Austral ECOLOGY A Journal of ecology in the Southern Hemisphere

Austral Ecology (2014) ••, ••–••

The impact of fire regimes on populations of an endangered lizard in montane south-eastern Australia

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Abstract The Blue Mountains water skink (*Eulamprus leuraensis*; Scincidae) is restricted to less than 40 fragmented swamp sites, all within the Blue Mountains and Newnes Plateau areas of New South Wales, Australia. Climate change is expected to increase fire frequency in the area, potentially degrading habitat quality for this endangered reptile. We quantified lizard abundances in 12 swamps using standardized surveys, and constructed a Global Information System (GIS) database to determine fire-histories for each swamp since 1967. The abundance of Blue Mountains water skinks was negatively correlated with fire frequency, but not with time since fire. Indirect impacts of fire (mediated via shifts in vegetation density, moisture levels, prey availability and post-fire predation) may be more important than direct effects in these cool, moist habitats. Although lizards were less common in swamps close to urban areas, and less common in frequently burnt areas, viable populations of this endangered reptile still persist even in anthropogenically disturbed swamps and in swamps that have experienced up to four fires in 20 years. Future research could usefully extend these analyses to other swamps in the locality, and explore the broader impacts of fire regimes on the distinctive flora and fauna of this threatened ecological community.

Key words: conservation, fire frequency, reptile, threatened species, urbanization.

INTRODUCTION

Populations of many reptile and amphibian species are declining globally (Gibbons *et al.* 2000; IUCN 2004), and understanding the factors responsible for these decreases is a critical first step towards conservation. Many populations are threatened by local processes, such as habitat destruction and pollution, but others are at risk from broader-scale processes linked to climate change (Gibbons *et al.* 2000; Collins & Storfer 2003; Dubey & Shine 2011). Montane taxa may be at especially high risk in a warming world, with a major decrease in the extent and connectedness of areas providing the distinctive thermal and hydric conditions currently available in montane habitats (Dubey & Shine 2011). Habitat specialists that depend upon specific thermal and hydric refugia may be particularly vulnerable, because climate change is predicted to modify these abiotic conditions (Kearney *et al.* 2009). For example, climate-change models suggest that montane areas of south-eastern Australia – a region of very high biodiversity and endemicity – will experience increasingly hotter drier conditions (CSIRO & BOM 2007). As a result, fires are likely to become more frequent and intense in this sclerophyllous woodland (IPCC 2013). Management authorities thus need to understand how changes in fire frequency are likely to impact remaining populations of endangered species in this landscape.

The Blue Mountains water skink (*Eulamprus leuraensis*; Scincidae) is known from less than 40 highland swamps (between 560–1060 m elevation) within the Blue Mountains and Newnes Plateau areas of south-eastern Australia (Fig. 1; Dubey *et al.* 2013). Accordingly, this species is listed as endangered by the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, the New South Wales (NSW) *Threatened Species Conservation Act 1995* and *The IUCN Red List of Threatened Species* (IUCN 2013). The small and isolated swamps on which these lizards depend are classified as an endangered ecological community under the *Environment Protection and Biodiversity Conservation Act 1999*. Reflecting the strong habitat specificity and low vagility of the skinks, and the physical separation of swamps amid a eucalypt woodland matrix, genetic studies have revealed strong differentiation among Blue Mountains water skink populations from different swamps (Dubey & Shine 2010a). Those divergences not only make it a priority to maintain as many viable populations as possible to retain overall genetic variation, but also suggest that local extirpation is unlikely to be followed by rapid recolonization by lizards from another population (Dubey & Shine 2010b). Clearly, one of the most critical issues for managers is whether or not populations of Blue Mountains water skinks are likely to

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Accepted for publication July 2014.

doi:10.1111/aec.12190

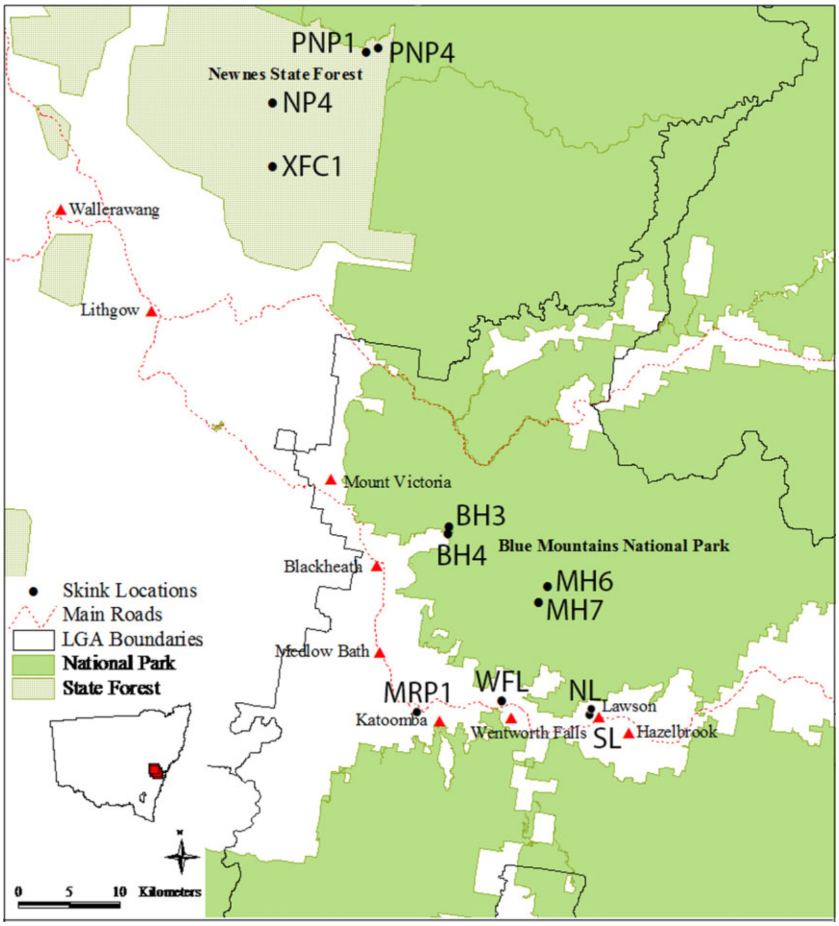

Fig. 1. Map of swamp study sites. Locations of the swamp sites within the Blue Mountains and Newnes Plateau and their land tenures (NSW NPWS 2001; see Table 1).

persist with increasing fire frequency. To address that question, we recorded lizard presence and abundance at a range of swamps, and focused on two aspects of fire regimes likely to be relevant to impacts on animals, and measurable from historical fire data: the time since last fire, and the periodicity of fires (Elzer *et al.* 2012).

METHODS

Study region

The temperate highland peat swamp habitats of the Blue Mountains water skink are restricted to between 560–1060 m (asl) in the Blue Mountains and the Newnes Plateau of NSW in south-eastern Australia (Fig. 1; NSW NPWS 2001). They formed upon an underlying sandstone geology (Benson & Baird 2012) in areas with a mean annual rainfall ranging from 464 to 1080 mm (Whinam & Chilcott 2002; DEC 2006). The region is subject to a temperate climate and experiences regular fires; the optimal fire interval for this vegetation community appears to be 6 to 35 years (Hammill & Tasker 2010).

Study sites

Swamps are dominated by sedge, grass, heath and shrub vegetation growing upon peaty soils (Beeton 2005), are bordered by sclerophyll forest or woodland, and contain one or more drainage lines (Appendix S1). Twelve such swamps (Fig. 1) were selected, with mean elevations between 687–1065 m asl (with a range of <9 m in elevation among traps within each swamp) and approximately 8900–266000 m^2 in extent. Four swamps were classed as 'Urban' (located within urban areas <2 km from a town centre at around 800 m asl, all in the Blue Mountains), and eight were classed as 'Bush' swamps (located >5 km from towns). Of the latter group, four were located in the Blue Mountains (at around 900 m asl) and four in the Newnes Plateau (at around 1000 m asl; see Table 1).

Study species

Eulamprus leuraensis is a medium-sized scincid lizard with a total length to around 200 mm (Dubey *et al.* 2013), a snout–vent length (SVL) to 85 mm and weight to 15 g (Dubey *et al.* 2011). *Eulamprus leuraensis* is viviparous, with young born in late December. These lizards are active on warm sunny days

doi:10.1111/aec.12190

Table 1. Swamp study sites

Swamp ID1	Swamp ID2	Class	Region	Mean elevation (m)	Area (m^2)	Individual skinks caught	Total fires	Major fires	Complete fires	Years since fire
BH3	PBH05	Bush	Blue Mountains	967	12 595	8	4	3	3	6
BH4	PBH04	Bush	Blue Mountains	955	27 208	8	4	3	2	6
MH6	PMH02	Bush	Blue Mountains	800	89 419	6	3	3	3	10
MH7	PMH03	Bush	Blue Mountains	808	60 029	5	3	3	3	10
MRP1	XKA01	Urban	Blue Mountains	955	8 933	10	0	0	0	0
NL	–	Urban	Blue Mountains	687	17 518	3	1	1	1	35
NP4	XNP11	Bush	Newnes Plateau	1050	266 100	21	0	0	0	0
PNP1	PNP01	Bush	Newnes Plateau	991	146 500	8	3	2	1	10
PNP4	PNP04	Bush	Newnes Plateau	973	42 400	5	4	2	1	10
SL	–	Urban	Blue Mountains	685	21 749	15	1	0	0	35
WFL	PWF14	Urban	Blue Mountains	878	105 722	3	0	0	0	0
XFC1	PFC01	Bush	Newnes Plateau	1066	29 100	11	2	2	2	15

Locations and types of swamps studied, with data on lizard captures (swamp traps only) and fire histories. Swamp ID1 refers to terminology of LeBreton (1996) and Dubey and Shine (2010b), whereas swamp ID2 refers to Baird (2012). The table shows number of fires affecting each swamp: of any magnitude (total fires), burning more than 75% of swamp by area (major fires) and those burning 100% of each swamp (complete fires) alongside the years since the most recent fire over the period January 1967 to January 2013. Traps set in transitional habitat caught an additional skink in BH4 and XFC1, and three additional skinks in SL.

from September until April (LeBreton 1996). To escape predation, *E. leuraensis* takes shelter either in holes in the peat substrate or in dense grass tussocks (Shea & Peterson 1985).

Quantifying lizard abundance

We conducted standardized surveys, each of three days duration, in each of the 12 swamps listed above, between December 2012 and March 2013. Trapping was conducted only on days with a maximum temperature of 20–35°C and no rainfall (BOM 2007). At each swamp, 30 traps were set at intervals of 10 m: 10 traps (S1–S10) within the swamp, 10 traps (W1–W10) within the surrounding woodland and 10 traps (T1–T10) on the fringe of the swamp within the 'transitional zone' between the swamp and woodland. Pitfall traps (10 L, 27 × 28 cm; without drift fences; 1/zone) and unbaited funnel traps (18 × 18 × 75 cm; 9/zone) were used. The two trapping methods catch similar sex ratios and body sizes of lizards (Dubey & Shine 2010a). Traps were checked in the late afternoon and we recorded SVL (mm) and mass (g, with a spring balance) of all captured lizards. Each animal was given a unique toe-clip for identification. Coordinates of the trap locations were recorded in the World Geodetic System (WGS 84) using a Garmin GPS device. We used capture rates (number of individuals, excluding recaptures) as an index of population size, based on the equivalent trapping effort per swamp. To analyse fire frequency in relation to number of lizards trapped, we calculated three values: the number of fires burning any part of a swamp's area (total fires), the number of fires burning more than 75% of a swamp's area (major fires) and the number of fires burning 100% of a swamp's area (complete fires), over the period January 1967 to January 2013 (Table 1).

Quantifying fire regimes

GIS data layers conform to the WGS 84 geographic coordinate system used in trapping, Google Earth and the employed satellite systems. Vegetation and fire layers from the Geocentric Datum of Australia 1994 (GDA 94) were converted to WGS 84 to ensure consistency.

Mapping swamps

Vegetation maps were used to produce polygons for each swamp, and added as new layers through projection into the database geographic reference system (DEC 2006; Blue Mountains City Council (BMCC), unpubl. report, 2013). Their accuracy was assessed through use of geo-referenced and projected satellite images. Inconsistent polygons for swamps BH3, MH6 and MH7 (see Fig. 1) were reconstructed within the ArcGIS geo-database to correspond to the Google Earth geo-referenced satellite images, providing boundary and area estimates for these swamps.

Fire mapping

Fire data (as polygons) were obtained from the NSW Office of Environment and Heritage (OEH), covering fire activity from 1967 to 2013 for the entire area (Northing 150 to 151 and Easting –33 to –34; OEH, unpubl. data, 2013). The accuracy of these data was verified by overlaying a secondary data set, in which fire points for 2002 to 2013 were obtained using FIRMS (Fire Information for Resource Management System: NASA FIRMS 2013), and detected using MODIS (Moderate Resolution Imaging Spectroradiometer) hotspot detection system (Mallinson 2013). The two data sets agreed very closely.

Time since fire

Data on the end date (to the nearest year) of swamp fires were incorporated by adding an additional field within the fire selection layer.

doi:10.1111/aec.12190

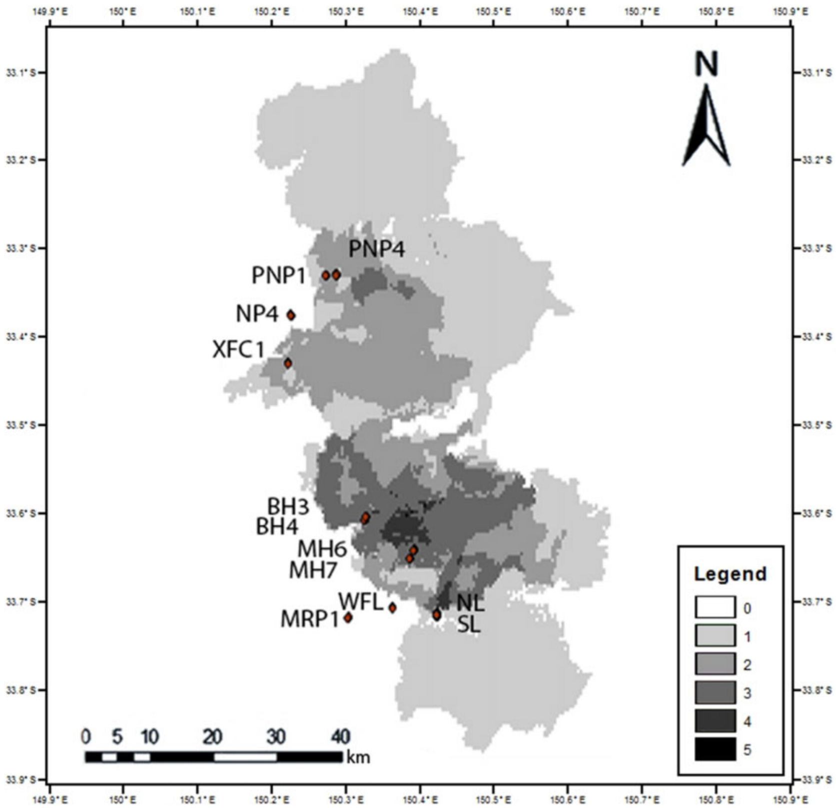

Fig. 2. Fire count (1967–2013). Raster surface of all fires impacting swamp sites showing the number of fires ('Legend') affecting those sites between 1967 and 2013 (see Table 1).

Fire frequency

Boolean maps of fire polygons in raster format were used to determine the number of fires in any given area. Shape files were converted to raster format to facilitate spatial analysis. Boolean maps of polygons were then created where every cell had a value of '1' (representing areas affected by fire) or '0' (for areas that were not). Using the raster calculator tool, maps were then summed to provide a new raster layer, which quantified the number of times each cell had been burnt within the timescale of the data (Fig. 2).

Spatial factors

Population dynamics of skinks might also be affected by swamp area, elevation and proximity to the next populated swamp or urban area (LeBreton 1996). Elevation was recorded using a GPS rather than a regional Digital Elevation Model to obtain greater accuracy and efficiency (Fisher 1998). Mean values were calculated per swamp.

Fire maps and population data

Quantitative values (e.g. for mean elevation, swamp area) were spatially calculated within the geo-database using purpose-built tools. Spatially determined values (time since fire, fire counts and area burnt) were derived from layer comparisons. For swamps with insufficient raster fire count resolution (i.e. where two or three fire count values were present within the swamp polygon), the total number and area of fires were calculated via layer selection tools within the database.

Statistical analysis

We used analysis of covariance (ANCOVA) to investigate the effects of swamp type (urban versus bush) and fire regimes (time since fire, and number of fires since 1967) on lizard abundance per swamp. Swamp type was entered as a factor, and the fire trait as a covariate; number of lizards trapped was used as the dependent variable. Non-significant interaction terms were deleted, and the ANCOVA recalculated to estimate main effects. Two values for numbers of lizards trapped were used – those *E. leuraensis* caught within swamp traps only, and those caught within all traps.

RESULTS

Lizard abundances

The number of individual *E. leuraensis* caught within each swamp site over the three days of trapping ranged

doi:10.1111/aec.12190

from three skinks in WFL and NL swamps, to 21 skinks in the NP4 swamp (Table 1). Five additional *E. leuraensis* were captured by transitional-habitat traps, but none by woodland traps.

Fire regimes

Of the 1069 fire polygons obtained (covering dates between 1967 and the first trapping session in January 2013), 12 fires were identified that had burnt our swamp sites. Eleven of these were natural bushfires, and one was a prescribed burn (Mallinson 2013). These fires burnt nine of the 12 swamps, six to 35 years before present (2013; Appendix S1); between 1967 and 2013, three swamps (WFL, MRP1 and NP4) did not experience any fires. The nine swamps that had been burnt experienced between one and four fires (Fig. 2), during which some of the swamp areas were only partially burnt.

Determinants of lizard abundance

Preliminary analyses showed that the number of lizards trapped per swamp was not significantly correlated with the mean maximum temperature during the trapping period ($n = 12$, $r^2 = -0.08$, $P = 0.66$), with swamp area ($n = 12$, $r^2 = 0.17$, $P = 0.10$) or with swamp elevation ($n = 12$, $r^2 = 0.02$, $P = 0.29$). Analyses where we included swamp area as a covariate did not affect any of our conclusions, so for simplicity we report the results of the analyses without that additional covariate. The ANCOVAs showed that our capture rates for lizards were higher in bush swamps than in urban swamps, and higher in swamps that had experienced fewer fires in the period since 1967. However, time since fire did not have a significant effect. For fire frequency, after deletion of the non-significant interaction term ($P = 0.69$), the capture rate of lizards was higher in bush than urban swamps ($F_{1,9} = 9.28$, $P < 0.014$) and negatively related to the number of fires that had burnt more than 75% of the swamp since 1967 ($F_{1,9} = 12.74$, $P = 0.006$; see Fig. 3). In contrast, analyses on time since fire showed no significant effects on lizard capture rates (swamp type: $F_{1,9} = 0.093$, $P = 0.77$; years since fire: $F_{1,9} = 0.005$, $P = 0.95$). Urban swamps were subject to fewer fires than bush swamps (presumably because fire-fighting activities were focused near towns); nonetheless, the urban-associated swamps had fewer lizards than did bushland sites (Fig. 3).

Analysis using all lizards trapped (i.e. including the animals caught in transitional habitat) yielded qualitatively similar results with respect to site type and fire frequency ($P = 0.037$ and 0.015, respectively) to those reported above. Analyses using other measures of fire history yielded similar but weaker effects of both swamp type and fire frequency on lizard capture rates (for number of total fires: $P = 0.06$ and 0.03, respectively; for number of complete fires: $P = 0.11$ and 0.05, respectively).

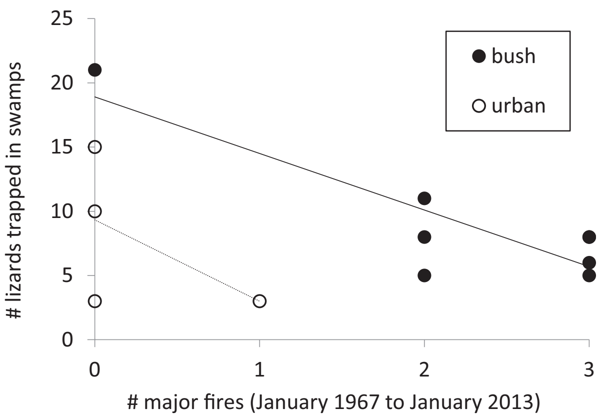

Fig. 3. Numbers of Blue Mountains water skinks. Relationships between swamp type (urban versus bush), fire history (number of fires in the preceding 6–35 years over the period January 1967 – January 2013), and the number of Blue Mountains water skinks (*Eulamprus leuraensis*) captured in montane swamps.

DISCUSSION

We caught >95% of our lizards within swamps, <5% in the swamp margins, and none in the adjacent woodland. This habitat specificity accords well with previous studies on these endangered skinks (Shea & Peterson 1985; LeBreton 1996). Thus, the viability of a population of *E. leuraensis* probably depends upon the swamp itself, with very slow recolonization of any extirpated populations (Dubey & Shine 2010a,b). Also, the restriction of lizards to swamp habitat justifies the use of swamps as sampling units in our study. Our analyses detected two significant correlates of the abundance of these lizards.

First, fewer lizards were found in urban swamps than in bush swamps. Many factors co-vary with proximity to urban areas (Smallbone *et al.* 2011), making it difficult to identify causal processes. Likely contenders include reduced water and/or soil quality (e.g. via polluted run-off: Piguet *et al.* 2008), weed invasion, predation by domestic cats or dogs, visitor disturbance, prescribed fires, mining and residential development (M. LeBreton and B. J. Fox, unpubl. report, 1997; NSW NPWS 2001; Smallbone *et al.* 2011; Benson & Baird 2012). These processes cause habitat loss and disturbance (e.g. fragmentation, degradation, alterations in hydrology such as sedimentation and channelling), shift prey abundance and vegetation composition, and indirectly increase lizard mortality.

doi:10.1111/aec.12190

The second significant correlate was fire history. The fire frequency (i.e. the number of major fires that burnt at least 75% of the swamp's total area) between 1967 and 2013 appears to have affected the abundance of these endangered lizards. *Eulamprus leuraensis* were less common in swamps that had experienced more major fires. Notably though, lizards were present even in the most frequently burnt swamps.

Although many studies have focused on the relationship of faunal abundance to years since fire, we saw no such pattern in our study. Such effects may be seen over shorter timeframes; the most recent fires at our swamp sites were >6 years ago, longer than the generation time of *E. leuraensis* (Dubey *et al.* 2013), and long enough for complete recovery of swamp vegetation (Hammill & Tasker 2010). Even if short-term effects of fire occurred, we would not have seen them. Immediately post fire, behavioural shifts in fauna induced by habitat change can invalidate survey data (Driscoll *et al.* 2012).

Even in major fires, actual fire damage is patchy due to vagaries of wind, heterogeneity of vegetation and areas of moist soil (Anderson *et al.* 2008). Our analyses did not show significant correlations of lizard numbers with minor fires, perhaps because such fires rarely impacted on the central swamp areas that contained most lizards. The region historically has experienced frequent fires (Hammill & Tasker 2010; Schrey *et al.* 2011), favouring an ability of *E. leuraensis* to survive fire events. Abundant holes in the moist substrate (including crayfish burrows) provide refuge sites for these lizards (Benson & Baird 2012). High frequency fire might cause drying of the burnt area (Barrett *et al.* 2010), with lizards thereby dependent on swamps with moister soils (LeBreton 1996; M. LeBreton and B. J. Fox, unpubl. report, 1997).

Indirect impacts of fire, mediated via changes in vegetation (Hammill & Tasker 2010), may be more important than direct fire-induced mortality for these swamp-dwelling lizards. Time since fire in these swamps affects swamp vegetation profiles (M. LeBreton & B. J. Fox, unpubl. report, 1997), with potential flow-on effects to the insects consumed by *E. leuraensis*. Because *E. leuraensis* feeds primarily on flying rather than ground-dwelling insects (LeBreton 1992), the removal of vegetation by fire might substantially modify the spectrum of insects available to the lizards. Reduced vegetation cover also may expose the skinks to post-fire predation (e.g. by birds, snakes, *Antechinus*, cats or humans), influencing the short-term outcome for reptiles after fire (Friend 1993).

Fire is a fundamental driver of floral assemblages in the Blue Mountains (Hammill & Tasker 2010). Impacts of fire depend not only on its frequency (the variable that we addressed), but also on its seasonality, intensity and severity. Fire seasonality can determine impacts on flora (Grant & Loneragan 2001; Knox & Clarke 2006) and fauna (Carrel 2008), and influence reptile abundance in the short-term (Friend 1993). We were unable to quantify this parameter, because the satellite data were insufficiently detailed. Most bushfires in the Blue Mountains occur in the hotter months between October and January, coinciding with skink activity (LeBreton 1996; Hammill & Tasker 2010). Springtime fires may disrupt reptile breeding activity (Friend 1993). Because the survival rate of newborn lizards may be critical for population viability (Dubey *et al.* 2013), burns in autumn may result in minimal disruption (Penn *et al.* 2003).

Intensity refers to energy release during a fire (Keeley 2009). Fire intensity has a substantial impact on the response of the landscape to fire, by driving fire severity (Hammill & Bradstock 2006; Williamson *et al.* 2013). Fire severity refers to the loss or change in organic matter following fire (Keeley 2009). The use of satellite imagery pre- and post-fire can aid the assessment of severity, as can data on soil organic depth (Barrett *et al.* 2010). Neither were available for our study. High intensity and severity would be expected to increase the detrimental effects of fire, especially in the short-term (Friend 1993). High frequency and intensity of fires in swamps also could result in prolonged peat fires that burn beneath the ground, smouldering at temperatures exceeding 100°C (Hammill & Tasker 2010). Peat fires can extend the duration of the surface fire event that precedes them (Gill 1997), potentially leading to devastating erosion, reduced soil-moisture retention and an overall decline in habitat quality (Hammill & Tasker 2010). Skinks might find it far more difficult to evade the impacts of a peat fire than an above-ground fire.

Our results have direct implications for management of this endangered lizard species. Because increased fire frequency may be detrimental for *E. leuraensis*, prescribed burning ('hazard-reduction') needs to be done with care, at appropriate frequencies, intensities, severities and seasons. Penn *et al.* (2003) suggest that more frequent prescribed burning will reduce forest biodiversity, for at least some ground-dwelling vertebrates. Inappropriate fire regimes already are recognized as a possible threat to populations of *E. leuraensis* (NSW NPWS 2001, 2002). From our study, *E. leuraensis* appears to benefit from less frequent or more minor fires; but the species can persist even when fire occurs as frequently as four times within 20 years. As noted above, the swamps are an endangered ecosystem, and other components of that ecosystem may have different fire requirements and tolerances than does *E. leuraensis*.

Skinks were abundant in swamps that had experienced no fires within the last 46 years, contrary to the idea that long periods without burning reduce habitat quality for the species (NSW NPWS 2001). However, the health of swamp vegetation clearly is a critical issue. This unique vegetation is a foundation of the endangered peat-swamp ecosystem, and its conservation should be central to fire

doi:10.1111/aec.12190

management strategies. Infrequent fire in montane swamps may facilitate encroachment of surrounding woodland, followed by drying and degradation of the swamps (Hammill & Tasker 2010). However, the swamp in which we found the most lizards (NP4) has remained unburnt at least since 1967, and has shown no significant encroachment at least since 1988, when satellite imagery became available (Keith & Benson 1988). Another motivation for prescribed burning is to reduce the build-up of fuel, minimizing the extent and severity of eventual fires events (Price 2012). Especially in urban swamps, nearby residential development brings with it the pressure for fire control measures to protect (people and) property, but also change vegetation structure (M. LeBreton and B. J. Fox, unpubl. report, 1997).

Our results also suggest a negative effect of urbanization on lizard numbers. Less than 50% of known *E. leuraensis* swamps are protected within National Parks (LeBreton 1996; Dubey & Shine 2010a; this study). Considering the geographic restriction of available habitat, the scarcity of swamps containing this endangered lizard, the extent of swamp fragmentation and the fragility of their tenure, swamp land must be protected to ensure survival of this species.

Eulamprus leuraensis populations negatively impacted by fire can be expected to recover only slowly, due to low annual fecundity coupled with a short adult life span (Dubey *et al.* 2013). If populations do not have time to recover before experiencing another fire, local extirpation is possible. Nonetheless, we saw no evidence of such dramatic effects. Viable populations of *E. leuraensis* persisted in all of the study swamps, even those that had experienced four fires within the last 20 years. Although fire does not currently appear to threaten the survival of endangered skink populations, anticipated changes in fire frequency due to climate change could be more damaging. Climate change is anticipated to cause south-eastern Australia to become both drier (by up to 40%) and warmer (by up to 5°C) within the next century (CSIRO & BOM 2007; IPCC 2013). Corresponding to these changes, the frequency and intensity of fires are predicted to increase. These changes may adversely affect *E. leuraensis* populations (Dubey & Shine 2011).

ACKNOWLEDGEMENTS

We thank Ian Baird, Frank Lemckert, Michael Hensen and Glenn Shea for discussions; Ian Baird, Daniel Howell, Damian Lettoof, Heinz Neubauer and Lachlan Petit for fieldwork assistance; and, Kate Hammill, NSW NPWS, OEH, NASA, DEC, and BMCC for data. The study was funded by the Fenner School of Environment and Society at ANU, the Blue Mountains City Council and the University of Sydney. We acknowledge the use of FIRMS data and imagery from the Land Atmosphere Near-real time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data and Information System (ESDIS) with funding provided by NASA/HQ. Procedures were conducted under the University of Sydney Animal Care and Ethics Committee authorization #L04/12–2012/3/5890.

REFERENCES

Anderson T. M., Dempewolf J., Metzger K. L., Reed D. N. & Serneels S. (2008) Generation and maintenance of heterogeneity in the Serengeti ecosystem. In: *Serengeti III: Human Impacts on Ecosystem Dynamics* (eds A. R. E. Sinclair, C. Packer, S. A. R. Mduma & J. M. Fryxell) pp. 135–82. University of Chicago Press, Chicago.

Baird I. R. C. (2012) *The wetland habitats, biogeography and population dynamics of* Petalura gigantea *(Odonata: Petaluridae) in the Blue Mountains of New South Wales* (PhD Thesis). University of Western Sydney, Australia.

Barrett K., Kasischke E. S., McGuire A. D., Turetsky M. R. & Kane E. S. (2010) Modeling fire severity in black spruce stands in the Alaskan boreal forest using spectral and non-spectral geospatial data. *Remote Sens. Environ.* **114,** 1494–503.

Beeton R. J. S. (2005) Advice to the Minister for the Environment and Heritage from the Threatened Species Scientific Committee (TSSC) on amendments to the List of Ecological Communities under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). [Cited 12 April 2013.] Available from URL: http://www.environment.gov.au/node/14561

Benson D. & Baird I. R. C. (2012) Vegetation, fauna and groundwater interrelations in low nutrient temperate montane peat swamps in the upper Blue Mountains, New South Wales. *Cunninghamia* **12,** 267–307.

BOM (2007) Climate Data Online. Bureau of Meteorology. [Cited 1 October 2013.] Available from URL: http://www.bom.gov.au/climate/data/

Carrel J. C. (2008) The effect of season of fire on density of female garden orbweavers (Araneae: Araneidae: *Argiope*) in Florida Scrub. *Fla Entomol.* **91,** 332–4.

Collins J. P. & Storfer A. (2003) Global amphibian declines: sorting the hypotheses. *Divers. Distrib.* **9,** 89–98.

CSIRO & BOM (2007) Climate change in Australia: observed changes and projections. Technical Report. Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology. [Cited 1 June 2013.] Available from URL: http://www.climatechangeinaustralia.gov.au/technical_report.php

DEC (2006) The vegetation of the western Blue Mountains, including the Capertee, Coxs, Jenolan & Gurnang Areas. Volume 2: Vegetation community profiles. Department of Environment and Conservation. [Cited 14 May 2013.] Available from URL: http://www.environment.nsw.gov.au/surveys/WesternBlueMountainsVegetation.htm

Driscoll D. A., Smith A. L., Blight S. & Maindonald J. (2012) Reptile responses to fire and the risk of post-disturbance sampling bias. *Biodivers. Conserv.* **21,** 1607–25.

Dubey S., Chevalley M. & Shine R. (2011) Sexual dimorphism and sexual selection in a montane scincid lizard (*Eulamprus leuraensis*). *Austral Ecol.* **36,** 68–75.

Dubey S. & Shine R. (2010a) Plio-Pleistocene diversification and genetic population structure of an endangered lizard (the Blue Mountains Water Skink, *Eulamprus leuraensis*) in south-eastern Australia. *J. Biogeogr.* **37,** 902–14.

Dubey S. & Shine R. (2010b) Restricted dispersal and genetic diversity in populations of an endangered montane lizard (*Eulamprus leuraensis*, Scincidae). *Mol. Ecol.* **19,** 886–97.

Dubey S. & Shine R. (2011) Predicting the effects of climate change on an endangered montane lizard, *Eulamprus leuraensis* (Scincidae). *Clim. Change* **107,** 531–47.

Dubey S., Sinsch U., Dehling M. J., Chevalley M. & Shine R. (2013) Population demography of an endangered lizard, the Blue Mountains Water Skink. *BMC Ecol.* **13,** 4.

Elzer A. L., Pike D. A., Webb J. K., Hammill K., Bradstock R. A. & Shine R. (2012) Forest-fire regimes affect thermoregulatory opportunities for terrestrial ectotherms. *Austral Ecol.* **38,** 190–8.

Fisher P. (1998) Improved modelling of elevation error with geostatistics. *Geoinformatica* **2,** 215–33.

Friend G. R. (1993) Impact of fire on small vertebrates in mallee woodlands and heathlands of temperate Australia: a review. *Biol. Conserv.* **65,** 99–114.

Gibbons J. W., Poppy S., Winne C. T. *et al.* (2000) The global decline of reptiles, déjà vu amphibians. *Bioscience* **50,** 653–66.

Gill A. M. (1997) Eucalypts and fires: interdependent or independent. In: *Eucalypt Ecology: Individuals to Ecosystems* (eds J. E. Williams & C. Z. Woinarski) pp. 151–67. University of Cambridge Press, Cambridge.

Grant C. D. & Loneragan W. A. (2001) The effects of burning on the understorey composition of rehabilitated bauxite mines in Western Australia: community changes and vegetation succession. *For. Ecol. Manage.* **145,** 255–79.

Hammill K. A. & Bradstock R. A. (2006) Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity. *Int. J. Wildl. Fire* **15,** 213–26.

Hammill K. A. & Tasker L. (2010) Vegetation, fire and climate change in the Blue Mountains World Heritage Area. Sydney, Australia: Department of Environment, Climate Change and Water (NSW). [Cited 13 May 2013.] Available from URL: http://www.environment.nsw.gov.au/protectedareas/GreaterBlueMountainsWorldHeritageArea.htm

IPCC (2013) Climate Change 2013: The Physical Science Basis. Working Group 1 contribution to the Fifth Assessment Report of the IPCC. Intergovernmental Panel on Climate Change. [Cited 1 October 2013.] Available from URL: http://www.ipcc.ch/report/ar5/wg1/#.Un84JOJyQ74

IUCN (2004) Global Amphibian Assessment. International Union for Conservation of Nature. [Cited 3 July 2014.] Available from URL: http://www.globalamphibians.org

IUCN (2013) IUCN Red List of Threatened Species. Version 2013.1. International Union for Conservation of Nature. [Cited 12 August 2013.] Available from URL: http://www.iucnredlist.org

Kearney M. R., Porter W. & Shine R. (2009) The potential for behavioral thermoregulation to buffer 'cold-blooded' animals against climate warming. *Proc. Natl Acad. Sci. USA* **106,** 3835–40.

Keeley J. E. (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *Int. J. Wildl. Fire* **18,** 116–26.

Keith D. A. & Benson D. H. (1988) The natural vegetation of the Katoomba 1:100 000 map sheet. *Cunninghamia* **2,** 107–43.

Knox K. J. E. & Clarke P. J. (2006) Fire season and intensity affect shrub recruitment in temperate sclerophyllous woodlands. *Oecologia* **149,** 730–9.

LeBreton M. (1992) Notes on the Blue Mountains Water Skink, *Costinisauria leuraensis* (Wells and Wellington) (Lacertilia: Scincidae). *Sydney Basin Nat.* **1,** 101–3.

LeBreton M. (1996) *Habitat and distribution of the Blue Mountains swamp skink* (Eulamprus leuraensis) (Honours Thesis). University of New South Wales, Australia.

Mallinson J. F. (2013) *The impact of fire regimes on the endangered Blue Mountains Water Skink (*Eulamprus leuraensis*) in montane south-eastern Australia* (Masters Thesis). University of Sydney, Australia.

NASA FIRMS (2013) MODIS Hotspot/Active Fire Detections. Data set. [Cited 15 January 2013.] Available from URL: http://earthdata.nasa.gov/firms

NSW NPWS (2001) Blue Mountains Water Skink (*Eulamprus leuraensis*) Recovery Plan. Hurstville, NSW: New South Wales National Parks and Wildlife Service. [Cited 17 May 2013.] Available from URL: http://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=59199

NSW NPWS (2002) Environmental Impact Assessment Guidelines – Blue Mountains Water Skink. Hurstville, NSW: New South Wales National Parks and Wildlife Service. [Cited 17 May 2013.] Available from URL: http://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=59199

Penn A. M., Sherwin W. B., Lunney D. & Banks P. B. (2003) The effects of a low-intensity fire on small mammals and lizards in a logged, burnt forest. *Wildl. Res.* **30,** 477–86.

Piguet P., Parriaux A. & Bensimon M. (2008) The diffuse infiltration of road runoff: an environmental improvement. *Sci. Total Environ.* **397,** 13–23.

Price O. F. (2012) The drivers of effectiveness of prescribed fire treatment. *For. Sci.* **58,** 606–17.

Schrey A. W., Fox A. M., Mushinsky H. R. & McCoy M. D. (2011) Fire increases variance in genetic characteristics of Florida Sand Skink (*Plestiodon reynoldsi*) local populations. *Mol. Ecol.* **20,** 56–66.

Shea G. M. & Peterson M. (1985) The Blue Mountains Water Skink, *Sphenomorphus leuraensis* (Lacertilia: Scincidae): a redescription, with notes on its natural history. *Proc. Linn. Soc. NSW* **108,** 141–8.

Smallbone L. T., Luck G. W. & Wassens S. (2011) Anuran species in urban landscapes: relationships with biophysical, built environment and socio-economic factors. *Landsc. Urban Plann.* **101,** 43–51.

Whinam J. & Chilcott N. (2002) Floristic description and environmental relationships of *Sphagnum* communities in NSW and the ACT and their conservation management. *Cunninghamia* **7,** 463–500.

Williamson G. J., Price O. F., Henderson S. B. & Bowman D. M. J. S. (2013) Satellite-based comparison of fire intensity and smoke plumes from prescribed fires and wildfires in south-eastern Australia. *Int. J. Wildl. Fire* **22,** 121–9.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Photographs of a swamp, pre- and post-fire.

doi:10.1111/aec.12190