMM   | 1, 7   | <i>F</i>  | 4.240 | 0.080             |                 |
| 3      | <i>E. l.</i>     | Abundance per trap             | U/B; TSF                | U/B × TSF       | GLMM   | 1, 7   | <i>F</i>  | 0.160 | 0.703             |                 |
| 4a     | <i>E. l.</i>     | Abundance                      | Burrows; DTW            | Burrows         | ANCOVA | 1      | <i>F</i>  | 10.26 | <b>0.0017</b>     | positive        |
| 4b     | <i>E. l.</i>     | Abundance                      | Burrows; DTW            | DTW             | ANCOVA | 1      | <i>F</i>  | 15.01 | <b>0.0002</b>     | negative        |
| 4      | <i>E. l.</i>     | Abundance                      | Burrows; DTW            | Burrows × DTW   | ANCOVA | 1      | <i>F</i>  | 24.39 | <b>&lt;0.0001</b> | positive at 1 m |
|        | <i>E. l.</i>     | Body condition                 | U/B; TSF                |                 | ANCOVA | 3, 293 | <i>F</i>  | 1.284 | 0.280             |                 |
|        | <i>E. l.</i>     | Relative tail length           | U/B; TSF                |                 | ANCOVA | 7, 289 | <i>F</i>  | 0.351 | 0.929             |                 |
|        | <i>E. l.</i>     | SVL                            | U/B; TSF                |                 | ANCOVA | 3, 293 | <i>F</i>  | 0.549 | 0.649             |                 |
|        | <i>E. l.</i>     | Sex ratio, juveniles           | U/B; TSF                |                 | ANCOVA | 3, 32  | <i>F</i>  | 0.982 | 0.414             |                 |
|        | <i>E. l.</i>     | Proportion of gravid females   | U/B; TSF                |                 | ANCOVA | 3, 30  | <i>F</i>  | 1.084 | 0.371             |                 |
|        | Wet-zone lizards | Abundance                      | U/B; TSF                | U/B             | GLM    | 1      | $\chi^2$  | 44.89 | <b>&lt;0.0001</b> | U < B           |
|        | Wet-zone lizards | Abundance                      | U/B; TSF                | TSF             | GLM    | 1      | $\chi^2$  | <0.01 | 1.000             |                 |
|        | Wet-zone lizards | Abundance                      | U/B; TSF                | U/B × TSF       | GLM    | 1      | $\chi^2$  | <0.01 | 1.000             |                 |
|        | <i>S. m.</i>     | Abundance                      | U/B; TSF                | U/B             | GLM    | 1      | $\chi^2$  | 14.90 | <b>0.0001</b>     | U < B           |
|        | <i>S. m.</i>     | Abundance                      | U/B; TSF                | TSF             | GLM    | 1      | $\chi^2$  | <0.01 | 1.000             |                 |
|        | <i>S. m.</i>     | Abundance                      | U/B; TSF                | U/B × TSF       | GLM    | 1      | $\chi^2$  | <0.01 | 1.000             |                 |
|        | Prey             | Abundance                      | U/B; TSF                | U/B             | GLM    | 1      | $\chi^2$  | 1.010 | 0.315             |                 |
|        | Prey             | Abundance                      | U/B; TSF                | TSF             | GLM    | 1      | $\chi^2$  | 10.80 | <b>0.001</b>      | positive        |
|        | Prey             | Abundance                      | U/B; TSF                | U/B × TSF       | GLM    | 1      | $\chi^2$  | 1.499 | 0.221             |                 |
|        | <i>E. l.</i>     | Abundance per swamp (season 1) | TSF (major)             |                 | GLM    | 1      | $\chi^2$  | 5.522 | <b>0.019</b>      | positive        |

captured pre- and again post-fire. Young-of-the-year juveniles were captured in burnt swamps during the same season as the fire: evidence of recruitment. The MNA was calculated to be 252 individuals (for the duration of the study).

In burnt swamps, there was a positive correlation between skink captures and burrow numbers (Fig. 4a, Table 3), but a negative correlation between skink numbers and distance from water (Fig. 4b, Table 3). Furthermore, we documented more skinks where there were many burrows close to water (1 m; at 10 m there were no skinks).

There were no significant effects of fire through time on the body condition of skinks; that is, fire did not result in skinks becoming consistently thinner or fatter over the course of the study (Table 3). Relative tail length and morphometrics (SVL; sex ratio, juveniles; proportion of gravid females) were also not significantly affected by fire through time (Table 3).

#### Impacts of fire on other fauna

The herpetofauna was diverse with 18 species in total, with similar species richness across the broader landscape in both unburnt (15 species) and burnt habitat (13 species). Within swamps, only three species were recorded in unburnt swamps, but there were seven in burnt swamps. *Eulamprus heatwolei* (yellow-bellied water skink) and *E. quoyii* (eastern water skink) were captured in the transitional zone and woodland respectively. Lizard species that typically do not inhabit the swamp ('wet-zone lizards' and *Saprosincus mustelinus*) were captured

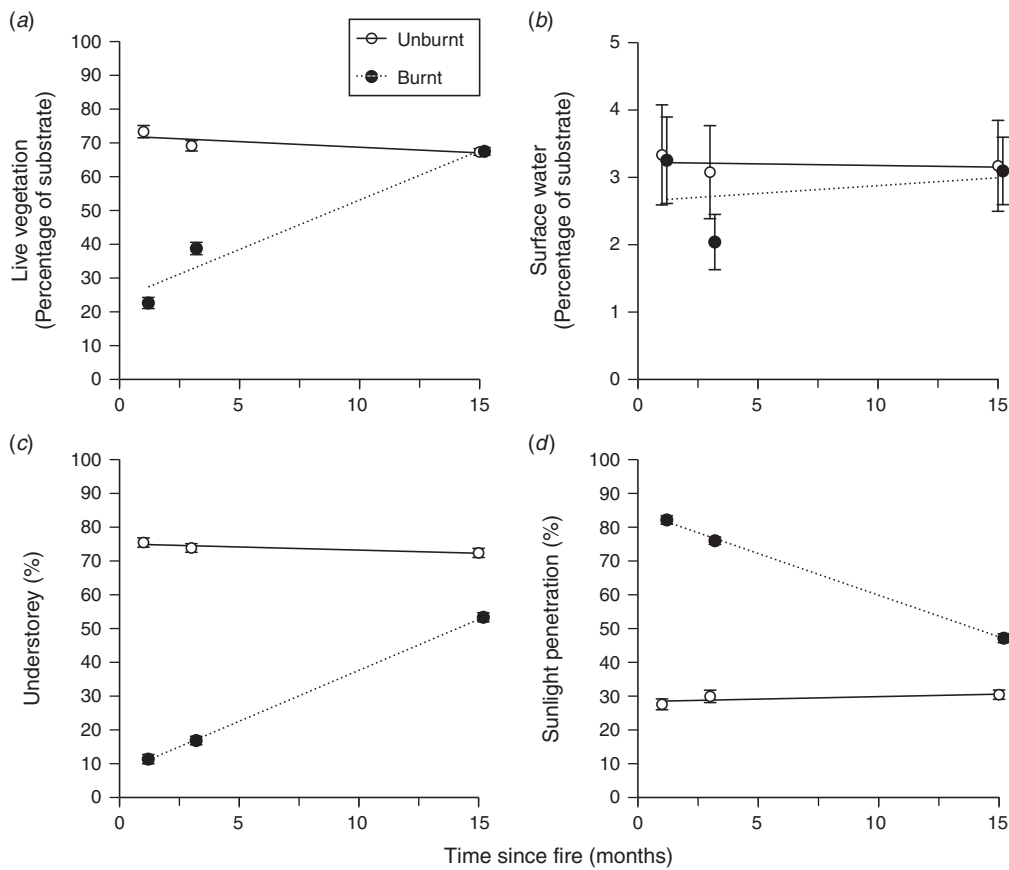
within swamps post-fire, but not within unburnt swamps (Table 3). These species were from the transitional zone (tussock skinks *Pseudemoia entrecasteauxii* and *P. pagenstecheri*) and the woodland (*S. mustelinus*; Gorissen *et al.* 2017b). The number of prey items trapped was not affected by fire over time (Table 3).

#### Broader-scale analyses

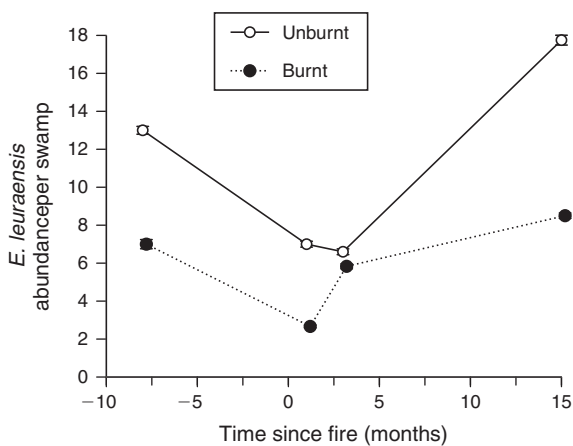
The abundance of *E. leuraensis* was positively correlated with time since major fire (Table 3).

#### Discussion

Our monitoring of burnt swamps (relative to nearby unburnt swamps) has clarified the nature and rate at which vegetation recovers post-fire in the swamp habitat. Although wildfire has a dramatic effect on this vegetation, it recovers substantially in just over 1 year. Immediately post-fire (3–14 days), the blackened landscape looks, to a naive observer, like a lifeless environment. Even at this time, however, drainage lines contain water, and tips of re-sprouting sedges are visible (S. Gorissen, pers. obs.). Wildfires have occurred in this area for millions of years (Hammill and Tasker 2010), and the swamp biota has evolved to survive fire events (Pianka and Goodyear 2012). Our surveys revealed that at 15 months post-fire, the vegetation had largely recovered within the swamp, albeit with more exposed ground than had occurred pre-fire. This exposure of the substrate was due to the slower recovery of the understorey – usually



**Fig. 2.** The impact of time since fire on features of the swamp habitat. The panels show changes in major habitat attributes of the two swamp types (unburnt and burnt) over time (1, 3 and 15 months post-fire) in terms of (a) live vegetation (percentage of substrate), (b) surface water (percentage of substrate), (c) understorey vegetation (% cover), and (d) sunlight penetration to ground level (%). Graphs show mean values and associated standard errors.



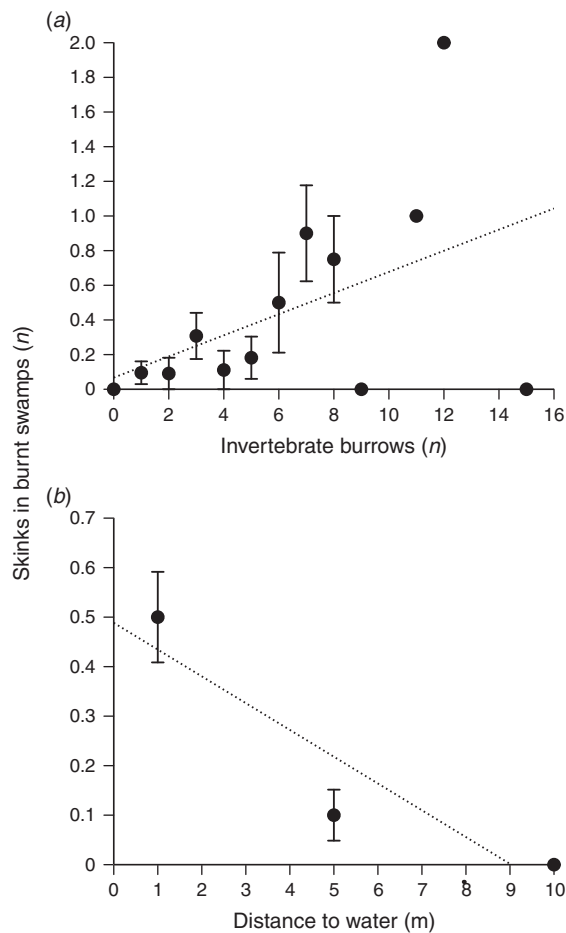
**Fig. 3.** The impact of fire on the abundance of *Eulamprus leuraensis*. The graph shows the mean number of skins per swamp within each of the two swamp types (unburnt and burnt) over time (-8, 1, 3 and 15 months post-fire) for *E. leuraensis*.

voluminous and dense, but now somewhat patchy and sparse. Over time, these and other habitat characteristics of burnt swamps presumably return to pre-fire conditions, although

long-term fire prevention may be needed to protect conservation values of peatlands (Johnson 2001).

Water is the distinguishing feature of the swamp habitat within the broader landscape (Gorissen et al. 2017b), with swamp-dwelling species dependent on it (Gorissen et al. 2017a). Immediately post-fire (3–14 days), we heard frogs (of two species: common eastern froglet *Crinia signifera* and banjo frog *Limnodynastes dumerilii*) calling from the drainage lines and other wet areas of swamps (S. Gorissen, pers. obs.). Our surveys showed that surface water remained stable over time within burnt swamps, and that soil moisture content within swamps was stable at 15 months post-fire. Higher sunlight penetration in the post-fire environment likely reduces surface moisture more strongly than subsurface moisture. Continuing availability of moisture within burnt swamps presumably enabled water-dependent species to persist (Russell et al. 1999). During prolonged dry periods, however, intense fires could be catastrophic to this fragile, ground-water dependent ecosystem (Russell et al. 1999; Baird 2012; Benson and Baird 2012).

Our faunal surveys at a fine scale revealed no significant effect of fire on the survival, distribution, morphology or demography of the endangered *E. leuraensis*. This species was found in all of the unburnt and burnt swamps that we surveyed over the 23-month period pre- and post-fire. Earlier surveys and



**Fig. 4.** The relationship between the number of *Eulamprus leuraensis* in burnt swamps and two habitat characteristics: (a) invertebrate burrows ( $n$ ), and (b) distance to water (m; at 1, 5 and 10 m). Graphs show mean values and associated standard errors.

records confirm that *E. leuraensis* previously occurred in all of our unburnt and burnt swamp sites. We also found neither an immediate nor longer-term effect of fire on skink abundance. Therefore, coupled with recapture records of skinks post-fire, it is clear that this endangered species can survive and persist through fire events that range from prescribed burns to bushfires. This result is consistent with a previous analysis of *E. leuraensis* abundance as a function of fire history (Gorissen *et al.* 2015; see also LeBreton and Fox 1997).

In contrast, our broader-scale GIS-based analysis revealed links between time since major fire and abundance of *E. leuraensis*: the swamps in which skinks were most abundant were those that had remained unburnt from major fires for longer periods. A previous GIS-based fire-history analysis on the species revealed similar effects, with fire-frequency and urbanisation both negatively correlating with skink abundance (Gorissen *et al.* 2015); but that earlier study did not detect a time-since-fire effect. That analysis was based on all recorded fires, regardless of their extent. By including only major fires, the present analysis revealed a significant correlation between skink abundance and time since major fire. In total, the GIS-based

approach suggests that populations of *E. leuraensis* are reduced by major fires over a long timescale.

Paradoxically, our detailed monitoring of swamps found that the abundance of *E. leuraensis* increased overall through time but did so in similar ways in unburnt and burnt areas. These skinks were more common in swamps that were not later burnt (partway through our study) than in swamps that were burnt. That pattern suggests that other factors may affect both the likelihood of fires within swamps, and the abundance of skinks. For example, swamps where ground-water levels are lower or more variable may be less optimal habitat for the lizards (Gorissen *et al.* 2017a), and more likely to be burnt. If so, the patterns detected by the GIS-based analyses may be correlations rather than reflecting any causal influence of fire frequency on skink populations.

Overall, our analyses suggest that multiple fires reduce skink abundance whereas the effect of a single fire is undetectable. This result is consistent with findings from other reptile species (e.g. Means and Campbell 1981; Braithwaite 1987; Lunney *et al.* 1991; Fenner and Bull 2007). Species that have evolved in fire-prone environments are behaviourally adapted to survive the direct effects of fire (Means and Campbell 1981), but multiple fires could affect skinks through cumulative effects. For example, reductions in rates of dispersal, survival, growth or reproduction might influence subsequent abundance (Smith *et al.* 2012). During spring and summer, when bushfires in the region are common (Hammill and Tasker 2010), a fire may affect critical phases of the annual cycle including mating and pregnancy.

The disparity between our fine- and broad-scale analyses might also be due to indirect effects mediated through shifts in habitat. Fires modify not only plant species composition, but also physical structure of the habitat (Means and Campbell 1981), potentially disrupting availability of shelter-sites and prey for the lizards. For example, a reduction in activity of the pygmy bluetongue lizard (*Tiliqua adelaidensis*) after a summer wildland fire was attributed to stress and a perceived greater vulnerability to predation due to the now-open habitat (Fenner and Bull 2007). In *E. leuraensis*, basking activity influences offspring phenotypes with a longer duration of basking resulting in faster-growing offspring that are born earlier (Dubey and Shine 2011). Environmental stressors to gravid females and juveniles might also alter survival-relevant traits over generations as in Owen *et al.* (2018). Any estimation of a recommended fire interval for this species should factor in these potential long-term effects on the species.

How can these lizards survive in the flat, exposed, post-fire landscape? Use of burrows as refugia is an effective strategy for reptiles to survive the immediate effects of fire (Main 1981; Moore *et al.* 2015; e.g. Friend 1993; Vitt and Caldwell 1993; Fenner and Bull 2007; Lindenmayer *et al.* 2008; Smith *et al.* 2012; Atkins *et al.* 2015). We observed *E. leuraensis* sheltering in burrows in burnt swamps immediately post-fire (14 days). Burrows in swamps are mainly constructed by invertebrates, primarily *Euastacus australasiensis* and *Petalura gigantea* (Gorissen *et al.* 2017a, 2017b, 2018); but also mammals such as rats. *Eulamprus leuraensis* use crayfish burrows as shelter (Swan 1990), to escape from predation (Shea and Peterson 1985; Benson and Baird 2012), and as fire refugia (Benson and



Baird 2012). Similarly, *Egernia coventryi* (the swamp skink) utilises freshwater crayfish burrows for refuge (in addition to constructing its own burrows: Chapple 2003; Clemann *et al.* 2004). Our analyses showed that the abundance of *E. leuraensis* is positively correlated with the numbers of burrows, and negatively correlated with distance from water. Our survey data suggest that the abundance of prey of *E. leuraensis* was not altered by fire over time.

The distribution of the non-swamp-dwelling congeners of *Eulamprus leuraensis* (*E. heatwolei* and *E. quoyii*) was not altered by fire across the greater ecosystem, with both species captured in their expected habitats (Gorissen *et al.* 2017a, 2017b). Similarly, other studies have reported that *E. heatwolei* were unaffected in the short term by a fire event (Braithwaite *et al.* 1984; Lunney *et al.* 1991; Penn *et al.* 2003). By removing understorey and ground vegetation, fire opens up the landscape and facilitates the ability of lizards to move between habitats (e.g. Lunney *et al.* 1991). Within swamps, fire increased the species richness of herpetofauna. Fire also increased the abundance of 'wet-zone lizards' and *Saproscincus mustelinus*, with more captured in burnt than unburnt swamps. These skink species were recorded only rarely in unburnt swamps but were found there post-fire. The peak in this phenomenon occurred directly after fire, when the swamp habitat most resembled the surrounding landscape. In effect, fire altered the distinctive features of swamp habitat, transforming it into an area that resembled the neighbouring habitat in terms of flora, fauna and physical characteristics. The three *Eulamprus* species, however, retained their usual distributions, with no compensatory shift in habitat preferences. Direct interspecific competition might play a role in driving this spatial separation among species (Langkilde *et al.* 2003) given the high levels of agonistic interaction among individuals within *Eulamprus* species (Done and Heatwole 1977).

The impact of fire on *E. leuraensis* is now clarified both by detailed studies post-fire (the present study) and GIS-based analyses of correlations between lizard abundance and fire history (the present study, and see also Gorissen *et al.* 2015). Clearly, *E. leuraensis* can survive a fire event, and fire itself may not be catastrophic for this species, provided it is part of an appropriate fire regime (Penman *et al.* 2011). Abundance of these skinks was lower in sites near urban areas, or where sites had been frequently burnt (although the relative importance of these two factors cannot be reliably distinguished with the present analyses because of low statistical power). Frequent major fires and urbanisation both reduce the abundance of these skinks, but do not extirpate them; skinks appear to persist wherever suitable swamp habitat is maintained. This species was recorded in all swamps surveyed for fire impacts, regardless of fire-history or proximal anthropogenic disturbance. However, although we have recorded groundwater-dependent species such as *E. leuraensis*, freshwater crayfish and the endangered giant dragonfly in swamps following fire, these species were not recorded after (and in some cases were extirpated by) hydrological disturbance (Gorissen *et al.* 2017a). The 'fast' life-history of *E. leuraensis* (rapid growth, early maturation, annual reproduction) may enable populations to recover from local, natural, pulse disturbances such as fire (Taylor and Fox 2001), but very low vagility means that re-colonisation of a swamp following a press disturbance, or following an extirpation of a population, is

unlikely (Dubey and Shine 2010). Water availability may then be the key ecological factor driving these wetland ecosystems. Management implications for the conservation of *E. leuraensis* are that its rare and fragile swamp habitat must be protected from the impacts of threatening processes such as frequent major fire, urbanisation and hydrological disturbance; and because increased fire frequency may be detrimental for *E. leuraensis*, prescribed burning should be undertaken with care, keeping to a fire regime with an appropriate frequency, intensity, severity and season (as outlined in NPWS 2001).

### Conflicts of interest

The authors declare that they have no conflicts of interest.

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