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Remnant vegetation, plantings and fences are beneficial for reptiles in agricultural landscapes

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Summary

1. Managing agricultural landscapes for biodiversity conservation is increasingly difficult as land use is modified or intensified for production. Finding ways to mitigate the negative effects of agriculture on biodiversity is therefore critical. We asked the question: *How do remnant patches, paddock types and grazing regimes influence reptile assemblages in a grazing landscape?*

2. At 12 sites, we surveyed reptiles and environmental covariates in remnant woodland patches and in four paddock types: (i) grazed pasture, (ii) linear plantings, (iii) coarse woody debris (CWD) added to grazed pasture and (iv) fences between grazed pasture. Each site was either continuously or rotationally grazed.

3. Remnant vegetation and other vegetation attributes such as tree cover and leaf litter greatly influenced reptiles. We recorded higher reptile abundance and species richness in areas with more tree cover and leaf litter. For rare species (captured in ≤4 sites <70 captures), there were 5·7 more animals and 2·6 more species in sites with 50% woody cover within 3 km compared to 5% woody cover.

4. The abundance and richness of rare species, and one common species differed between paddock types and were higher in linear plantings and fence transects compared to CWD and pasture transects.

5. *Synthesis and applications*. Grazed paddocks, particularly those with key features such as fences and plantings can provide habitat for reptiles. This suggests that discrete differentiation between patch and matrix does not apply for reptiles in these systems. Management to promote reptile conservation in agricultural landscapes should involve protecting existing remnant vegetation, regardless of amount; and promote key habitat features of trees, leaf litter and shrubs. Establishing plantings and fences is important as they support high numbers of less common reptiles and may facilitate reptiles to move through and use greater amounts of the landscape.

Key-words: agriculture, conservation, dispersal, grazing, herpetofauna, matrix, remnant woodland, reptiles, trees, vegetation

Introduction

Human-modified landscapes, including agricultural areas, cover the majority of the Earth's terrestrial land surface (Ellis & Ramankutty 2008). Some forms of landscape modification are causing a rapid decline in biodiversity (Barnosky *et al*. 2011; Venter *et al*. 2016). There is a need to understand how to best manage agricultural areas, to balance both human use and biodiversity conservation (Tilman *et al*. 2011).

Agricultural landscapes often comprise patches of remnant vegetation surrounded by a matrix of other land use types. The matrix was once considered to be an inhospitable 'sea' between patches of habitat (Haila 2002). More recent studies define the matrix as the dominant (usually non-native) land cover, in which other cover types are embedded, and in which species cannot form self-sustaining populations (Driscoll *et al*. 2013). The matrix is species-specific and context-specific. For

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example, Blaum & Wichmann (2007) found that shrub-dominated land cover acted as a matrix for the hairy-footed gerbil *Gerbillurus paeba* during normal rainfall conditions, but became suitable habitat during exceptionally high rainfall events.

Several attributes of human-modified landscapes have been suggested to influence native biota including landscape type (Kennedy *et al.* 2011; Pedro & Simonetti 2015), contrast between the human-modified land cover and habitat patches (Prevedello & Vieira 2010), size and configuration of landscape elements (Templeton, Brazeal & Neuwald 2011; Russildi *et al.* 2016), and changes across time (Kupfer, Malanson & Franklin 2006; Driscoll *et al.* 2013). Human-modified landscapes can have a major influence on movement, influencing dispersal between habitat patches (Kupfer, Malanson & Franklin 2006; Kay *et al.* 2016), mortality during dispersal (Ewers & Didham 2006), and tendency to depart patches and enter the matrix (Prevedello & Vieira 2010).

Our study examined three management elements (remnant vegetation, paddock types and grazing regime) that provide contrasting conditions and resources likely to influence reptile abundance and richness in grazing landscapes (Prevedello & Vieira 2010; Driscoll *et al.* 2013) (see Table 1). Our research question was: *How do remnant patches, paddock types and grazing regimes influence reptile assemblages in a grazing landscape?* We developed predictions about each management element's influence on the reptile assemblage and stated our rationale for choosing each one (Table 1).

The management elements examined in this study encompass common features of agricultural landscapes globally. However, our understanding of how they influence reptile assemblages is limited. New perspectives and methods are needed to tackle the global challenge of balancing biodiversity outcomes and agricultural production (Glamann *et al.* 2015; Tanentzap *et al.* 2015). Our research provides a key insight in understanding how appropriate management of the production landscape can improve habitat suitability for native biota.

Materials and methods

STUDY AREA

We conducted our study in the central and southern Tablelands of New South Wales, south-eastern Australia (Fig. 1). This area contains remnants of critically endangered Box Gum Grassy Woodland (EPBC Act 1999). This ecological community is characterised by a heterogeneous cover of yellow box *Eucalyptus melliodora*, Blakely's red gum *Eucalyptus blakelyi* and white box *Eucalyptus albens* interspersed by native grasslands. The study area has been highly modified and cleared for agriculture in the 200 years since European arrival. The limited remaining woodland is highly fragmented, isolated and often degraded due to clearing and livestock grazing.

STUDY DESIGN

Remnant patches

We selected 12 farms that contained remnant woodland patches that were directly adjacent to four different habitat types within a managed paddock (hereafter 'paddock type'; Fig. 1). Remnant patches were between 0·7 and 400 ha (mean = 62·9 ha, SD = 101·6) (see Table S2, Supporting Information), comprised open woodland, and were typically not grazed during spring and summer. Land-uses adjacent to each patch formed our four paddock types: (i) open grazed pasture, (ii) fenced linear planting within pasture, (iii) grazed pasture with coarse woody debris (CWD) added, and (iv) fence within pasture (Fig. 1, Table 1). These paddock types were chosen because they are common in grazing landscapes both within our region and globally (Table 1).

Table 1. Management elements of the grazing landscape examined in this study

Management elements	Influence on grazing landscape	Predictions
1. Retained woodland remnants	Better habitat than grazed paddocks (Daily, Ehrlich & Sánchez-Azofeifa 2001)	Remnants will have higher reptile abundance and richness than paddocks
2. Paddock type		
(a) Open grazed pasture	Baseline paddock that was expected to have high contrast in habitat attributes to remnant patches (Driscoll 2004; Urbina-Cardona, Olivares-Pérez & Reynoso 2006)	Pasture will have the lowest reptile abundance and richness
(b) Linear planting	Plantings reduce contrast and provide habitat (Cunningham *et al.* 2007)	Plantings will have higher reptile abundance and richness than grazed pasture
(c) Coarse woody debris (CWD)	Addition of habitat (Michael *et al.* 2014)	Addition of coarse woody debris will result in higher reptile abundance and richness than pasture
(d) Fences	Reduce the contrast of paddocks compared to remnants through vegetation and debris build-up. This landscape feature has not been examined previously but hedgerow networks have positive impacts on reptile diversity (Nopper *et al.* 2017)	Fences will have greater reptile richness and abundance than pasture
3. Grazing regime	Rotational grazing may result in a different level of habitat amenity of paddocks compared to a continuous grazing regime, as grazing can influence tree recruitment (Fischer *et al.* 2009; Sato *et al.* 2016)	There will be greater reptile richness and abundance in rotationally grazed sites than continuously grazed sites

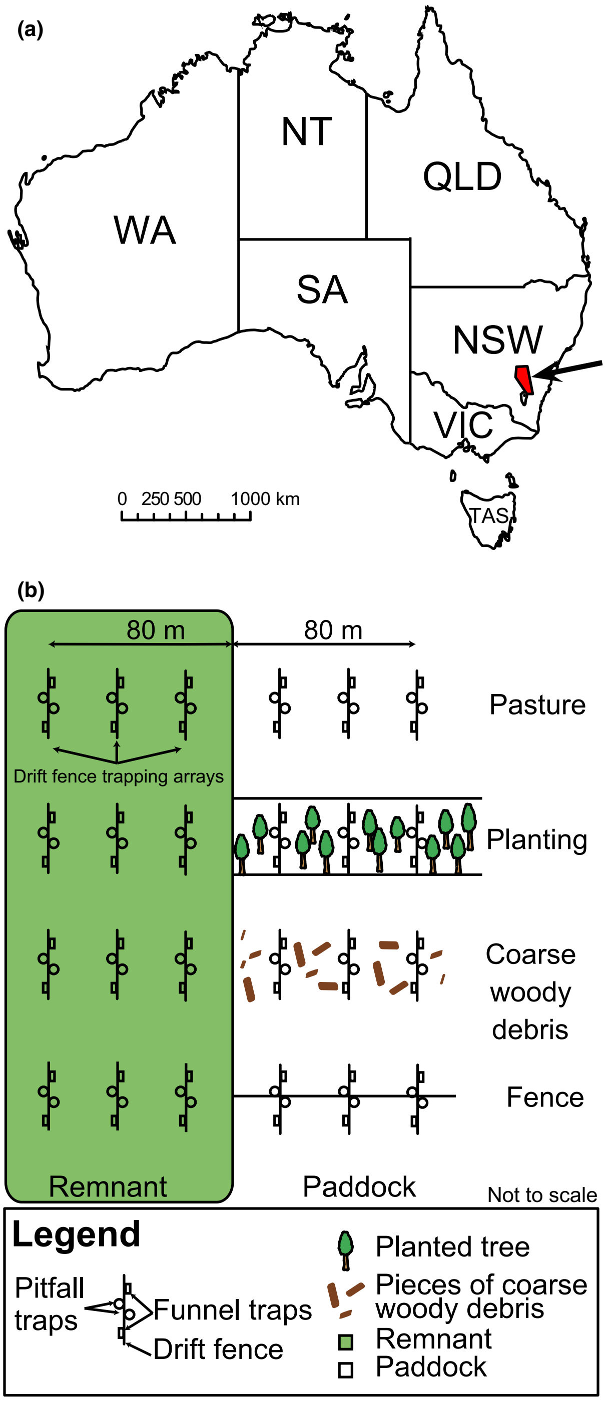

Fig. 1. (a) Map with study area indicated by red polygon and arrow, (b) stylised study design diagram indicating the four paddock types and transect layout. [Colour figure can be viewed at wileyonlinelibrary.com]

Paddock type

1 Open grazed pasture were paddocks vegetated predominantly with grasses and forbs. Some scattered trees remain in these largely cleared and open environments. All paddocks were grazed by livestock, either cattle *Bos taurus* or sheep *Ovis aries*.

2 Linear plantings were between 10 and 25 m wide, comprising a mix of local *Eucalyptus* and *Acacia* species, which had been planted in the last 30 years. Few properties in the region contained linear plantings directly adjacent to remnants with grazed pasture on either side. Six surveyed farms had a planting, with four continuously grazed properties and two rotationally grazed properties containing plantings (see Grazing regimes below).

3 Coarse woody debris was a linear strip of timber pieces laid out from the remnant edge to 80 m into the pasture. We distributed 600 kg of timber pieces approximately 50 × 50 × 40 cm in size and spaced at approximately half metre intervals. The CWD was 10 m wide at the remnant edge and tapered within the first 10 to 3 m wide. The strip was installed approximately 2 months prior to the first survey.

4 Fences were existing and constructed from either single strands of wire or coarse mesh wire with wood, metal or concrete posts. Fences extended from the edge of a fenced remnant for at least 160 m and were surrounded by pasture.

Grazing regimes

Each farm (site) was subject to one of two grazing regimes by domestic livestock. Seven farms had a continuous grazing regime, and five had a rotational grazing regime. Continuous grazing regimes involve leaving livestock in the same paddock for extended periods. Under rotational grazing, livestock is moved between paddocks every few days and the livestock do not return to the same paddock for weeks or months. Rotational grazing regimes can result in increased natural tree regeneration (Fischer *et al.* 2009) although some studies have found no difference in vegetation structure between grazing regimes (e.g. Dorrough *et al.* 2012).

REPTILE TRAPPING

We surveyed reptiles using 160 m long transects extending from within a remnant into one of the four paddock types (Fig. 1). Six farms contained four transects (one for each paddock type). The other six contained three transects as they were missing the planting. Along each transect, trapping arrays were located at 20, 50 and 80 m in the remnant, and 20, 50 and 80 m in the adjoining paddock type (= three trapping arrays for each half of the transect). Each trapping array consisted of a 10-m long drift fence running parallel to the remnant edge and perpendicular to the transect with two pitfall traps (15 L bucket) and two funnel traps (Terrestrial Ecosystems, Perth, Australia), one of each on each side of the drift fence. These trap types are complementary and result in the capture of a broader range of species than any single trap type alone (Greenberg, Neary & Harris 1994). We checked under the pieces of CWD for reptiles at approximately 12 and 15 months after installation and analysed these data separately to understand if there were temporal effects post-installation.

We surveyed every farm five times during the austral spring/summer between January 2014 and March 2015. Traps were open for 5 days for each survey, during which captured animals were marked and released. We performed a total of 25 200 trapping nights across all farms, surveys and traps. We pooled all captures across the five survey periods and three arrays in each of the remnant and paddock type halves of each transect, giving one sample from each half of the transect.

ENVIRONMENTAL VARIABLES

We collected data on environmental variables expected to influence reptile occurrence. We measured percentage vegetation cover (grass, shrubs, forbs, ferns/rushes, bare ground, leaf litter, cryptogams, rock and native trees) and *in situ* CWD volume (>5 cm diameter) in a 10-m diameter circle which was centred on the middle of each trapping array. We averaged these measurements across the three arrays in each of the remnant and paddock halves of the transect.

We calculated area and proportion of woody vegetation around each remnant using Zonal statistics (ESRI 2013). We calculated the proportion of native woody vegetation in a 3 km radial circle around the mid-point of each remnant using data of the extent of native woody vegetation in 2011 obtained through TERN Auscover (http://www.auscover.org.au) (Office of Environment and Heritage 2015). Vegetation cover at this scale was considered an indicator of isolation. Area was calculated by drawing polygons around each remnant with the edges determined visually using vegetation maps and satellite images.

ANALYSIS

We first analysed vegetation cover data using principal components analysis (PCA) with the 'FactoMineR' package (Husson *et al.* 2015) because the vegetation cover categories were correlated and we wanted to examine the main gradients of variation in vegetation cover.

To test our predictions (Table 1), we used a suite of Generalised Linear Mixed Models (GLMMs) with the fixed effects based on if reptiles were captured in: (i) remnant or paddocks, (ii) the four paddock types (pasture, linear planting, CWD and fence), and (iii) sites subject to either rotational or continuous grazing. We modelled each fixed effect individually and their interactions, with transect nested in site fitted as random effects using the 'glmmADMB' package (Skaug *et al.* 2014). Models with just the paddock type variable analysed differences between the four transect types. We examined four aspects of the reptile assemblage (total abundance, total richness, and 'rare' species abundance and richness) and each of the common species individually (Table 2). 'Rare' species were those captured in ≤4 sites and for which there were <70 captures overall. These species could not be analysed separately, but 'rare' species, analysed together, can reveal different responses to the few common species (Schutz & Driscoll 2008).

We next used GLMMs to assess the influence of environmental variables, which we modelled: (i) alone, (ii) additive with the best management element (see below), and (iii) as an interaction with the best management element variables. A single environmental variable was modelled at a time. The environmental fixed effects were vegetation cover PCA1 and PCA2, proportion of woody vegetation within 3 km, remnant area, livestock animal and volume of *in situ* CWD. Correlations between environmental variables were 0·35 or less.

For all GLMMs, we modelled the different reptile response variables using different error distributions to account for differences in mean/variance relationships (Table 2). Akaike's information criterion corrected (AICc) for small sample sizes was calculated using the 'bbmle' package (Bolker 2014). Models within two AICc of the lowest value were considered to be the best models. We calculated *P*-values using the ANOVA function in the 'car' package (Fox & Weisberg 2011) to identify significant components of the model. We used the general linear hypothesis method in the 'multcomp' package (Hothorn, Bretz & Westfall 2008) to determine the relative differences between the levels of the management element variables. These steps are necessary because AICc identifies the best model but does not differentiate among levels of a factor. Plots were drawn using the 'ggplot' package (Wickham 2009) (see Appendix S2 for R code).

Finally, we analysed separately the number of reptiles found under the pieces of CWD using a GLMM with a Poisson distribution and site as a random effect.

Results

We made 1186 captures, comprising 28 reptile species (Table S1). Most captures were from the Family Scincidae (19 species). All species captured more than three times were captured both within remnants and in paddocks. Seven of the 12 species captured three or fewer times were never captured in paddocks and three were only captured in paddocks. Approximately 60% of all reptile captures were in remnants, and of the captures in the paddocks, 17% were in CWD, 23% were along fences, 15% were in pasture and 44% were in plantings (of the six sites that contained

Table 2. The reptile response variables used in the GLMMs indicating the type of data and distribution

Reptile data subset	Type of data	Distribution
Total abundance	Count	Negative binomial (NB2)
Rare* species abundance		
Total species richness		Gaussian
Rare* species richness		
Morethia boulengeri		Negative binomial (NB1)
Carlia tetradactyla		Poisson
Lampropholis guichenoti†		Negative binomial (NB2)
Lampropholis delicata	Presence–absence	Binomial
Amphibolurus muricatus		
Hemiergis decresiensis talbingoensis		
Ctenotus robustus		
Menetia greyii†		

*≤4 sites, <70 captures.
†Was captured in only five sites, so was modelled for the subset of sites it was present in only using dplyr package (Wickham & Francois 2015).

plantings). From a separate analysis of the number of reptiles under the CWD pieces, we found greater reptile counts at approximately 15 months compared to 12 months after the CWD installation ($P < 0{\cdot}001$) (Fig. S1).

VEGETATION CHARACTERISTICS

We identified two distinct gradients of variation among our sites. PCA1 (22·5% of variation) described a gradient from primarily grass to woodland-like cover of native trees and leaf litter (Appendix S1). For PCA1, remnants had positive (i.e. woodland) values and the paddock types of pasture, CWD and fences mostly had negative (i.e. grassy) values (Appendix S1). Plantings, however, were differentiated from the other paddock types along PCA1 and generally contained more tree cover and litter or bare ground (Appendix S1). PCA2 (16·1% of the variation) encompassed a gradient of cover from cryptogams, shrubs and rocks to forbs, litter and tree cover and the paddock types did not differ strongly across this axis.

Rotationally grazed properties supported taller grass with larger variation (compressed grass height = 6·2 cm, SD = 3·5) than continuously grazed properties (compressed grass height = 3·8 cm, SD = 1·6).

RESPONSES TO REMNANT PATCHES

Reptile species richness was influenced by an interaction between remnant/paddock and PCA2 ($P = 0{\cdot}002$). Higher richness in remnants was associated with cryptogams, shrubs and rocks, whereas higher richness in paddocks was associated with forbs, trees and litter (Fig. 2a, Table S3). *Lampropholis delicata* was more commonly present in remnants than paddocks (Fig. 2b, Table S4).

RESPONSES TO PADDOCK TYPE

Rare species abundance and richness responded to paddock type plus the proportion of surrounding woody vegetation (Table S3). Rare species were more abundant in plantings and fences than in CWD transects by 2·4 and 2·3 times, respectively, ($P = 0{\cdot}002$) (Fig. 3a, Table S4) and the CWD transect supported the lowest richness ($P = 0{\cdot}002$) (Fig. 3b, Table S4). Rare species abundance and richness were positively associated with the proportion of surrounding woody vegetation (abundance $P < 0{\cdot}001$, richness $P = 0{\cdot}017$) (Fig. 3d,e); there were 2·6 more rare species and 5·7 more counts of rare animals in sites with 50% compared to 5% woody cover.

Carlia tetradactyla was 2·5 times more abundant in fence transects and 3·0 times more abundant in plantings transects compared to CWD transects ($P = 0{\cdot}028$ and $P = 0{\cdot}03$) (Fig. 3c, Table S4). Higher captures of this species were associated with cryptogams, rocks and shrubs ($P = 0{\cdot}005$) (Fig. 3f).

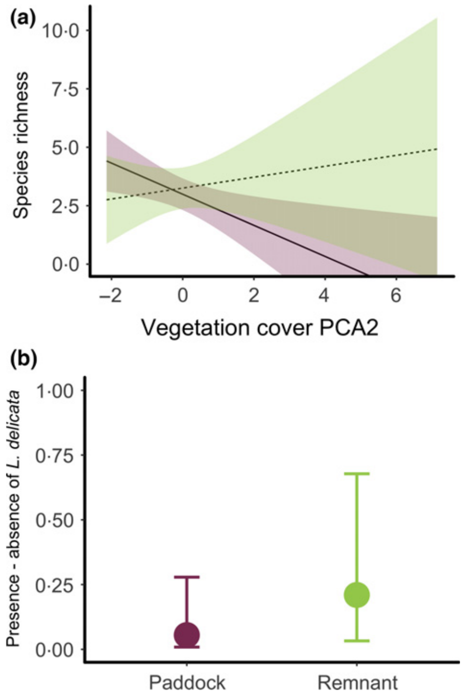

Fig. 2. Reptile responses that included the remnant/paddock variable: (a) total species richness was higher in remnants associated with cryptograms, shrubs and rocks and higher in paddocks associated with forbs, trees and litter, (b) there was greater *Lampropholis delicata* presence in remnants than paddocks. Shaded polygons and error bars indicate 95% confidence intervals and estimates are plotted on the original scale. [Colour figure can be viewed at wileyonlinelibrary.com]

RESPONSES TO GRAZING REGIME

Rare species abundance and *Amphibolurus muricatus* presence–absence had grazing regime as a variable in the best models, but there were no significant trends.

OTHER RESPONSES

The best models for total reptile abundance, *Morethia boulengeri* and *Lampropholis guichenoti* suggested a positive association with tree cover and leaf litter (PCA1, all $P < 0{\cdot}001$) (Fig. 4a–c, Table S3).

There was a higher probability of *A. muricatus* presence in sites grazed by sheep rather than cows ($P = 0{\cdot}03$) and this species was more commonly associated with larger remnants ($P = 0{\cdot}021$) (Fig. 4d,e).

Discussion

THE INFLUENCE OF REMNANT PATCHES AND OTHER VEGETATION CHARACTERISTICS

As predicted (Table 1, point 1), there was generally higher overall reptile abundance and richness in remnants than paddocks. We found a positive influence of three vegetation characteristics on the abundance and richness of the reptile

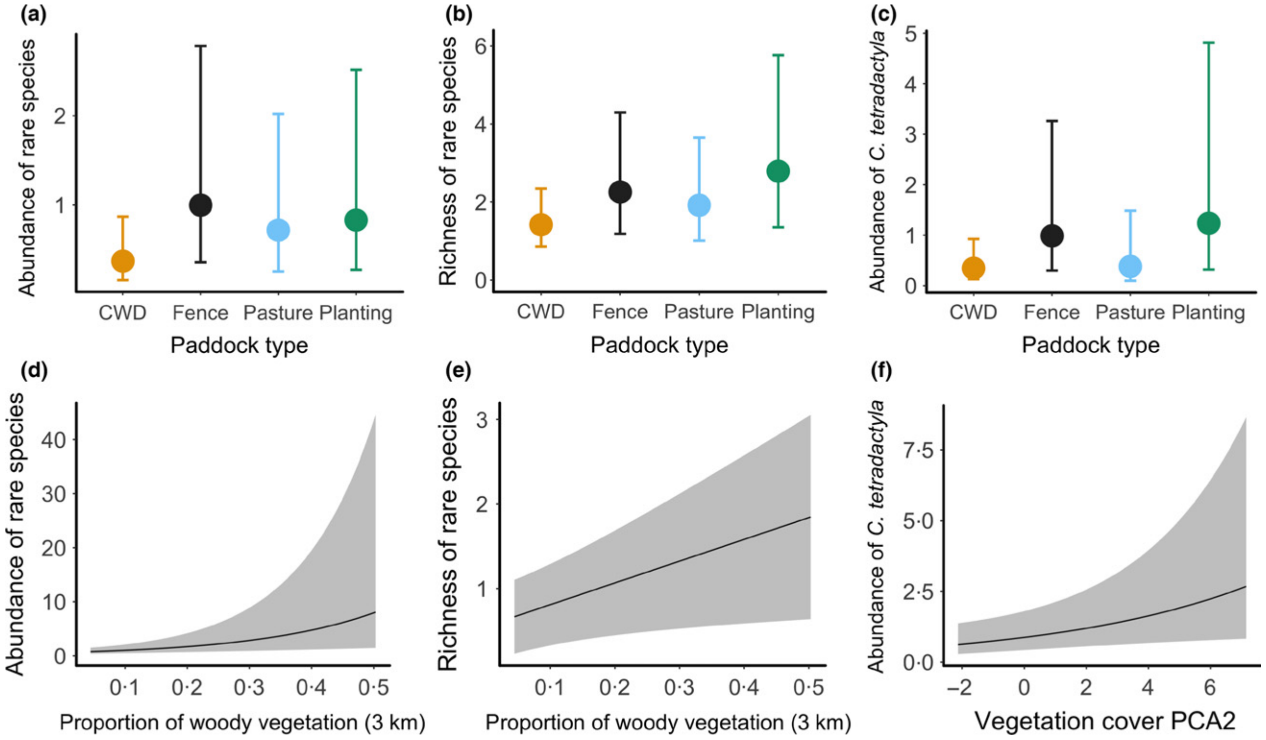

Fig. 3. Reptile responses that included paddock type: (a) rare species had highest abundance at fences and lowest in CWD, (b) greatest rare species richness in plantings and lowest in CWD, (c) *Carlia tetradactyla* abundance was influenced by paddock type, (d) rare species abundance increased with higher proportions of woody vegetation, (e) rare species richness increased with higher proportions of woody vegetation, (f) *Carlia tetradactyla* abundance was higher with greater shrubs, rock and cryptogam cover. Grey polygons and error bars indicate 95% confidence intervals and estimates are plotted on the original scale. CWD, coarse woody debris. [Colour figure can be viewed at wileyonlinelibrary.com]

assemblage: (i) remnant woodland patches, (ii) proportion of woody vegetation within 3 km and, (iii) local vegetation characteristics of tree cover and leaf litter, and to a lesser extent, rocks, cryptogams, forbs and shrubs. We found tree cover and litter were positively associated with reptile abundance across the landscape and with species richness in paddocks. Tree presence and cover can affect reptile abundance and richness (Dorrough *et al.* 2012; Michael *et al.* 2015), and both leaf litter and rocks are important habitat features for many reptiles in this study (Michael *et al.* 2015). Vegetation structure and cover is likely to influence the microclimate and therefore influence reptile thermoregulation (e.g. Ackley *et al.* 2015).

Isolation and area of remnants can be important factors driving species distribution (Andrén 1994; Prevedello & Vieira 2010). Fahrig (2013) posited that the total amount of habitat in an area, not patch size, is important for species richness. Supporting this, we found greater proportions of woody vegetation within 3 km resulted in increased rare species richness and abundance.

Patch size was important for only one species in our study; probability of *A. muricatus* presence increased with larger remnants. There have been conflicting findings about the influence of patch size on populations in fragmented landscapes for a range of taxa including reptiles (e.g. Jellinek, Driscoll & Kirkpatrick 2004; Antongiovanni & Metzger 2005; Pardini *et al.* 2005). These conflicts relate to the extent of patch dependence and the influence of the surrounding matrix on patches (Ewers & Didham 2006; Prevedello & Vieira 2010). We used the same sample effort regardless of patch size, and found local abundance and alpha diversity did not vary with patch size. However, if beta diversity was high within patches, then overall richness may be higher in larger patches.

The reptile responses to vegetation quantified in this study highlights the importance of retaining native vegetation of all patch sizes in modified grazing landscapes, and the negative consequences clearing and habitat loss have on native biota (Andrén 1994; Bonte *et al.* 2012; Baguette *et al.* 2013). These results highlight the deleterious effects conventional intensification processes have on reptile populations due to changes to vegetation structure and extent, which has also been seen in birds (Green *et al.* 2005).

THE INFLUENCE OF PADDOCK TYPE

A key finding was the positive response of rare species and *C. tetradactyla* to linear plantings and fences. These findings are congruent with our predictions that plantings and fences would result in increased reptile abundance and richness (Table 1, point 2). This is consistent with previous studies showing that linear plantings have

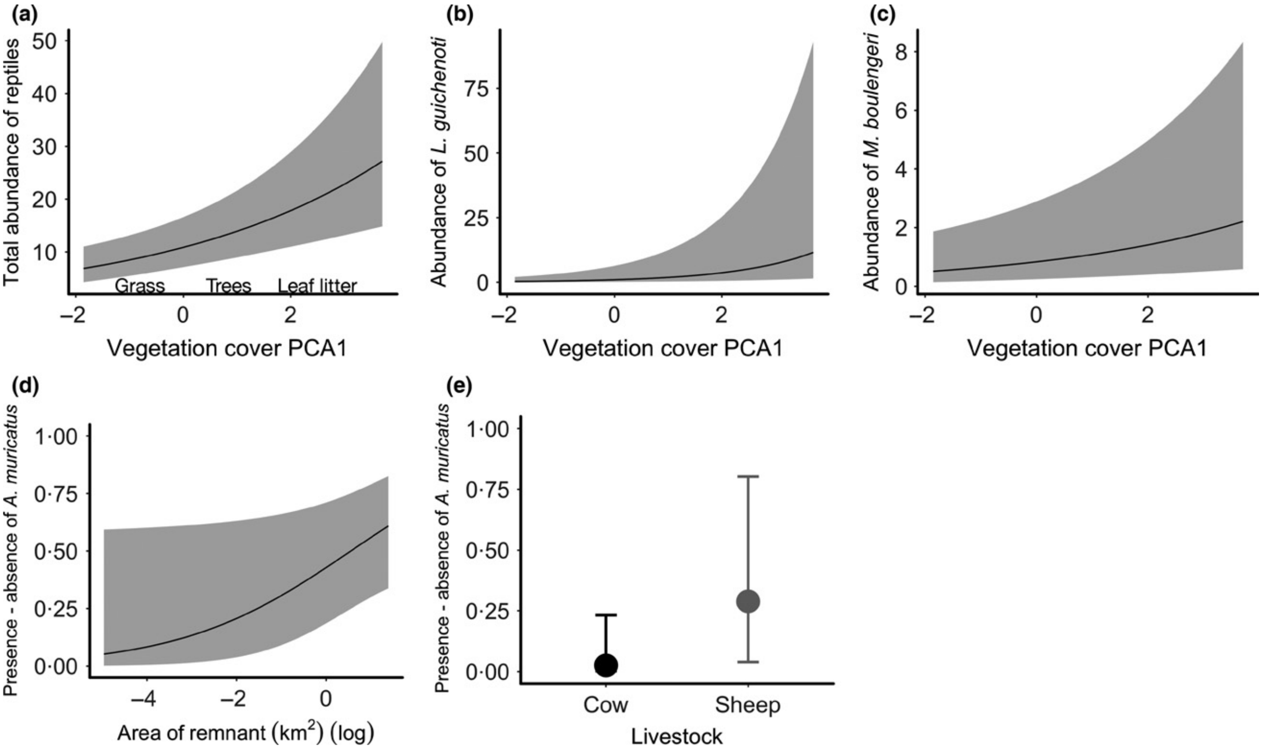

Fig. 4. Other responses: (a) total reptile abundance was higher with greater tree and leaf litter cover, (b) *Lampropholis guichenoti* was more abundant with greater tree and leaf litter cover, (c) *Morethia boulengeri* was more abundant with greater tree and leaf litter cover, (d) *Amphibolurus muricatus* had greater presence in larger remnants, (e) *Amphibolurus muricatus* was present more in sites grazed by sheep rather than cows. Grey polygons indicate 95% confidence intervals and estimates are plotted on the original scale.

positive impacts on native biota, including reptiles in agricultural landscapes, but are generally not a replacement for remnant vegetation (Kavanagh *et al*. 2005; Cunningham *et al*. 2007; Munro, Lindenmayer & Fischer 2007).

As a vast interconnected network within our study system, fences have the potential to be conduits for movement of some reptiles. While limited research has been conducted on the impacts of fences on reptile movement, most studies on a range of taxa, including reptiles, amphibians and mammals, have found fences to be barriers (e.g. Lasky 2011). One study found turtles in particular, and other reptiles to a lesser extent, were negatively impacted by a predator-proof fence which was less permeable than the fences examined in this study (Ferronato, Roe & Georges 2014). However, networks of hedges can have positive impacts on reptile diversity in agricultural landscapes (e.g. Nopper *et al*. 2017) and our results suggest fences have a positive impact on some small reptiles. This is an area of landscape ecology that warrants further research.

The CWD did not result in greater reptile captures in the traps compared to grazed pasture. This was contrary to our prediction (Table 1, point 2c) with low capture rates likely due to the short time between timber installation and surveys. There was an increase in reptiles under the timber after 15 months compared to 12 months after installation (Fig. S2). This suggests CWD addition has the potential to increase habitat suitability of grazing landscapes by reptiles over the longer term. The shorter term impact was limited and even resulted in lower capture rates of rare reptiles. It is not possible to determine if the lower capture rates of rare reptiles in CWD is due to actual lower presence or reduced movement due to increased shelter. Other studies have found the influence of CWD on reptile abundance is affected by timber size and type, how long it is in place, vegetation structure and the level of grazing in the surrounding area (Michael, Lunt & Robinson 2004; Manning, Cunningham & Lindenmayer 2013).

THE INFLUENCE OF GRAZING REGIME

Although livestock grazing has many ecological impacts and can strongly influence reptile populations (Fleischner 1994; Driscoll 2004), that is not always the case (Dorrough *et al*. 2012). We found the grazing regime did not result in significant differences in the reptile assemblage, possibly because there was substantial variation in grazing intensity and historical grazing practices among our sites. This may have obscured differences between our two grazing regimes.

MANAGEMENT IMPLICATIONS

The influence of multiple vegetation attributes on the reptile assemblage suggests that future management actions

Table 3. Management recommendations and supporting evidence

Variable	Management recommendations	Evidence from this study
1. Vegetation cover	Retain endemic vegetation. Promote and recruit key habitat features such as trees, leaf litter and shrubs. Reducing grazing intensity and fertiliser application increases native vegetation recruitment (Fischer *et al.* 2009; Sato *et al.* 2016). Active methods of vegetation restoration include planting and rock addition (Rey Benayas, Bullock & Newton 2008; McDougall *et al.* 2016). In paddocks, increase tree, litter and forb cover	Many reptiles responded to vegetation gradients. Total reptile abundance, *Morethia boulengeri* and *Lampropholis guichenoti* abundance were positively associated with tree and litter cover. *Carlia tetradactyla* abundance was associated with cryptogams, rocks and shrubs. Rare species abundance and richness positively responded to greater proportions of woody vegetation within 3 km. Higher species richness in paddocks were associated with higher tree, leaf litter and forb cover, while higher richness in remnants was associated with cryptogams, shrubs and rocks
2. Remnants of vegetation	Retain remnant vegetation patches within the agricultural landscape. All sizes of patches can provide positive outcomes	Many remnants in this study were small (smallest = 0·7 ha) but they still provided habitat for the reptile assemblage. For example, *Lampropholis delicata* was present at a logs odd ratio of 4·6 in remnants compared to paddocks. Overall, there were 1·5 times more captures in remnants compared to in paddocks
3. Linear plantings	Create new plantings and retain existing plantings. These plantings have the potential to promote reptile diversity and abundance in agricultural landscapes. The impact of plantings width, age, length and configuration needs further study	The abundance of rare species and of *Carlia tetradactyla* were two to three times greater in the plantings than the least abundant paddock type
4. Fences	Position fences so they connect to habitat patches. This may improve the ability of reptiles to use and move along these linear features, which have potential to be a vast interconnected network. Fence type may be important as fences with low permeability can have negative impacts for some reptile species (Ferronato, Roe & Georges 2014). More research is needed on whether fences provide connectivity in these systems	Fences had around two times higher rare and *C. tetradactyla* abundances than the least abundant paddock type

need to be at multiple scales. At a landscape scale, management actions need to increase the proportion of woody vegetation (trees and shrubs) within the landscape (Table 3, point 1). At the individual farm scale, management recommendations include: (i) retaining existing native vegetation remnants regardless of patch size (Tulloch *et al.* 2015) (Table 3, point 2); and (ii) retaining and recruiting important habitat features including trees, leaf litter and shrubs within the landscape (Table 3, points 1 and 2). Within paddocks, reptile species richness could be improved by increasing tree, litter and forbs cover (Fig. 2a). Methods for achieving these recommendations include: (i) reducing grazing pressure and fertiliser use (Fischer *et al.* 2009; Sato *et al.* 2016), particularly in areas with remnant vegetation or important resources such as rocks (Michael *et al.* 2015), and (ii) embracing active restoration techniques including planting (Rey Benayas, Bullock & Newton 2008) or addition of rock where previously removed (McDougall *et al.* 2016). Agricultural intensification that reduces tree, litter and forb cover of paddocks should be minimised.

Linear landscape features such as plantings and fences have the potential to promote increased rare reptile abundance and diversity in agricultural landscapes (Table 3, points 3 and 4). Plantings and fences that are adjacent to population sources may be more beneficial than isolated features, as they are likely to better facilitate movement and reduce isolation of populations (Pardini *et al.* 2005; Favre-Bac *et al.* 2016). Further research on how these management elements influence reptile movement is needed to better understand their impact.

While reptiles were captured frequently in all paddock types, many did not respond strongly to difference between paddocks and remnants, and most responded to environmental gradients. This suggests that traditional patch-matrix concepts and models do not apply (MacArthur & Wilson 1967) and paddocks, especially those with key features such as fences, plantings and other habitat features can provide habitat to reptiles. Management should focus both within paddocks and remnants, and avoid intensification of paddocks that would remove habitat features.

In summary, our study has shown that plantings and fences benefitted rare species, and reptiles may respond positively to restoration or maintenance of these landscape features in extensively cleared agricultural landscapes. To maximise the benefit to rare reptile species, we need to understand more about what these animals use these features for, and if they are habitat for resident animals or movement corridors. Remnant patches of any size and local vegetation features were key influences on the reptile assemblage. We found a continuous increase in rare reptiles with increasing woody vegetation cover, with gains in abundance and richness from 5% to at least 50% cover. Maintenance of native vegetation in agricultural land is important to the ongoing existence of most reptiles in this system. Future land-use modification should not be at the expense of existing vegetation.

With pressure increasing to fulfil the joint goals of food security and biodiversity conservation (Chappell & LaValle 2011; DeFries *et al.* 2012), our findings on the influence of management elements and existing vegetation characteristics can assist future decision making for improved biodiversity outcomes in human-modified landscapes.

Authors' contributions

S.A.P. designed the study and methodology, collected the data, performed analysis and lead writing. D.A.D. designed the study, assisted with analysis and edited. P.S.B. assisted with analysis and edited. D.B.L. designed the study and edited.

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Data accessibility

Data are archived through the ÆKOS Data Portal https://doi.org/10.4227/05/57ad6c5071b23 (Pulsford 2016).

References

Ackley, J.W., Angilletta, M.J. Jr, DeNardo, D., Sullivan, B. & Wu, J. (2015) Urban heat island mitigation strategies and lizard thermal ecology: landscaping can quadruple potential activity time in an arid city. *Urban Ecosystems*, **18**, 1447–1459.

Andrén, H. (1994) Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos*, **71**, 355–366.

Antongiovanni, M. & Metzger, J.P. (2005) Influence of matrix habitats on the occurrence of insectivorous bird species in Amazonian forest fragments. *Biological Conservation*, **122**, 441–451.

Baguette, M., Blanchet, S., Legrand, D., Stevens, V.M. & Turlure, C. (2013) Individual dispersal, landscape connectivity and ecological networks. *Biological Reviews*, **88**, 310–326.

Barnosky, A.D., Matzke, N., Tomiya, S. *et al.* (2011) Has the Earth's sixth mass extinction already arrived? *Nature*, **471**, 51–57.

Blaum, N. & Wichmann, M.C. (2007) Short-term transformation of matrix into hospitable habitat facilitates gene flow and mitigates fragmentation. *Journal of Animal Ecology*, **76**, 1116–1127.

Bolker, B. & R Development Core Team (2014) bbmle: Tools for general maximum likelihood estimation. R package version 1.0.17.

Bonte, D., Van Dyck, H., Bullock, J.M. *et al.* (2012) Costs of dispersal. *Biological Reviews*, **87**, 290–312.

Chappell, M.J. & LaValle, L.A. (2011) Food security and biodiversity: can we have both? An agroecological analysis. *Agriculture and Human Values*, **28**, 3–26.

Cunningham, R.B., Lindenmayer, D.B., Crane, M., Michael, D. & MacGregor, C. (2007) Reptile and arboreal marsupial response to replanted vegetation in agricultural landscapes. *Ecological Applications*, **17**, 609–619.

Daily, G.C., Ehrlich, P.R. & Sánchez-Azofeifa, G.A. (2001) Countryside biogeography: use of human-dominated habitats by the avifauna of southern Costa Rica. *Ecological Applications*, **11**, 1–13.

DeFries, R.S., Ellis, E.C., Chapin, F.S. *et al.* (2012) Planetary opportunities: a social contract for global change science to contribute to a sustainable future. *BioScience*, **62**, 603–606.

Dorrough, J., McIntyre, S., Brown, G., Stol, J., Barrett, G. & Brown, A. (2012) Differential responses of plants, reptiles and birds to grazing management, fertilizer and tree clearing. *Austral Ecology*, **37**, 569–582.

Driscoll, D.A. (2004) Extinction and outbreaks accompany fragmentation of a reptile community. *Ecological Applications*, **14**, 220–240.

Driscoll, D.A., Banks, S.C., Barton, P.S., Lindenmayer, D.B. & Smith, A.L. (2013) Conceptual domain of the matrix in fragmented landscapes. *Trends in Ecology & Evolution*, **28**, 605–613.

Ellis, E.C. & Ramankutty, N. (2008) Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, **6**, 439–447.

EPBC Act (1999) Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The Australian Government. Available at: http://www.environment.gov.au/epbc (accessed 16 June 2015).

ESRI (2013) *ArcMap 10.2.1*. ESRI (Environmental Systems Resource Institute), Redlands, CA, USA.

Ewers, R.M. & Didham, R.K. (2006) Confounding factors in the detection of species responses to habitat fragmentation. *Biological Reviews*, **81**, 117–142.

Fahrig, L. (2013) Rethinking patch size and isolation effects: the habitat amount hypothesis. *Journal of Biogeography*, **40**, 1649–1663.

Favre-Bac, L., Mony, C., Ernoult, A., Burel, F. & Arnaud, J.F. (2016) Ditch network sustains functional connectivity and influences patterns of gene flow in an intensive agricultural landscape. *Heredity*, **116**, 200–212.

Ferronato, B.O., Roe, J.H. & Georges, A. (2014) Reptile bycatch in a pest-exclusion fence established for wildlife reintroductions. *Journal for Nature Conservation*, **22**, 577–585.

Fischer, J., Stott, J., Zerger, A., Warren, G., Sherren, K. & Forrester, R.I. *et al.* (2009) Reversing a tree regeneration crisis in an endangered ecoregion. *Proceedings of the National Academy of Sciences*, **106**, 10386–10391.

Fleischner, T.L. (1994) Ecological costs of livestock grazing in western north America. *Conservation Biology*, **8**, 629–644.

Fox, J. & Weisberg, S. (2011) *An R Companion to Applied Regression*, 2nd edn. Sage, Thousand Oaks, CA, USA.

Glamann, J., Hanspach, J., Abson, D.J., Collier, N. & Fischer, J. (2015) The intersection of food security and biodiversity conservation: a review. *Regional Environmental Change*, 1–11.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W. & Balmford, A. (2005) Farming and the fate of wild nature. *Science*, **307**, 550–555.

Greenberg, C.H., Neary, D.G. & Harris, L.D. (1994) A comparison of herpetofaunal sampling effectiveness of pitfall, single-ended, and double-ended funnel traps used with drift fences. *Journal of Herpetology*, **28**, 319–324.

Haila, Y. (2002) A conceptual genealogy of fragmentation research: from island biogeography to landscape ecology. *Ecological Applications*, **12**, 321–334.

Hothorn, T., Bretz, F. & Westfall, P. (2008) Simultaneous inference in general parametric models. *Biometrical Journal*, **50**, 346–363.

Husson, F., Josse, J., Le, S. & Mazet, J. (2015) FactoMineR: multivariate exploratory data analysis and data mining. R package version 1.31.3. http://CRAN.R-project.org/package=FactoMineR (accessed 26 October 2015).

Jellinek, S., Driscoll, D.A. & Kirkpatrick, J.B. (2004) Environmental and vegetation variables have a greater influence than habitat fragmentation in structuring lizard communities in remnant urban bushland. *Austral Ecology*, **29**, 294–304.

Kavanagh, R., Law, B., Lemckert, F., Stanton, M., Chidel, M. Brassil, T., Towerton, A. & Herring, M. (2005) *Biodiversity in Eucalypt Plantings Established to Reduce Salinity*. Rural Industries Research and Development Corporation, Joint Venture Agroforestry Program, Canberra, ACT, Australia.

Kay, G.M., Driscoll, D.A., Lindenmayer, D.B., Pulsford, S.A. & Mortelliti, A. (2016) Pasture height and crop direction influence reptile movement in an agricultural matrix. *Agriculture, Ecosystems & Environment*, **235**, 164–171.

Kennedy, C.M., Grant, E.H.C., Neel, M.C., Fagan, W.F. & Marra, P.P. (2011) Landscape matrix mediates occupancy dynamics of Neotropical avian insectivores. *Ecological Applications*, **21**, 1837–1850.

Kupfer, J.A., Malanson, G.P. & Franklin, S.B. (2006) Not seeing the ocean for the islands: the mediating influence of matrix-based processes on forest fragmentation effects. *Global Ecology and Biogeography*, **15**, 8–20.

Lasky, J.R. (2011) Conservation biogeography of the US-Mexico border: a transcontinental risk assessment of barriers to animal dispersal Biogeography of US-Mexico border. *Diversity & Distributions*, **17**, 673–687.

MacArthur, R.H. & Wilson, E.O. (1967) *The Theory of Island Biogeography*. Princeton Univeristy Press, Princeton, NJ, USA.

Manning, A.D., Cunningham, R.B. & Lindenmayer, D.B. (2013) Bringing forward the benefits of coarse woody debris in ecosystem recovery under different levels of grazing and vegetation density. *Biological Conservation*, **157**, 204–214.

McDougall, A., Milner, R.N., Driscoll, D.A. & Smith, A.L. (2016) Restoration rocks: integrating abiotic and biotic habitat restoration to conserve threatened species and reduce fire fuel load. *Biodiversity and Conservation*, **25**, 1–14.

Michael, D.R., Kay, G.M., Crane, M., Florance, D., MacGregor, C., Okada, S., McBurney, L., Blair, D. & Lindenmayer, D.B. (2015) Ecological niche breadth and microhabitat guild structure in temperate Australian reptiles: implications for natural resource management in endangered grassy woodland ecosystems. *Austral Ecology*, **40**, 651–660.

Michael, D.R., Lunt, I.D. & Robinson, W.A. (2004) Enhancing fauna habitat in grazed native grasslands and woodlands: use of artificially placed log refuges by fauna. *Wildlife Research*, **31**, 65–71.

Michael, D.R., Wood, J.T., Crane, M., Montague-Drake, R. & Lindenmayer, D.B. (2014) How effective are agri-environment schemes for protecting and improving herpetofaunal diversity in Australian endangered woodland ecosystems? *Journal of Applied Ecology*, **51**, 494–504.

Munro, N.T., Lindenmayer, D.B. & Fischer, J. (2007) Faunal response to revegetation in agricultural areas of Australia: A review. *Ecological Management & Restoration*, **8**, 199–207.

Nopper, J., Lauströer, B., Rödel, M.-O. & Ganzhorn, J.U. (2017) A structurally enriched agricultural landscape maintains high reptile diversity in sub-arid south-western Madagascar. *Journal of Applied Ecology*, **54**, 480–488.

Office of Environment and Heritage (2015) NSW SPOT Woody extent and FPC for 2011 with 5 m pixels. Office of Environment and Heritage. Available at: http://qld.auscover.org.au/public/data/spot/woody_fpc_extent/nsw-2011/, made available by the AusCover facility (http://www.auscover.org.au) of the Terrestrial Ecosystem Research Network (TERN, http://www.tern.org.au) (accessed 16 June 2015).

Pardini, R., de Souza, S.M., Braga-Neto, R. & Metzger, J.P. (2005) The role of forest structure, fragment size and corridors in maintaining small mammal abundance and diversity in an Atlantic forest landscape. *Biological Conservation*, **124**, 253–266.

Pedro, A.R.S. & Simonetti, J.A. (2015) The relative influence of forest loss and fragmentation on insectivorous bats: does the type of matrix matter? *Landscape Ecology*, **30**, 1561–1572.

Prevedello, J.A. & Vieira, M. (2010) Does the type of matrix matter? A quantitative review of the evidence. *Biodiversity and Conservation*, **19**, 1205–1223.

Pulsford, S.A. (2016) Reptile agricultural matrix data, eastern Australia 2014 - 2015. ÆKOS Data Portal. Available at: https://doi.org/10.4227/05/57ad6c5071b23

Rey Benayas, J.M., Bullock, J.M. & Newton, A.C. (2008) Creating woodland islets to reconcile ecological restoration, conservation, and agricultural land use. *Frontiers in Ecology and the Environment*, **6**, 329–336.

Russildi, G., Arroyo-Rodríguez, V., Hernández-Ordóñez, O., Pineda, E. & Reynoso, V.H. (2016) Species- and community-level responses to habitat spatial changes in fragmented rainforests: assessing compensatory dynamics in amphibians and reptiles. *Biodiversity and Conservation*, **25**, 375–392.

Sato, C.F., Wood, J.T., Stein, J.A. *et al.* (2016) Natural tree regeneration in agricultural landscapes: The implications of intensification. *Agriculture, Ecosystems & Environment*, **230**, 98–104.

Schutz, A.J. & Driscoll, D.A. (2008) Common reptiles unaffected by connectivity or condition in a fragmented farming landscape. *Austral Ecology*, **33**, 641–652.

Skaug, H., Fournier, D., Bolker, B., Magnusson, A. & Nielsen, A. (2014) Generalized linear mixed models using AD model builder. R package version 0.8.0.

Tanentzap, A.J., Lamb, A., Walker, S. & Farmer, A. (2015) Resolving conflicts between agriculture and the natural environment. *PLoS Biology*, **13**, e1002242.

Templeton, A.R., Brazeal, H. & Neuwald, J.L. (2011) The transition from isolated patches to a metapopulation in the eastern collared lizard in response to prescribed fires. *Ecology*, **92**, 1736–1747.

Tilman, D., Balzer, C., Hill, J. & Befort, B.L. (2011) Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, **108**, 20260–20264.

Tulloch, A.I.T., Barnes, M.D., Ringma, J., Fuller, R.A. & Watson, J.E.M. (2015) Understanding the importance of small patches of habitat for conservation. *Journal of Applied Ecology*, **53**, 418–429.

Urbina-Cardona, J.N., Olivares-Pérez, M. & Reynoso, V.H. (2006) Herpetofauna diversity and microenvironment correlates across a pasture–edge–interior ecotone in tropical rainforest fragments in the Los Tuxtlas Biosphere Reserve of Veracruz, Mexico. *Biological Conservation*, **132**, 61–75.

Venter, O., Sanderson, E.W., Magrach, A. *et al.* (2016) Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications*, **7**, 12558.

Wickham, H. (2009) *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, NY, USA. Available at: http://ggplot2.org (accessed 26 October 2015).

Wickham, H. & Francois, R. (2015) dplyr: a grammar of data manipulation. R package version 0.4.3. Available at: http://CRAN.R-project.org/package = dplyr (accessed 26 October 2015).

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Supporting Information

Details of electronic Supporting Information are provided below.

Fig. S1. Reptiles under timber in coarse woody debris transect.

Table S1. Species list.

Table S2. Area of the remnants.

Table S3. Best models from the GLMMs.

Table S4. Pairwise differences in reptile response to management element.

Appendix S1. Vegetation cover PCA and loadings.

Appendix S2. R code of analysis.