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Habitat preference of the striped legless lizard: Implications of grazing by native herbivores and livestock for conservation of grassland biota

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Abstract Across the globe, many species of reptile are threatened with extinction, with changes in grazing pressure as a significant factor in their decline. Few studies have investigated the role of native herbivores, yet studying natural grazers may provide insight into natural grazing regimes, not apparent in studies of domestic livestock. In this study, we investigate the habitat requirements of a threatened Australian grassland reptile, the striped legless lizard, *Delma impar*, in grasslands grazed by a native herbivore, the eastern grey kangaroo *Macropus giganteus*. *Delma impar* appears sensitive to habitat change resulting from altered grazing intensity, but a lack of information hinders implementation of appropriate grazing regimes. To address this gap, we investigated habitat preferences of *D. impar* at multiple spatial scales across a grazing gradient. We found that the occurrence of *D. impar* was not affected by the size of grassland remnants, but was negatively related to the density of native grazers. This result was likely a consequence of the negative effect of high grazing intensity on grass structural complexity, as the probability of encountering a *D. impar* was positively related to grass structural complexity at the fine scale (1 m²). We recommend that conservation efforts should avoid high intensity grazing (equivalent to > 1.3 kangaroos/ha), yet ensure enough grazing disturbance is maintained to promote the formation of complex grass structures. We also recommend that small floristically degraded and fragmented grassland habitat should be included in conservation efforts. These recommendations will likely benefit a number of faunal species in grasslands grazed by domestic and native grazers. Importantly, our data highlight the need for managing grazing regimes, even in environments dominated by native herbivores.

Key words: complexity, conservation, grass, grazing, herbivore, kangaroo, overgrazing, reptile.

INTRODUCTION

Animals select habitat based on various environmental factors operating across multiple spatial scales (Mackey & Lindenmayer 2001; Luck 2002; Rodríguez *et al.* 2007). Understanding what these environmental factors are is especially important for species at risk of extinction (Caughley *et al.* 1996; Lindenmayer & Burgman 2005). Such information can be used to guide habitat restoration (Sato *et al.* 2014a) to identify priority areas for biodiversity conservation (Wintle *et al.* 2005) and to provide insight into likely impacts of environmental change (Lindenmayer *et al.* 2014). Unfortunately for many species, their ecology remains poorly understood, and few data are available to assist their conservation management (IUCN Red List of Threatened Species

2014). Addressing these data deficiencies is important for conservation managers developing management strategies to reverse population decline (Caughley & Sinclair 1994; Morrison *et al.* 2006). In ecosystems where threatening processes are still acting on populations, such research should be a high priority for conservation managers.

The conservation of reptiles is seriously hampered by the global lack of basic ecological research for most species (Gibbons *et al.* 2000; Böhm *et al.* 2013). This data deficit is attributable to inherent challenges in studying reptiles because they are cryptic, occur across a diverse and often challenging terrain and are often ignored in the allocation of research and conservation resources (Böhm *et al.* 2013). We address this gap for the striped legless lizard, *Delma impar*, which is a threatened semi-fossorial grassland insectivore once widely distributed in natural temperate grasslands across south-eastern Australia (Coulson 1990; Robertson & Smith 2010). However, over 99% of natural temperate grasslands have

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been lost through clearing or agricultural intensification in the last 200 years (Kirkpatrick *et al.* 1995; ACT Government 2005), with natural temperate grasslands now listed as an endangered ecological community (Department of the Environment and Heritage 2003). Consequently, *D. impar* has undergone a dramatic range contraction and is now classified as threatened under state and federal environmental laws (Department of the Environment and Heritage 2014). Where *D. impar* persists, it is threatened by pasture improvement, weed invasion, urban development and inappropriate fire and grazing regimes (Hadden 1998; Dorrough & Ash 1999; O'Shea 2005; Robertson & Smith 2010). Despite the recognition of these threats to the conservation of the species, few empirical data are available to guide the conservation management of the relict populations of *D. impar* and the maintenance of their habitat. We investigate the role of grazing regimes in influencing habitat selection by *D. impar*.

Grazing by large herbivores can have a profound influence on reptiles by changing the structural complexity of grasslands (Castellano & Valone 2006; Brown *et al.* 2011; Howland *et al.* 2014; Larson 2014). Intense grazing reduces grass cover and can expose small ground-dwelling reptiles to elevated rates of predation, reduced prey abundance and heat stress (Osmond 1994; Castellano & Valone 2006; Sato *et al.* 2014b). Conversely, suppression of grazing may also be detrimental, as without grazing grass can form tall and dense structures, reducing the access to sunlight needed for metabolic function in many reptiles (Scott 1962; Hacking *et al.* 2014). Hence, some grazing is considered important in maintaining habitat quality for grassland reptiles (Coulson 1990; Thompson 2006; Candy 2008; Robertson & Smith 2010; Pettigrew & Bull 2014), but information is limited on optimal grazing regimes for *D. impar*. We address this knowledge gap by determining *D. impar* habitat preferences in grasslands grazed by native kangaroos in the Australian Capital Territory.

Populations of the large native grazer, the eastern grey kangaroos, *Macropus giganteus*, have increased in many parts of Australia over the past decade, with impacts on native biodiversity recorded (Meers & Adams 2003; McIntyre *et al.* 2010; Barton *et al.* 2011; Manning *et al.* 2013; Howland *et al.* 2016), including *D. impar* (Howland *et al.* 2014). Importantly, grazing impacts of native herbivores may provide insight into natural grazing patterns not apparent from studies of domestic livestock (Foster *et al.* 2014). Effective management of this impact will depend on robust quantitative investigation into links between habitat quality, species persistence and kangaroo abundance, such as being undertaken here. Furthermore, given the paucity of ecological knowledge of the impact of varying levels of grazing by native herbivores, single species studies such as ours can provide important

insights that have broader relevance (Gordon *et al.* 2004; Mysterud 2006; Foster *et al.* 2014).

We investigated the habitat preferences of *D. impar* across a grazing intensity gradient at three spatial scales (fine (1 m²); intermediate (1 ha) and landscape (>10 ha)) to address four questions. First, are *D. impar* more common under low or high kangaroo densities? As high grazer densities negatively affect the amount and cover of grass (Rook *et al.* 2004; McIntyre & Tongway 2005), we hypothesized that *D. impar* will be more common in areas of low kangaroo density, compared with areas of high kangaroo density. Second, does *D. impar* preferentially use areas of high grass structural complexity? We hypothesized that individuals would be more likely to be encountered where fine-scale grass structural complexity is higher, because of the positive effect of complexity on important biotic (prey availability and predation risk) and abiotic (microclimate) conditions and their relationship to an individual's fitness (Sato *et al.* 2014b and references therein). Third, is *D. impar* associated with a particular floristic community? We hypothesized that the occurrence of *D. impar* will not vary according to floristic community as this species is found in natural grasslands as well as secondary and exotic grasslands, suggesting some flexibility in habitat choice (Dorrough & Ash 1999; O'Shea 2005). Fourth, does the size of grassland patches influence occupancy by *D. impar*? We hypothesized that the size of grassland patches will not have a negative effect on occurrence of *D. impar*, as small reptiles are less susceptible to the negative effects of habitat fragmentation compared with similar-sized endotherms (Case 1975; Schutz & Driscoll 2008), and *D. impar* are known to persist in small (<10 ha) isolated grasslands (Candy 2008).

The results of our study provide much needed information on the habitat preferences of a grasslands specialist reptile, *D. impar*. Based on this information, we provide recommendations for managing grazing pressure to improve the quality of habitat for this species. This result also has implications for the conservation of biota worldwide, where natural grazing patterns have been altered by anthropogenic change.

METHODS

Study area

Our study was conducted within natural grasslands in the Australian Capital Territory (ACT, Fig. 1). Prior to European settlement, up to 20 000 ha of the ACT may have supported natural temperate grassland (ACT Government 2005), but 95% of this habitat has been cleared or degraded. The remaining 5% occurs in small fragmented patches embedded in an urban and agricultural matrix (ACT Government 2005). Remnant grasslands are largely dominated by native grasses (e.g. *Austrostipa* spp., *Bothriochloa macra*, *Rytidosperma* spp.,

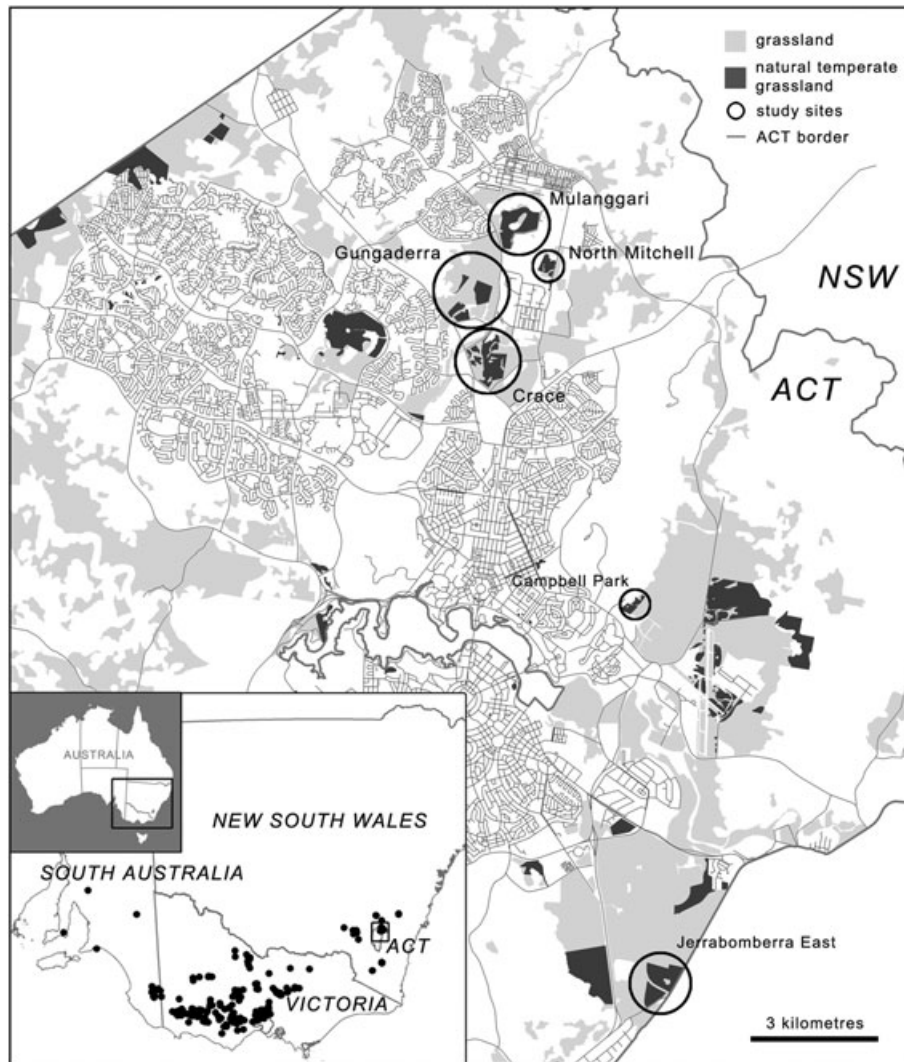


Fig. 1. Current distribution of the striped legless lizard in south-eastern Australia (inset). Distribution of natural grasslands (grey), natural temperate grasslands (dark grey) and the location of our study sites (black circle) in the Australian Capital Territory. Adapted from Dorrough and Ash (1999).

Themeda triandra) and exotic perennial grasses (e.g. *Phalaris aquatica*), with a smaller component of exotic annual grass species (e.g. *Avena fatua*).

Site selection

Data were collected by the ACT Government Environment and Planning Directorate for an investigation of kangaroo grazing impacts on native plants and animals, adapted from Howland *et al.* (2014). From this dataset, we used data from six grassland reserves (three nature reserves and three informally protected areas) where *D. impar* had been recorded (Fig. 1). Reserves varied in size and quality (Appendix S1) and were historically subject to grazing by domestic livestock (at the time of surveys, the most recent livestock grazing had occurred over 5 years previously). The dominant grazer in the study area is the native eastern grey kangaroo (hereafter,

kangaroo). Exotic herbivores also occur in the study area, but their impact as grazers is negligible in comparison with kangaroos (Fletcher 2006; ACT Government 2010).

Experimental design

We investigated habitat preferences at multiple spatial scales simultaneously using a hierarchical experimental design (Meentemeyer & Box 1987). Within the six reserves, between two and six 1-ha plots (100 × 100 m; Fig. 2a) were placed within different grassland communities (i.e. natural temperate grassland, native pasture and exotic pasture) based on mapping (ACT Government 2005), with a greater number of plots placed at larger properties. In 2012, 23 plots were used, with 18 of these and three new plots used in 2013. Concrete roof tiles are a cost-effective, unbiased and efficient method to survey for *D. impar* (Thompson 2006), so at each plot, 30 tiles were

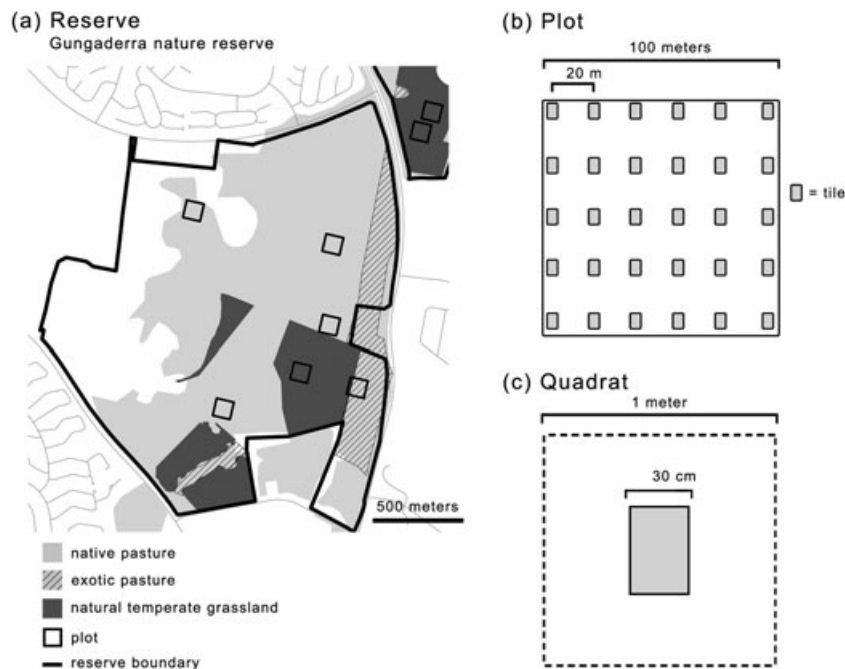


Fig. 2. Experimental design. (a) An example of placement of plots within a reserve showing natural temperate grassland (dark grey), native pasture (light grey) and exotic pasture (cross hatch) grassland communities, (b) layout of tiles (box) within the plot at intermediate scale and (c) survey quadrat at the fine scale.

deployed. Tiles were arranged in either a 3×10 , or 6×5 grid pattern, with tiles spaced ≥ 10 m apart (Fig. 2b). As *D. impar* has a very small home range (Robertson & Smith 2010) and moves on average as little as 4 m year^{-1} (O'Shea 2005), we considered tiles independent.

Reptile surveys

Surveys for *D. impar* were conducted between September and December in 2012 and 2013, with tiles deployed before spring sampling. This allowed sufficient time for reptiles to become accustomed to the tiles. At the end of the sampling period, tiles were removed to limit the impact on vegetation, so tiles were not placed in the same location in consecutive years. To improve detection, tiles were checked during daylight hours on fine days, and at temperatures between 15 to 25°C (Thompson 2006). Overall, each tile was checked five times in 2012, and seven times in 2013. We pooled survey results from all visits to estimate presence/absence at each tile over each survey period. All field work procedures were approved by the New South Wales Government Department of Primary Industries ethics committee (approved project no. 13/1641#2).

Habitat characteristics

Habitat characteristics were estimated at three spatial scales (fine, intermediate and landscape). At the fine scale, we placed a 1 m^2 survey quadrat around each tile (Fig. 2c) to measure the following: (i) grass structural complexity; (ii) non-grass biomass (kilogram dry matter per hectare); (iii) percent bare ground; and

(iv) grass type. We calculated grass structural complexity following Brown *et al.* (2011) ($\ln(\text{variance in grass height} \times \text{average grass height})$), where average grass leaf height was estimated using a ruler at each quadrat corner. Non-grass biomass was estimated using the 'comparative yield' technique (Haydock & Shaw 1975), and percent bare ground was estimated visually. To assign grass type, we classified a quadrat according to whether it was dominated by native or exotic grass species.

At the intermediate scale (1 ha), we assigned plots to one of three grassland community classifications based on previous spatial mapping: natural temperate grassland (high cover of native grasses and high native forb richness), native pasture (high cover of native grasses and low native forb richness), exotic pasture (low cover of native grasses and low native forb richness) (ACT Government 2005). Where the grassland community had clearly changed since original mapping in 2005, we reclassified plots using the same classification.

At the landscape scale, estimates of kangaroo density were made using total count of individuals and pellet count techniques (Southwell 1989) in 2013 with a count at a single reserve performed in early 2014. Density estimates for a single reserve (North Mitchell) were excluded because grazing was suppressed there for several years, and hence, current grazer density is not representative of grazing effects on vegetation. To assess grazing intensity, we used kangaroo density rather than a direct measure of grass structure. This was because management of grazing pressure is often undertaken based on animal densities and not grass structure at this scale (ACT Government 2010). We used an ACT vegetation structure map (Howland *et al.* 2014) and management boundaries to estimate

grassland area within a reserve in ArcGIS 10× (ESRI 2011). Details of explanatory variables are provided in Table 1.

Data analysis

Prior to analysis, we checked explanatory variables for multicollinearity (Spearman rank coefficient >0.5), transformed skewed variables and standardized all continuous variables to enable meaningful comparison between multiple variables (Zuur *et al.* 2009). Next, we used logistic hierarchical generalized linear mixed modelling (Lee & Nelder 1996) procedures to simultaneously model the probability of occupancy (presence/absence) of *D. impar* in response to seven habitat variables (grass structural complexity, non-grass biomass, percent bare ground, grass type, grassland community, kangaroo density and grassland area) measured over three scales. We included all variables as additive effects plus an interaction between grass structural complexity and grass type. We included the interaction to test whether preference for grass structural complexity was influenced by the type of grass present. To account for our nested study design and sampling over consecutive years, we included reserve, plot and year as random effects (Lee & Nelder 1996). Nesting structure was stipulated as reserve/plot/year. We modelled the relationship with a binomial distribution and a logit link function, with random effects fitted with a beta distribution and a logit link function. Residual plots and distribution of residuals were examined to check model fit. All analysis was undertaken in Genstat 12 (VSN International 2012).

RESULTS

We recorded *D. impar* a total of 179 times across all six reserves and at 20/23 plots and under 139 individual tiles. The probability of recording an individual under a tile varied between the survey years, with *D. impar* recorded under 13% of tiles in 2012, compared with

8% of tiles in 2013. No individuals were recorded at the four plots at Jerrabomberra East in 2012, but they were recorded at one plot in 2013. The highest number of tiles occupied by *D. impar* occurred in 2013 at North Mitchell with 30% of tiles occupied during the sampling period (Appendix S2).

Regression model

The logistic regression model showed that *D. impar* occupancy of tiles was significantly related to variables at landscape and fine scales, but not on the intermediate scale (Table 2).

Preference for low kangaroo densities

At the landscape scale, the occurrence of *D. impar* was significantly negatively related to kangaroo density ($P < 0.001$), with the encounter probability declining from 18.7% at the lowest kangaroo densities (i.e. 1.3 kangaroo per hectare) to 1% at the highest kangaroo densities (i.e. 5.2 kangaroos per hectare) (Fig. 3a).

Preference for high grass structural complexity and floristic community

The probability of encountering *D. impar* under a tile at fine scale was positively related to grass structural complexity with a significant interaction with grass type ($P = 0.031$). Occupancy was lower for native than exotic grass, but grass structural complexity had a greater effect on native grass than exotic grass types. For example, as grass structural complexity increased from lowest to highest values, encounter rate for exotic grass types increased from 9.1% to 12%. At tiles placed in native grass types, as grass structural complexity increased from lowest to highest values, encounter rate increased

Table 1. Description and summary of explanatory variables which were collected at three spatial scales (fine, medium and landscape)

Scale	Variable	Description	Range (mean)	<i>n</i>
Fine	Grass structural complexity	Measure of complexity: Ln (mean height \times variance in height).	−2.14 to 9.13 (2.77)	1320
	Non-grass biomass (kilograms dry matter per hectare)	The weight of above-ground non-grass biomass.	0–4978 (253)	1320
	Percent bare ground (%)	Visual estimate of the exposed bare earth.	0–80 (20)	1320
	Grass type	Grass type within each quadrant based on origin (native or exotic).	Native grass Exotic grass	944 375
Intermediate	Grass community	Classification of pasture communities based on floristic composition.	Natural temperate	24
			Exotic pasture	9
			Native pasture	11
Landscape	Grassland area (hectare)	The area of grassland vegetation within reserve boundary.	12.1–237.3 (91.4)	6
	Kangaroo density (animals per hectare)	The density of kangaroos within reserve boundary based on pellet count and total count techniques.	1.34–5.23 (2.67)	5

Table 2. Results of hierarchical generalized linear mixed models for the striped legless lizard showing trends (slope) including SE

Scale	Model term	d.f.	χ^2	Slope	SE	Graphical summary
Landscape	Intercept			−2.02	0.35	Fig. 3a
	Kangaroo density	1	16.93***	−1.13	0.27	
	Grassland area	1	2.77	−0.34	0.20	
Intermediate	Grass community	2	1.47			
	Native pasture			−0.03	0.43	
	Natural temperate grassland			−0.33	0.36	
Fine	Grass complexity × native grass	1	4.65*	0.35	0.16	Fig. 3b
	Grass complexity			0.06	0.13	
	Native grass			−0.56	0.20	
	Percent bare ground	1	1.29	−0.11	0.10	
	Non-grass biomass	1	1.14	0.09	0.08	

Significance is indicated by the Wald statistic (χ^2) and *P*-value as follows: **p* < 0.05, ***p* < 0.01, ****p* < 0.001. Exotic pasture and exotic grass have been used as a reference level for grassland community and grass type respectively. d.f., degrees of freedom; SE, standard error.

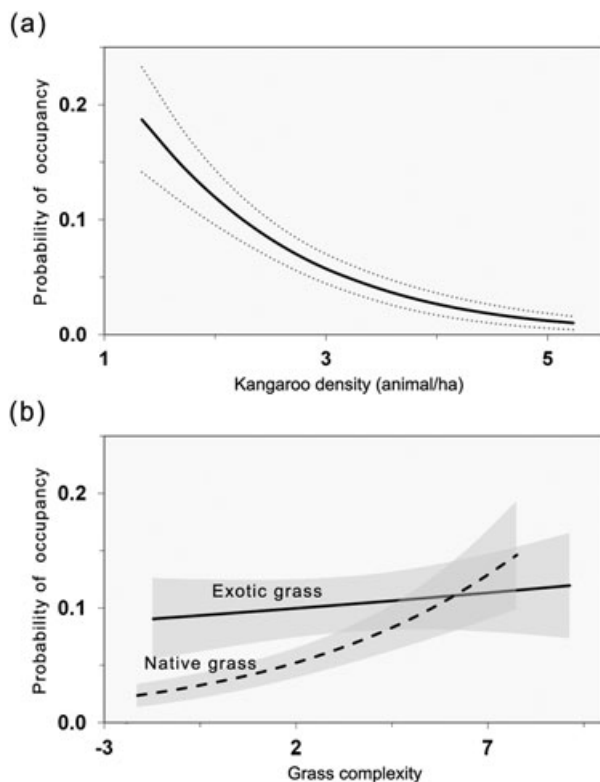


Fig. 3. Graphical representation of logistic regression models summarized in Table 2. The graphs show significant relationships between the probability of encountering the striped legless lizard under a tile and (a) kangaroo density estimates at the landscape scale, and (b) grass structural complexity for two different grass types (exotic grass and native grass) at the fine scale. Standard error of the model predictions is shown. To aid interpretation of results, variables have been back-transformed to the original scale.

from 2.4% to 15%. Thus, exotic grasses were preferred by *D. impar* when grass structural complexity was low, and native grasses were favoured when grass structural complexity was high (Fig. 3b). Other measures of fine

scale structure like percent bare ground (*P* = 0.26) and non-grass biomass (*P* = 0.286) were not significantly related to the occurrence of *D. impar*. At the intermediate spatial scale, we found no significant relationship between occurrence of *D. impar* and grass community (*P* = 0.48).

Preference for grassland area

We found no significant relationship between probability of encountering a *D. impar* and the area of grassland (*P* = 0.102), despite area varying from 12 to > 200 ha.

DISCUSSION

Preference for low kangaroo densities

As a result of anthropogenic change, native herbivore density has been either inflated or suppressed in many areas, with cascading impacts on native biodiversity (Gordon *et al.* 2004; Myserud 2006; Foster *et al.* 2014). We have shown that the encounter rate of threatened *D. impar* dramatically decreased as kangaroo density increased from 1.3 animals per hectare to over five animals per hectare (Fig. 3a). While the impacts of livestock grazing on *D. impar* (Dorrough & Ash 1999; Robertson & Smith 2010) and other grassland biota have been documented (Dorrough *et al.* 2004a; Davies *et al.* 2010; O'Connor *et al.* 2010; Kutt & Gordon 2012; Laidlaw *et al.* 2013), relatively few studies have considered the impact of native grazers on grassland biota. The density of large native grazers is increasing in many protected areas (Gordon *et al.* 2004; Myserud 2006; Foster *et al.* 2014), and our results show that irrespective of whether the grazers are native or exotic, they exert major influence on the suitability of habitat for grassland-dependent species.

Preference for high grass structural complexity

The main mechanism by which large grazers affect ground-dwelling species is by altering vegetation structure. As we hypothesized at the onset of our study, the occurrence of *D. impar* was positively associated with grass structural complexity (Fig. 3b). This finding is consistent with previous research into habitat preferences of legless lizards (Brown *et al.* 2011; Howland *et al.* 2014). Small ground-dwelling reptiles such as *D. impar* may prefer complex habitats because of the diverse microhabitats they contain (McIntyre & Tongway 2005; Pöyry *et al.* 2006), with flow on consequences for foraging efficiency (Pianka 1966; Castellano & Valone 2006; Pettigrew & Bull 2014), thermoregulation (Scott 1962; Willott 1997; Hacking *et al.* 2014; Sato *et al.* 2014b), predation risk (Castellano & Valone 2006; Pettigrew & Bull 2012; Sato *et al.* 2014b) and prey abundance (Dennis *et al.* 1998; Castellano & Valone 2006). More broadly, grass structural complexity has been identified as an important driver of habitat selection for a range of taxa (McNett & Rypstra 2000; Vickery *et al.* 2001; Castellano & Valone 2006; Whittingham *et al.* 2006). Unlike intense grazing, low to moderate grazing intensity can increase grass structural complexity (Rook *et al.* 2004; McIntyre & Tongway 2005) and is considered necessary to maintain animal and plant species richness in many grassland ecosystems (Milchunas *et al.* 1988; Kruess & Tschardtke 2002; Dorrough *et al.* 2004b; Fuhlendorf *et al.* 2006). Our results support this view because *D. impar* was most likely to occupy habitat with fine-scale grass complexity.

Preference for floristic composition

Delma impar has most commonly been encountered in natural temperate grasslands dominated by native grasses (Coulson 1990). This may be an artefact of limited disturbance in these communities, rather than a particular preference for native grasses, because *D. impar* can persist in floristically degraded grasslands (Dorrough & Ash 1999; O'Shea 2005; Thompson 2006). Our results confirm this tolerance for degraded native and exotic grass communities at the intermediate scale. At a fine scale, *D. impar* was more common near exotic grasses at low grass structural complexity, but more common near native grasses when grass structural complexity was high (Fig. 3b). This may be explained by the dense leafy structure formed by several common exotic grasses compared with native grasses (Lamp *et al.* 2001). This characteristic of exotic grasses may provide additional cover when grass structural complexity is low, but at high complexity, may impede movement and reduce solar radiation compared with native grasses. Exotic grasses are often regarded as providing poor-quality habitat for reptiles (Germano *et al.* 2001; Michael *et al.*

2010; Wong *et al.* 2011; Hacking *et al.* 2014), but this was not the case in our study. This result adds to a growing body of evidence that local grassland fauna (Gilmore *et al.* 2008; Stevens *et al.* 2010) and fauna elsewhere around the world (Tews *et al.* 2004; Garden *et al.* 2007) can persist in floristically degraded habitat, provided that appropriate vegetation structure is available.

Preference for grassland area

Natural grassland communities across the globe have been highly fragmented by human activities (Herkert 1994; Kirkpatrick *et al.* 1995; Rösch *et al.* 2013), with the area of fragments known to be a major factor influencing the survival of many bird and mammal species (Andren 1994). However, this does not appear to be the case for *D. impar* in this study (also see Candy 2008), nor other small-bodied species (Case 1975; Abensperg-Traun *et al.* 1996; Wood & Pullin 2002; Schutz & Driscoll 2008). Small patches of grassland are often not prioritized for conservation, but are valuable habitat for *D. impar* and other threatened grassland species (ACT Government 2005). Protection and management of small habitat patches will increasingly become important for the conservation of grassland biota as grasslands continue to be reduced and fragmented by anthropogenic change (Case 1975; Tschardtke *et al.* 2002; Wood & Pullin 2002; ACT Government 2005; Schutz & Driscoll 2008; Jellinek *et al.* 2014).

Conservation implications

For species at risk of extinction, detailed research on habitat requirements is fundamental to developing management strategies to prevent or reverse population decline (Lindenmayer & Burgman 2005; Morrison *et al.* 2006). Based on our findings, we recommend that conservation efforts for many reptile species in Australian natural temperate grassland extend beyond the large patches of high-quality habitat to also encompass smaller patches of floristically degraded habitat. We also suggest that to promote the conservation of *D. impar*, management should aim to minimize high-intensity grazing by kangaroos (equivalent to more than 1.3 kangaroos per hectare), prevent the loss of native grasses and ensure that sufficient grass structural complexity is maintained at the fine scale. Structural complexity is often achieved by grazing at low to moderate intensity (Rook *et al.* 2004; McIntyre & Tongway 2005), and this level of grazing is known to benefit biodiversity across a range of ecosystems (e.g. Milchunas *et al.* 1988; Dorrough *et al.* 2004a; Fuhlendorf & Engle 2004).

A common consequence of anthropogenic change in grasslands is either an increase or decrease in the number of native grazers relative to historic levels (Caugley 1987; Gordon *et al.* 2004). Given that management of

grasslands is a global conservation challenge (Watkinson & Ormerod 2001; Kemp & Michalk 2007), there is an urgent need to actively manage the impact of large grazers, irrespective of whether they are native or exotic to the particular area (Gordon *et al.* 2004; Gordon 2006; Foster *et al.* 2014). Failure to do so has already led to global loss of grassland biota, and without ongoing active management, this trend is likely to continue (e.g. Dorrough *et al.* 2004b; Mysterud 2006; Kemp & Michalk 2007; Vavra *et al.* 2007; Ceballos *et al.* 2010; Stevens *et al.* 2010). Because population control of native herbivores is often controversial (Herbert *et al.* 2006; Young *et al.* 2009), conservation actions need to be based on robust scientific evidence such as we have provided here, to ensure societal support and to maximize the conservation benefits (Gordon *et al.* 2004; ACT Government 2010). Our results demonstrate that management intervention is necessary to minimize biodiversity loss in grasslands where native grazer densities are either elevated or suppressed by anthropogenic change.

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SUPPORTING INFORMATION

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

Appendix S1. Characteristics of reserves.

Appendix S2. Details of striped legless lizard captures at each reserve.