Herpetofauna responses to agricultural matrix management

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Cover images (from left to right): *Limnodynastes interioris, Parasuta dwyeri* and *Carlia tetradactyla* © Nicole Hansen

Candidate's Declaration

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief it contains no material previously published or written by another person, except where reference is made in the text or chapter statements of contribution (see Acknowledgments and Preface).

Nicole Hansen

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Preface

This thesis is a Thesis by Compilation as outlined in the *Higher degree by research - thesis by compilation and thesis by creative works* (https://policies.anu.edu.au/ppl/document/ANUP_003405). Thus, the thesis begins with a brief Introduction outlining the background literature to the topic followed by the papers which provide further detailed discussion of the relevant literature. Therefore, the Introduction is not designed to be an extensive literature review. Further, each paper has either been published, in review, submitted or in preparation for a peer reviewed scientific journal, and as such, are written as distinct and targeted journal papers resulting in some stylistic and thematic differences. There is also some unavoidable repetition between Chapters particularly in relation to the methods sections as the same or similar study design was adopted for all empirical research presented in this thesis.

The majority of the thesis was conceived, developed, and written by the candidate Nicole Hansen, including developing the research questions, designing the study, selecting study sites, planning and implementing the fieldwork, data collection, statistical analysis, sourcing volunteers, and building relationships with landholders and relevant regional natural resource management organisations. My supervisors, Damian Michael, Don Driscoll and David Lindenmayer, and co-authors assisted with the research question conceptualization and design and advised on the analysis and manuscript revisions. To ensure my statistical approach was robust, I also sort advice from professional statistician, Wade Blanchard. Additional acknowledgments have been recognized in the Acknowledgments section of this thesis and papers where relevant.

Chapter’s 2, 3, 4 and 5 of this thesis correspond to the following papers listed below. All collaborating authors agree to the inclusion of papers listed below and agree to the description of their contribution to papers (where applicable).

Chapter Two

Linear plantings benefit reptile abundance and richness in an agricultural matrix

Authors: **Nicole A. Hansen**, Damian R. Michael, David B Lindenmayer and, Don A. Driscoll

Status: *Under review*

Journal: Agriculture, Ecosystems and Environment

Contributions: NAH and DAD conceived and developed the idea, designed the study and methodology; NAH collected the data in the field, performed analysis and lead writing. DAD assisted with analysis; NAH, DRM, DBL and DAD wrote the paper.

Chapter Three

Amphibians in agricultural landscapes: the habitat value of crop areas, linear planting and remnant woodland patches

Authors: **Nicole A. Hansen**, Benjamin C. Scheele, Don A. Driscoll and, David B Lindenmayer

Status: Published; 12th of August 2018

Journal: Animal Conservation; https://doi.org/10.1111/acv.12437

Contributions: NAH, BCS and DAD conceived and developed the idea; NAH and DAD designed the study and methodology; NAH collected the data, performed analysis and lead writing. DAD assisted with analysis; NAH, BCS, DAD and DBL wrote the paper.

Chapter Four

Predation risk for reptiles is highest at remnant edges in an agricultural landscapes

Authors: **Nicole A. Hansen**, Chloe F. Sato, Damian R. Michael, Don A. Driscoll and, David B Lindenmayer

Status: Published; 11th of September 2018

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Contributions: NAH, CFS and DAD conceived and developed the idea; NAH and DAD designed the study and methodology; NAH collected the data, performed analysis and lead writing. DAD assisted with analysis; NAH, CFS, DRM, DAD and DBL wrote the paper.

Chapter Five

Movement patterns of an arboreal gecko species *Gehyra verisolor* in fragmented agricultural landscapes reveal matrix avoidance

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Authors: **Nicole A. Hansen**, Damian R. Michael, David B Lindenmayer and, Don A. Driscoll

Status: *In press*

Journal: Animal Conservation

Contributions: NAH and DAD conceived and developed the idea, designed the study and methodology; NAH collected the data in the field, performed analysis and lead writing. DAD assisted with analysis; NAH, DRB, DBL and DAD wrote the paper.

Publications during candidature

The following list incorporates all articles, presentations and reports published during the candidature, in addition to those chapters within the thesis. These include:

Journal publication

Hansen, N. and Crosby, K (2016) Habitat use of the threatened Booroolong Frog (*Litoria booroolongensis*) in the Central West Catchment Management Area. Australian Zoologist **38**: 161-170.

Conference and workshop presentations

Hansen, N.A and Ng, K (2014) Reconnecting landscapes; can it be done in paddocks. Department of Environment connectivity forum, Canberra, Australian Capital Territory

Hansen, N.A (2015) How does matrix management influence connectivity for herpetofauna? 6th Biodiversity across the Borders Conference, Federation University Australia, Mount Helen, Victoria. Abstract

Hansen, N.A (2015). How does matrix management influence connectivity for herpetofauna? Biodiversity Dreaming Conference, Charles Sturt University, Bathurst, New South Wales

Hansen, N.A (2016). How does land management influence connectivity for herpetofauna? ACT Herpetological Association, Canberra, Australian Capital Territory

Hansen, N.A (2016). Evaluating matrix quality for reptiles in agricultural landscapes. Australasian Wildlife Management Society Conference, Auckland, New Zealand. Abstract

Hansen, N.A (2017) Testing predation risk on reptiles using replica models in an agricultural landscape. EcoTas Conference, Pokolbin, New South Wales. Abstract

Reports

Hansen, N.A and Ng, K (2017) Reconnecting ecosystems across a fragmented landscape: Final Milestone Report for the Central Tablelands Local Land Services. Report prepared for the Central Tablelands Local Land Services.

Newsletters

Hansen, N.A and Ng, K (2014) Reconnecting fragmented agricultural landscapes project: fauna in the fields, the story so far. Issue 1. Newsletter link

Hansen, N.A and Ng, K (2016) Reconnecting fragmented agricultural landscapes project. Issue 2. Newsletter link

Hansen, N.A (2016) ACTHA News Inc. Oct-Nov ’16 newsletter: how land management influences connectivity for herpetofauna. Newsletter link

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I have been incredibly fortunate throughout my PhD candidature to be surrounded and supported by a village. Undertaking a PhD can feel like a one (wo)man race at times and intensely isolating, but it is the PhD family that keeps an author moving forward to the finish line with (most of) her sanity intact.

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Don is an exceptional supervisor and has nurtured and guided me throughout my candidature. He has always encouraged my ideas and freedom to explore them (none were too small or unattainable), challenged my critical thinking beyond what I thought I was capable of, helped me navigate the murky waters of R, injected his dry sense of humor, incredible optimism and overall supported me through some tough fieldwork. Even Don leaving ANU, did not diminish his generosity with his time or attention. Thank you for your wisdom and taking my frantic emails and phone calls at the drop of a hat.

David stepped into Don’s former role as chair of my panel. Now, David is an incredibly busy man, writing 550 million papers a week while supervising another 700 students and projects. Nevertheless, I was the beneficiary of his incisive intellect, depth of knowledge, independence and lightning fast review process - that was everything I could hope for in a supervisor. Receiving my first “good work” and big red tick is still one of my proudest supervisor moments in my candidature.

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This thesis is dedicated to my parents, Sue and John Hansen. Mum was my right-hand woman; best field assistant and it was an incredible privilege to work alongside my best friend and share our love for nature. Mum not only helped me with the physical load of the fieldwork and wrangling unwieldy volunteers, but my emotional burden too. I cannot express how much I appreciated your intuitive support and lifting me up in the tough times (and there were many) - we are always in step, like two peas in a pod. Dad, the silent (sometimes, not so much) warrior and provider, your strong work ethic and encouragement has always inspired me to grow and pushed me to strive for my best self, whatever that may be. Your belief in me has always been that quiet voice pushing me forward and the knowledge that, you both, always have my back. I am what I am today because of you two, so thank you for your love, patience, and everlasting faith in me.

Abstract

Preventing biodiversity loss in fragmented agricultural landscapes is a global problem that requires knowledge of how species move through landscapes. Farming practices can increase the contrast between remnant patches of native vegetation and adjoining habitats, with negative consequences for species movement and the preservation of biodiversity. Yet, the relationships between habitat attributes and the presence of species are poorly understood, and the mechanisms influencing cross-habitat movement has rarely been empirically tested, particularly for less mobile organisms such as frogs, snakes and lizards (herpetofauna).

To address this important knowledge gap, I used a large-scale, empirical experiment to examine herpetofauna abundance, species richness, body condition, risk of predation, and inter-habitat movement between remnant woodland patches, edges and four contrasting farm land use types: 1) crop fields, 2) pasture paddocks, 3) linear plantings, and 4) woody mulch applied to a crop paddock after harvest. I also examined the effect of crop harvesting and seasonal effects on the distribution and abundance of herpetofauna.

In the second and third chapters of the thesis, I compared the habitat preferences and abundance and, richness and body condition (frogs only) of reptiles and frogs to predictions developed from a conceptual matrix model and literature review. I found the structure and quality of the matrix was a stronger influence on reptile abundance, species richness and movement than the temporal effect of crop harvesting (chapter 2). My results demonstrate remnant patches and farmland, particularly those with woody vegetation plantings, can provide suitable habitat for common reptile species, but this environment is not readily interchangeable as habitat for uncommon reptile species. The negative response of uncommon reptile abundance and species richness to farmland, irrespective of restoration, indicate that farmland not only reduced their abundance but also the likelihood of presence. I also observed a negative trend in uncommon reptile abundance in remnant patches adjacent to crop paddocks. These findings suggest that crop paddocks and associated farming activities may be negatively influencing animals within both patches and matrix, further isolating populations, and reinforcing the negative consequences of conversion to agriculture for reptile populations.

In Chapter three, my study revealed while frog abundance was positively associated with woody vegetation plantings within farmland, many frog species were found ubiquitously throughout the landscape, reflecting the dominance of a few disturbance tolerant species in the amphibian assemblage. My movement data demonstrated that frogs used multiple farmland types, moved between remnant patches and farmland, and into and out of cropped paddocks across harvesting periods. Unexpectedly, I found crop harvesting did not reduce frog abundance in crop paddocks, with some individuals persisting in farmland after harvesting. Body condition analyses indicated that farmland areas may provide good quality habitat for frogs and allow movement, dispersal, and foraging opportunities. My findings provide important insights into the utilisation of highly modified farmland as terrestrial habitat for frogs. This new knowledge is valuable in the context of land use intensification, and global amphibian declines. While much effort has focused on the protection of aquatic habitats for amphibians, management strategies must also consider the range of contrasting farmland types present in cropping areas, and the habitat requirements of the target species.

In the fourth chapter, I explored how contrasting habitats and farm management influences predation risk in lizards using wildlife cameras and plasticine replica lizard models. I found predation pressure from multiple predators, operating across the landscape, could be compounding the effects of habitat degradation and fragmentation. Predation attempts on models were highest at habitat edges, with a reduced risk within farmland and remnant patches. My findings suggest edge habitats are ‘risker’ for lizards than farmland, and may act as a population sink, preventing reptiles from moving into the farmland if individuals suffer increased mortality at the edge. Such trends have not been previously reported for cropped landscapes.

Finally, in the fifth chapter, I examined detailed movement patterns and behavior of a patch-dependent gecko species, Eastern Tree Dtella *Gehyra versicolor*, using radio-telemetry, fluorescent powder and an experiment displacement to examine movement and avoidance behaviour in response to different woodland to farmland edges. Unexpectedly, I found edge effects with a strong partitioning of individuals away from farmland, irrespective of the presence of complex habitat (e.g. linear plantings), in preference for remnant patches. We found pasture environments promoted direct movements of displaced geckos at a set distance from remnant patches into pastures. However, none of the radio-tracked geckos crossed the woodland-pasture edge, suggesting pastures may reduce homing ability of geckos. These findings contrast with the known ecology of the species and suggest, despite efforts to improve farmland quality by planting, farmland is not a preferred habitat for this species and does not promote longer distance dispersal movements.

By examining the influence of anthropogenic habitat change on herpetofauna it is possible to improve our understanding of the distribution of species outside of remnant native vegetation. My research findings provide new insights into the complex responses of herpetofauna to contrasting farmland uses in cropping landscapes. I provide evidence for potential drivers to explain herpetofauna distribution within highly disturbed areas. Importantly, I have demonstrated the relative value of different farmland types for facilitating and reducing movement and providing habitat across diverse agricultural landscapes. Through my series of inter-connected studies, I highlight important opportunities to promote herpetofauna conservation in agricultural landscapes by protecting remnant native vegetation and by increasing restoration efforts in cropping landscapes by establishing linear plantings. I also identify management practices to reduce mortality risk in areas where dispersal may be important by focusing on implementing strategies that increase shelter opportunities for lizards and to reduce the size of edges particularly where dispersal may be important (such as between remnants and linear plantings). This new knowledge is valuable in the context of promoting landscape connectivity, targeted restoration programs, and arresting global herpetofauna decline.

Key words

Connectivity, conservation, habitat restoration, land-use, edge-effects, reptiles, frogs, corridors

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CHAPTER ONE:

INTRODUCTION

Agricultural intensification and expansion, leads to biodiversity loss

Figure 1 Example of agricultural land use within study area. Note: Red star=study site; Green = tree/shrub cover; Yellow=cropping; Pink = grazing

Managing agricultural landscapes for biodiversity is becoming increasingly difficult with growing pressure for more intensive land use (Bennett et al. 2006, Baudron and Giller 2014). The influences of agriculture on biodiversity are complex (Pita et al. 2009, Šálek et al. 2009, Gastón et al. 2016). Agricultural systems may support medium to high levels of biodiversity (Plieninger and Bieling 2012, Baudron and Giller 2014, Scheele et al. 2014). However, increasing demand for food has transformed traditional low intensity, rotationally managed systems into high intensity, high yield, homogenized farmland (Figure 1; Foley et al. 2011, Garnett et al. 2013, Herrero and Thornton 2013). Subsequently, these systems are associated with the degradation of remnant native vegetation, water, soil and air quality, and biodiversity erosion (Flynn et al. 2009, Stoate et al. 2009a, Tilman et al. 2011). Given that agroecosystems have the potential to support substantial amounts of biodiversity, and the growing trend to intensify production as global population size and consumption increases, it is critical to identify which land management practices support biodiversity while also permitting ongoing agricultural production (Driscoll et al. 2013b, Garnett et al. 2013).

The matrix matters

Agricultural practices fragment landscapes leaving remnant patches of native vegetation embedded within a matrix of crops and pastures (Figures 1 and 2; Didham and Lawton 1999, Haila 2002, Driscoll et al. 2013b, Kay et al. 2016b). The quality and condition of the matrix can strongly influence habitat use, dispersal and movement between patches and survival of animals entering and moving through the matrix (Driscoll et al. 2013b, Collins and Fahrig 2017, Duflot et al. 2017). In some cases, the size and condition of the matrix can be more important than the size and arrangement of remnant patches (Bender and Fahrig 2005, Pita et al. 2007, Phillips et al. 2018). Changes in landscape elements within agricultural areas over time also may influence native biota (Eycott et al. 2010, Driscoll et al. 2013b, Ng et al. 2017). For example, cropped areas can create periodic dispersal opportunities (Kay et al. 2016b) and provide increased prey resources (Westphal et al. 2003) when a crop stratum is present, and temporally isolate patches when crops are harvested (Figure 2; Rotem et al. 2013). Despite the importance of the matrix for biodiversity conservation, are large knowledge gaps on how patch-dependent species move through the matrix (Driscoll et al. 2013a).

Figure 2 An example of spatial and temporal variation within the matrix. Left: Crops at full height provide shelter and food resources for fauna; Right: shows the temporary removal of shelter and subsequent habitat resources in the same paddock (as left photo) after crop harvest.

Additionally, in an effort to counteract large-scale clearing and intensification for agricultural development, enhancing the quality of the matrix has been the focus of significant investment and intense land management in recent years, primarily through planting programs (Manning et al. 2013, Smith et al. 2015, Michael et al. 2018). Linear plantings connected to remnant patches, and strategic revegetation along field margins, can provide a potential strategy to increase biodiversity and functional connectivity across landscapes (Lindenmayer et al. 2010, Michael et al. 2011), while maintaining industrial production levels. However, the relationships between biodiversity and the influence of the differing land uses on restoration efforts are not well understood for many species.

Different landscape elements influence reptiles and frogs

Previous studies examining faunal responses to changes in agricultural land use focus primarily on birds, mammals and invertebrates. There are few studies on frogs and reptiles (Arthur et al. 2010, Gastón et al. 2016, Ng et al. 2017). There is now significant evidence suggesting reptiles and frogs are experiencing severe population and range declines due to habitat loss, degradation and fragmentation in agricultural landscapes (Gibbons et al. 2000, Thompson et al. 2017, Michael et al. 2018). Frogs and reptiles are sensitive to habitat modification (Mott et al. 2010, Böhm et al. 2013, Thompson et al. 2017). However, the underlying mechanism influencing changes to herpetofauna responses to common farming practices and habitat restoration have rarely been empirically tested (Collins and Fahrig 2017, Michael et al. 2018).

Research approach

Thesis aim and research questions

My research builds on previous work by my supervisors who developed a conceptual model defining how the matrix influences the viability of patch-dependent species within fragmented agricultural landscapes (Driscoll et al. 2013b). In essence, the model defined how changes within the matrix can promote or limit movement through human-modified landscapes, and the consequences for populations of native species (Driscoll et al. 2013b). I advanced this theoretical framework by testing and quantifying how two of the five dimensions of the conceptual model of the matrix influence core effects such as movement and dispersal (see Figure 3; Driscoll et al. 2013a). I examined Spatial variation in matrix quality by comparing four differing matrix types and Temporal variation (or changes over time) in matrix quality by sampling throughout the year in paddocks that were cropped and paddocks that were rotationally grazed. I also explored the influence of the matrix mortality pathway on species.

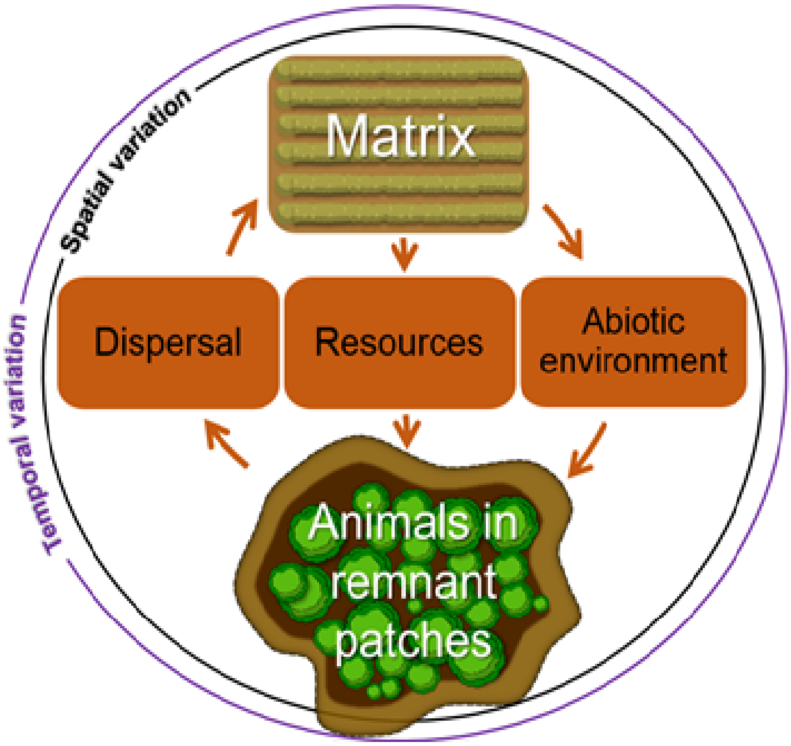

Figure 3 The conceptual matrix model, adapted from Figures 1 and 2 respectively from Driscoll et al. 2013.The model shows how the matrix influences species through the three core effects: dispersal (or movement), resources and the abiotic environment (or non-living). These three core effects and their subsequent ecological pathways lead to population level outcomes. We can challenge these key pathways by testing how modifying dimensions (e.g. spatial and temporal variation) influence the core effects.

By considering how farming practices influence the contrast between adjoining edges and remnant patches, my work can provide practical recommendations for conservation planning, restoration and sustainable farming practices. I pursue this broad research aim by addressing the following sub-research questions:

Research question (RQ) 1: Does species abundance and community composition within the matrix depend on (a) spatial variation in farmland quality (b) temporal variation in farmland quality?

RQ 2: Could mortality risk be a key mechanism driving farmland use by reptiles?

RQ 3: Do movement patterns and behaviour into and out of the matrix depend on (a) spatial variation in farmland quality (b) temporal variation in farmland quality?

Thesis structure

The thesis is a compilation, where I answer my research questions through the publication of articles in the peer-reviewed scientific literature (Figure 4). I examine reptile (in **Chapter Two**) and amphibian (in **Chapter Three**) temporal responses to remnant patches, edges and crop harvesting. In **Chapter Four**, I examine predation risk as a likely component of matrix mortality in lizards and changes in responses to spatial and temporal variation in habitat condition in the matrix. In **Chapter Five**, I examine the movement behaviour of targeted, patch-dependent reptile species in response to the farmland. I conclude the thesis and provide management recommendations and future research directions in **Chapter Six**.

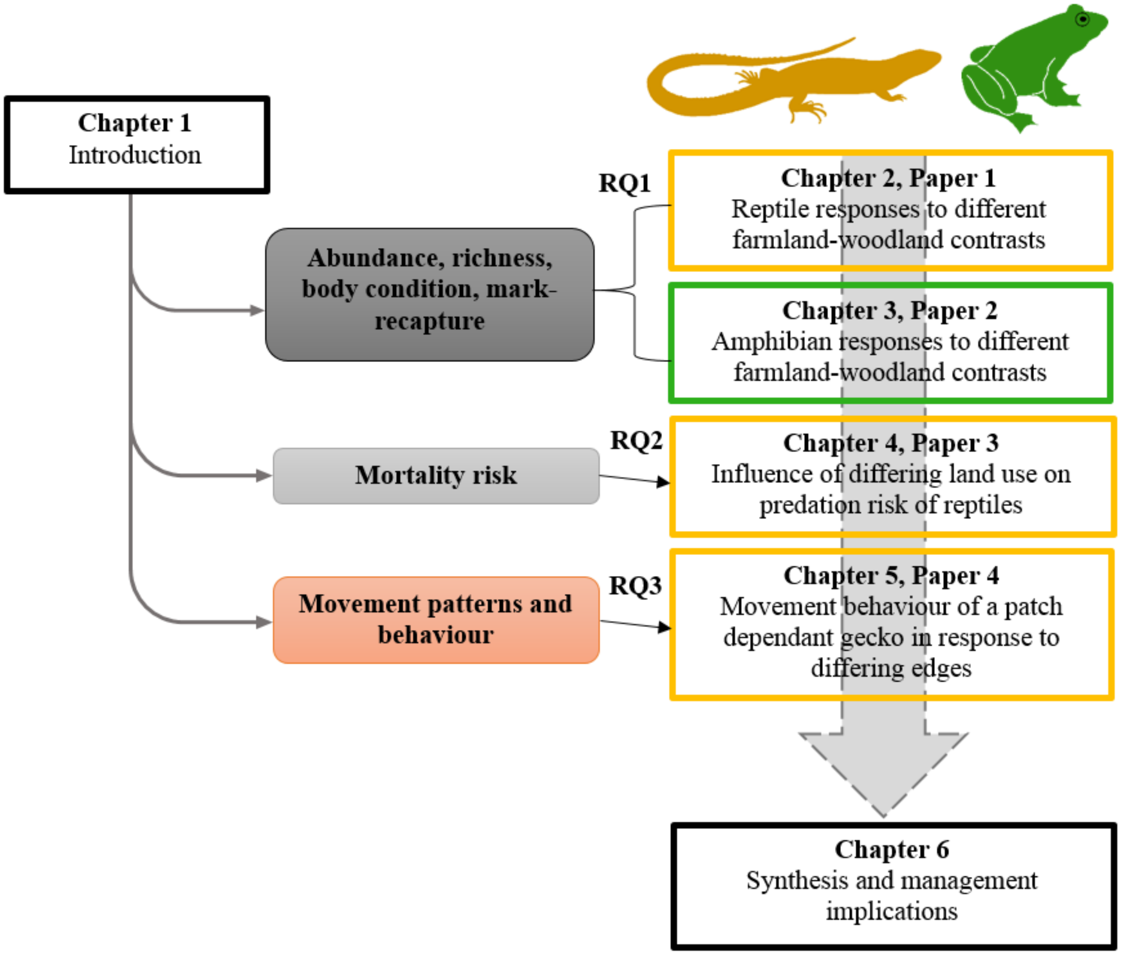

Figure 4 A conceptual model of the thesis structure showing the links between methods, research questions, fauna groups (reptile - yellow or frog - green) and corresponding papers.

Methodological approaches

Study region

My study region was located in the rural landscape of western New South Wales (Figure 5) and is one of the most fragmented and cleared agricultural regions of Australia (New South Wales Department of Land Water Conservation and Mid Lachlan Regional Vegetation Committee 2001). The dominant land-use is agriculture which has resulted in extensive clearing of native vegetation for cereal cropping (e.g. wheat, canola, lupins and barley) and grazing by sheep (*Ovis aries*) and cattle (*Bos taurus*) (Figure 1). The dominant native vegetation types within the remnant patches in the western part of the study area include mallee woodland, shrubland and White Cypress Pine (*Callitris glaucophylla*). The eastern part of the study area was dominated by patches of Box Gum and White Cypress Pine woodland, including the critically endangered White Box (*Eucalyptus albens*), Yellow Box (*Eucalyptus melliodora*), Blakely's Red Gum (*Eucalyptus blakelyi*) grassy woodland and derived native grassland ecological vegetation community. Land tenure in the study is a mixture of privately owned and reserved lands (Department of the Environment 2018).

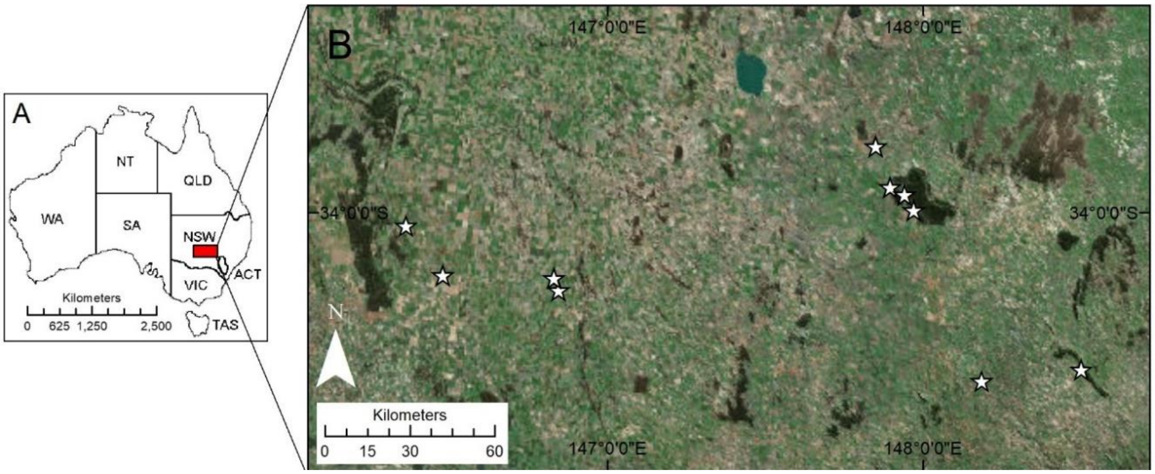

Figure 5 Maps of (A) study area within New South Wales and (B) study sites shown by white stars.

Study design

To study the responses and movement of herpetofauna into the matrix, I used a combination of survey methods including pitfall and funnel trapping, radio-telemetry, fluorescent powder tracking, wildlife cameras and plasticine replica gecko models. For Chapters Two to Four, I sampled along transects extending from woodland patches into three contrasting matrix types (crop, pasture and linear planting), and one experimental treatment (wood mulch applied over a bare crop paddock after harvest; Figure 6). These matrix types were selected because they (1) provide contrasting resources for herpetofauna and (2) are management practices that land managers currently implement but their value for providing habitat and connectivity is poorly understood.

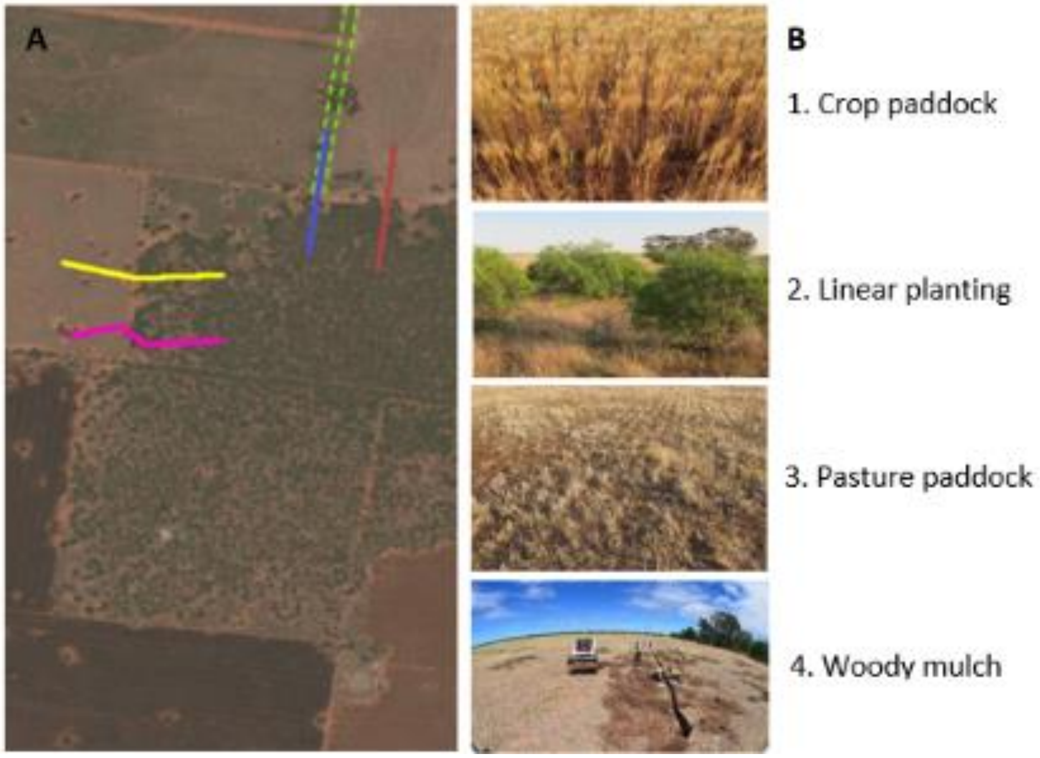

Figure 6 (A) Study site layout showing transects extending from a remnant patch into four matrix types (coloured lines). (B) Example photographs of the four matrix types within each study site.

The experimental mulch treatment used for my fourth land use type (Figure 6) comprised applying a linear strip of native woody mulch to a cereal cropping paddock at each study site immediately after crop harvesting (Figures 5 and 6). Woody mulch comprised of processed blue mallee (*E. polybractea*) (hereafter "woody debris"). I patchily applied between 20 and 25 tons of woody debris (per site) to a harvested crop paddock to examine if we could increase ground layer complexity and temporarily increase herpetofauna movement in crop paddocks (Figure 7). Mulch was used due to the practical limitations of larger material (e.g. logs and branches) obstructing cropping machinery.

Figure 7 Left: Delivery of woody mulch to a study site, before it was manually applied; Right: Example of woody mulch applied at the matrix side of the zero metre trap station.

Sampling herpetofauna

In **Chapters Two** and **Three**, pitfall and funnel trap sampling (Figure 8) of reptiles and frogs was conducted for one season, across two trapping sessions, (between September and early December 2014), prior to crops being harvested. This was repeated on a second occasion after crop harvesting between late January and March 2015. Each study site was part of a replicated and blocked experimental design consisting of a remnant patch of native vegetation surrounded by four modified land use types (cropping paddock, pasture paddock, linear planting, and applied woody mulch; Figure 6). Each transect comprised trap stations at different distances extending from the interior of the bushland patch into each land use type. Drift fences bisected the placement of each trap station, perpendicular to remnant patches to measure direction of an individual's movement into and out of the patch (Figures 5 and 7). All animals were marked using Visual Implant Elastomers

(Sapsford et al. 2014) to examine short-term matrix exploration and movement (Lewke and Stroud 1974, Lindner and Fuelling 2002).

Figure 8 Trap array showing pitfall (left) and funnel (right) traps.

For **Chapter Four**, plasticine replica models of geckos (Figure 9) were placed in each transect (patch, edge and matrix) for five days to estimate predation risk and identify key predators (birds or mammals; see Sato et al. 2014). Wildlife cameras were used to identify species predator that attacked models. Some models also were scented with gecko odour to examine odour-driven predators, as well as species hunting using visual cues. The trials evaluated predation risk as the matrix and levels of predator pressure changed.

Figure 9 Left: Plasticine model prototype next to a real individual photo; Right: painted models

The study in **Chapter Five**, focused on the movement behavior of a patch-dependent gecko species, *Gehyra versicolor*. This study provided further insight into why the target species might avoid particular edges and matrix types. Geckos were dusted with fluorescent powder to monitor short-term movement patterns and orientation towards or away from the patch edge (Figure 10). Geckos also were radio-tracked (Figure 10) and released within, and at the edge of, remnant vegetation adjacent to different matrix types to evaluate longer term movement behavior.

Figure 10 Left: Gehyra versicolor with a miniature radio tag attached (Model PIP3 AD337, Sirtrack Pty Ltd); Middle: Fluorescent powdered footprints from G. versicolor under UV light; Right: Fluorescent powder trail from an individual G. veriscolor under UV light

CHAPTER TWO:

LINEAR PLANTINGS INCREASE REPTILE ABUNDANCE, RICHNESS AND CROSS-HABITAT MOVEMENT IN AN AGRICULTURAL MATRIX

Spatial and temporal changes in matrix quality can influence the degree of contrast between habitat types, with consequences for species responses and movement (Driscoll et al. 2013a, Cooney et al. 2015, Kay et al. 2016b). Using reptiles – a group threatened globally by agricultural practices – I used a landscape approach to assess the relative habitat value of different forms of land use, remnant patches and edges over time for facilitating movement and population level responses.

A version of this chapter is *under review* in the journal Agriculture, Ecosystems and Environment.

Abstract

Agricultural intensification is a growing threat to biodiversity worldwide, influencing connectivity between habitat patches with consequences for the distribution of native fauna. Despite the known vulnerability of reptiles to habitat change, little is known of their use of farming areas over time, or how they move between different types of habitat in agricultural landscapes. To address this knowledge gap, we examined reptile responses to differing patch-matrix contrasts using reptile species richness, abundance, and movement across remnant patches, edges and four modified matrix types: (1) cropping paddock, (2) rested paddock, (3) linear planting, and (4) woody mulch applied over a bare crop paddock. We found total reptile species richness and abundance was positively associated with complex habitats, notably remnant native vegetation and linear plantings, and negatively associated with the matrix particularly crops and rested paddocks. However, recapture locations showed that some reptiles used multiple matrix types and moved between both patches and the matrix. By contrast, uncommon species did not respond positively to linear plantings, and abundance and richness were lower in the matrix compared to edges and remnant patches. Our findings suggest that uncommon reptiles may be influenced by edge effects, amplified by crop harvesting and seasonal effects, seasonally reducing the core area of remnant patches available for edge sensitive reptiles. Plantings may reduce edge effects and increase cross habitat movement for common reptile species (habitat generalists), as well as provide additional habitat, but are not readily interchangeable as habitat for uncommon species. Our findings reinforce the value of remnant native vegetation for preserving reptile diversity and highlights the need to establish linear plantings to increase habitat, reduce edge effects and enhance connectivity in cropping landscapes.

Keywords: connectivity, agricultural landscapes, edge, farming, conservation, habitat restoration

Introduction

Globally, agricultural expansion and intensification is a growing threat to biodiversity (Lindenmayer and Fischer 2006, Stoate et al. 2009a, Secretariat of the Convention on Biological Diversity 2010, Thompson et al. 2017). A substantial amount of research has focused on the occurrence of species within native vegetation in fragmented agricultural landscapes (e.g. habitat patches and roadside remnants; Bennett et al. 2006, Gaublomme et al. 2008, Pita et al. 2009). However, there is increasing recognition that the surrounding matrix is important habitat for native species within pastures (Majer and Delabie 1999, Fahrig et al. 2011, Kay et al. 2016b), crops (Perfecto and Vandermeer 2002, Rotem et al. 2013, Bosem Baillod et al. 2017), restoration plantings (Michael et al. 2011, Jellinek et al. 2014b, Lindenmayer et al. 2016), coffee (Pineda et al. 2005, Santos-Barrera and Urbina-Cardona 2011, Murrieta-Galindo et al. 2013) and cacao plantations (Heinen 1992, Rice and Greenberg 2000, Faria et al. 2007).

Previous studies define the matrix as an extensive, typically non-native, land cover type comprising of different land use types (Haila 2002, Driscoll et al. 2013b, Cooney et al. 2015). The matrix does not provide for self-sustaining populations of patch-dependent species, but several studies suggest changes in matrix quality may improve the suitability of habitat, increasing an individual's ability to move through the matrix (Guerry and Hunter Jr 2002, Bender and Fahrig 2005, Driscoll et al. 2013b, Kurz et al. 2014, Kay et al. 2016b). Despite the important influence that the matrix can have on species' distributions, a bias towards the retention of protected reserves and restoration of natural habitat (Haila 2002, Lindenmayer et al. 2016) means our understanding of the influence of the matrix on landscape use remains poorly understood (Driscoll et al. 2013b).

Studies on matrix permeability suggest the quality of the matrix may influence the outcome of animal movement into and through the matrix (Prevedello and Vieira 2010, Driscoll et al. 2013b, Cooney et al. 2015, Kay et al. 2017). Some matrix habitats may represent a barrier to movement such as high crops directionally sown away from preferred habitats

(Kay et al. 2016b) and grassland cover (Prevedello and Vieira 2010, Cooney et al. 2015, Kay et al. 2016b), while others may facilitate movement between patches of native vegetation (Long et al. 2005, Eycott et al. 2010, Ferrante et al. 2017). For example, cropped areas can temporally alter connectivity between neighbouring habitat patches by creating ephemeral dispersal opportunities such as when a crop is at full height (Cosentino et al. 2011, Kay et al. 2016b). Crops also may promote connectivity by encouraging individuals to follow lines between crops sown between patches (Kay et al. 2016b), or conversely by temporarily isolating species after harvesting (Rotem et al. 2013). What constitutes the matrix also may be species-specific (Rittenhouse and Semlitsch 2006, Pulsford et al. 2017) and system-specific (Long et al. 2005, Driscoll et al. 2013b). Therefore, quantifying species responses to changes in condition remains a fundamental challenge (Driscoll et al. 2013b).

There are few large-scale empirical studies on the effects of anthropogenic farmland change on patch-dependent, ground-dwelling groups of animals such as reptiles (Gardner et al. 2007, Ribeiro et al. 2009, Mingo et al. 2016) despite the worldwide decline of reptiles in agricultural landscapes (Gibbons et al. 2000, Böhm et al. 2013). Reptiles are also one of the least represented taxonomic groups in connectivity research (Doerr et al. 2010, Driscoll et al. 2014) suggesting reptiles should be a high priority for research. .

In this study, we used a landscape-scale natural and manipulative experiment to examine contrasting farmland management types that are likely to affect matrix quality and influence reptile abundance, richness and movement in agricultural landscapes (for example Figure 4). In doing so, we also tested two aspects of the conceptual model of the matrix, whereby: (1) the matrix is spatially variable in quality and condition and, (2) the matrix is temporally variable, changing in quality over time (e.g. from high to low quality habitat) both of which influence species' responses leading to population level outcomes (Driscoll et al. 2013b). Our three research questions were: Does reptile richness, abundance and movement depend on: (1) habitat types (remnant patch, edge, matrix); (2) spatial variation in matrix quality (crop, rested, planting and woody debris)?, and; (3) temporal variation in matrix quality due to crop harvest? We developed predictions about each farm management type and the rationale and species responses for each one (Table 1).

Improving our understanding of land management practices that support biodiversity while permitting ongoing commodity production is critical to successfully integrating agriculture with conservation (Flynn Dan et al. 2009, Driscoll et al. 2013b, Garnett et al. 2013). Our research examines features of cropping landscapes that are common worldwide to address the important problem of how to increase habitat suitability in productive agricultural landscapes by demonstrating the relative importance of different matrix types on reptile species richness and abundance.

Methods

Study area

Our study area was located within western New South Wales, Australia (and bounded by the following coordinates: Young: 34° 26' 18.723" S; 148° 10' 54.975" E, Grenfell: 33° 55' 58.249" S; 147° 53' 48.729" E, Ardlethan: 34° 10' 34.776" S; 146° 50' 7.522" E; Figure 1A and B). Extensive clearing for agriculture has restricted eucalypt woodland to steeper, rocky or infertile areas. Remnant patches of native vegetation include mallee woodland and shrubland with some White Cypress Pine (*Callitris glaucophylla*) in the western part of the study area. Box Gum and White Cypress Pine woodland, including threatened White Box (*Eucalyptus albens*) woodland, Yellow Box (*E. melliodora*) woodland, Blakely’s Red Gum (*E. blakelyi*) woodland and derived grasslands in the eastern part of the study area (Table S1). Land tenure in our study is a mixture of privately owned and reserved lands (Table S1). Many of the remnant patches have been modified by livestock and macropod grazing, historical logging and fire regimes.

Study design

We selected 11 study sites comprising a remnant patch of native vegetation surrounded by a matrix of four contrasting matrix types (Figure 11A; Table S2). All matrix types adjoined remnant native vegetation for pairwise comparison (shown in Figure 11C), and were adjacent to one another to quantify interacting effects of matrix types (Figure 11C). Three matrix types were considered: (1) a cropping paddock consisting of a wheat crop (or "crop"), (2) fenced restoration plantings or "linear plantings": strip of vegetation (≤30m) comprising primarily *Acacia* mid-storey with occasional eucalypts and grassy groundcover which is subject to intermittent sheep grazing, and (3) a rotationally grazed pasture or "rested" areas which were paddocks vegetated with grasses and cleared of canopy and mid-story vegetation with occasional, scattered paddock trees (or "pasture"; Figure 11C). A fourth experimental treatment was added to a cereal cropping paddock at each study site immediately after crop harvesting: native woody mulch made of coarsely ground wood from Blue Mallee (*E. polybractea*) (hereafter "woody debris"). Between 20 and 25 tonnes of woody debris was patchily applied (per study site) to a harvested crop paddock to examine if we could increase ground layer complexity and temporarily increase reptile movement in crop paddocks (Figure 1). Mulch material was used due to the practical limitations of adding larger material (e.g. logs, branches) that can obstruct cropping machinery.

Our study design consisted of four 400m transects extending from inside the remnant patch and out into the four adjoining matrix types. We placed trap stations along each transect at seven distances: -200m, -75m, -20m, 0, 20m, 75m, 200m, from inside the remnant into the farmland (Figures 1 and S1A). Remnant patch size (mean 5240.89 ± SE 3003.3 ha) was found previously not to have an effect on reptile species richness and abundance (also see Pulsford et al. 2017) and thus was not considered further in this study.

Sampling reptiles

Each trap station comprised two pitfall traps and two funnel traps on both sides of a 15m long and 0.35m high drift fence (5m spacing between traps) (Figure S1A). The drift fences ran parallel to the patch edge to capture animals moving into and out of a patch (Figure S1A). Traps were placed on either side of the fence to indicate the likely direction of travel for each captured individual (i.e. moving towards or away from the remnant patch; Figure S1A).

Traps were opened for six days and five nights twice during spring (pre-harvest) and then twice during summer (post-harvest). Pre-harvest surveys were completed between

September - December 2014 and coincided with mid- and high- growth phases of crops (Figure S1B). Post-harvest surveys were completed between January - March 2015 (Figure S1C). Two to three study sites were monitored simultaneously and checked daily throughout the survey period. A total of 1,232 traps were monitored across all study sites, equating to 24 trap days per trap, per study site across the entire survey period.

All animals were individually marked using Visible Implant Elastomer (Smith et al. 2012), measured and then released ten metres from the trap array on the opposite side from the capture trap to minimise barriers the drift fence may represent to normal animal movement. Nomenclature for identifying animals to species level followed Wilson and Swan (2013). Individuals were released in accordance with Australian National University ethics guidelines (protocol A2014/29).

We recognise pitfall and funnel trapping represents one of the many sampling methodologies for surveying reptiles (Hutchens and DePerno 2009, Michael et al. 2012). Our study did not aim to survey all species, but rather to compare species assemblages across habitats. Using both pitfall and funnel traps provides a consistent and efficient method for sampling cryptic species like reptiles (Ribeiro-Júnior et al. 2008) and limits observer bias encountered using other methods such as active searches (Willson and Gibbons 2010). Using drift fences simply increased the efficiency of captures.

Statistical analysis

To test our predictions and quantify the interactive effects on reptiles of the matrix, differing matrix types, and crop harvesting (Table 1), we used generalized linear mixed models (GLMM; Bolker et al. 2009) with a Poisson error distribution. Conservation actions typically target rare, or uncommon species (Thompson et al. 2017), so we analysed total reptile abundance and species richness and the abundance and richness of uncommon reptiles (<10% of captures; Triska et al. 2017) as response variable separately. Total and uncommon reptile species abundance and richness was calculated by pooling the total captures during the entire period of the survey within each trap array (one fence, two pitfalls, two funnel traps). Analysing uncommon species separately may reveal different patterns to more common species (Kay et al. 2016a, Pulsford et al. 2017). The main effects tested were 'treatment' (crop, planting, rested, and woody debris), 'habitat' (remnant, edge, and paddock; see Figure S1) and 'harvesting period' (before and after harvesting) and their interactions. Given the spatial clustering of the study sites and to account for broad climatic differences (e.g. climate and geographic variation) of the study sites, the three 'regions' (Young, Grenfell and West) were fitted as an additive fixed effect in all models. We fitted study site, transect number, and the study site of each trap fitted as random effects to account for spatial structure and repeated measures of the study design.

We examined the direction of animal movement and the effect of distance from the edge on direction by calculating a direction variable using the proportion of animals caught on the remnant side of the drift fence (or those animals moving towards the matrix) against those caught on the matrix side (or those moving in the direction of the remnant) (Figure S1). Direction was analysed by fitting GLMMs with a binomial error distribution. Fixed and random effects were fitted as described above. All analyses were completed using R 3.3.2 (R Studio Team 2016, R Core Team 2017).

Results

We captured 854 individuals (excluding recaptures) from 34 species across eight families (Table S2). Most captures were from Scincidae. Species richness per study site ranged from five to 16 species (mean 12 ± 1.11SE), and total abundance ranged from 27 to 127 (mean 77.64 ± 9.23SE) individuals per study site. Three species accounted for 55% of all observations; Boulenger's skink, *Morethia boulengeri*; Grey's skink, *Menetia greyii* and robust skink, *Ctenotus spaldingi* (Table S2).

We found lower reptile counts and richness in the eastern region of Young compared to the other regions ($P < 0.01$) (Table S3). Uncommon reptile abundance and richness did not differ significantly between regions ($P = 0.12$; $P = 0.06$ respectively) (Table S3).

Does reptile richness, abundance and movement differ between habitat types?

We found significant differences in total reptile abundance and richness, and uncommon reptile abundance and richness between habitat types (P < 0.01; respectively) (Table S3). We found a negative effect of the matrix on total reptile abundance and richness and abundance and richness of uncommon reptiles, compared to remnant patches ($P < 0.01$) (Tables S3 and S4), but these effects depended on matrix type and are addressed in the next section. Approximately 50% of all reptile captures were within the remnant patches (where 43% of traps were), 34% were within the matrix (with 43% of traps), and 17% at edges (with 14% of traps). Notably, reptile species sensitive to soil disturbance, timber and rock removal such as fossorial guild (e.g. *Lerista* and *Anilios*) and cryptozoic guild (e.g. *Underwoodisaurus, Vermicella,* and *Diplodactylus*), were present in remnant patches, but absent within the matrix (see Table S2; guilds classified by Michael et al. 2015). Twenty-five individuals of six species were captured more than once (Table S5). Of these recaptures, 24% did not move from their initial capture location within the matrix, 8.3% moved between matrix types, 8.3% moved from the matrix into the patch and 16.7% moved from the remnant patch into the matrix (Table S5). We found no direction response from reptiles moving towards the patch, moving toward the matrix, or the interaction between any of the explanatory variables (P > 0.07) (Table S3).

Does spatial variation in matrix quality influence reptile responses?

We found significant interactive effects of 'treatment' and 'habitat' on total reptile abundance and richness, and uncommon reptile abundance and richness ($P < 0.01$ respectively) (Table S3). We found total reptile abundance and richness was higher in plantings, than other matrix types ($P < 0.03$) (Tables S3 and S4; Figures 2A and 2B). Using pairwise comparisons, we found that abundance and richness of total reptiles were similar in remnant patches and edges, but were generally lower in the matrix, with the notable exception that reptiles did not decline in the plantings (Figures 2A and 2B). Total abundance of reptiles declined from edges into the crop matrix type (Figure 2A), and richness declined from edges into the crop and rested matrix types (Figure 2B).

Uncommon reptile abundance and richness showed trends similar to the overall results, with lower richness and abundance in the matrix compared to patches (*$P = 0.01$*) (Table S4). Although we found a positive effect of plantings on uncommon reptile abundance and richness (*$P < 0.03$*) (Table S4), we failed to detect significant pairwise differences between matrix types (for abundance see: Figure 13).

Does the temporal influence of crop harvesting reduce matrix quality for reptiles?

We expected that if cropping cycles influenced reptiles, we would see a significant habitat by matrix type by harvesting interaction, with abundance and richness declining in crop paddocks after harvest more than in other places. However, we did not find a three-way interaction on reptile responses (Tables S3 and S4). Total reptile abundance was influenced by 'treatment', 'harvesting', and 'habitat type' -'harvesting' interactions (*$P < 0.01$*) (Table S3). Uncommon reptile abundance and richness was influenced by the interaction of 'treatment' and 'harvesting' (*$P = 0.01$*) (Table S3).

We found total reptile abundance and uncommon species abundance was generally lower across the entire woody debris transect, prior to crop harvesting, than after harvesting (*$P < 0.03$)* (Table S4), although pairwise comparisons were not significant. Uncommon species were significantly less abundant in cropped transects after harvesting (Figure 4), an effect observed across the entire transect.

Reptiles were more abundant in remnant patches pre-, than post-harvest ($P = 0.02$) (Table S4 and Figure 5A). Prior to harvesting, total reptile abundance and richness was not different at edges compared to the matrix but was higher at the edge compared with patch and matrix after harvesting, in all matrix types (Figures 5A and 5B).

Discussion

Our findings revealed: (i) farmland is a selective filter for uncommon species; (ii) farmland may provide habitat for reptiles, particularly if linear plantings are present; (iii) no direct association of crop harvesting with reptile responses, but interactive effects of matrix type and season, which extended across edges and deep into the adjacent remnant patches. Our findings support recommendations from recent studies to both protect remnant native patches of vegetation as habitat for reptiles and to continue habitat restoration in agricultural landscapes (Attum et al. 2006, Valentine and Schwarzkopf 2009, Jellinek et al. 2014a, Pulsford et al. 2017, Lindenmayer et al. 2018).

Does reptile richness, abundance and movement differ between habitat types?

Reptile species richness and abundance, particularly uncommon species such as reptile species sensitive to soil disturbance, timber and rock removal (see Table S2; guilds classified by Michael et al. 2015), was positively associated with remnant native vegetation and declined across the edge into open, degraded areas within the matrix (Tables S3 and S4).

This is consistent with many recent studies demonstrating remnant native vegetation is an important predictor of reptile occurrence in modified agricultural landscapes (Jellinek et al. 2014b, Pulsford et al. 2017, Michael et al. 2018). Agricultural activities alter the fundamental structure of affected environments by removing canopy cover and exposing the ground to increased sunlight and wind, which increases surface temperature, dries microhabitats and reduces ground cover (Stoate et al. 2009b, Collins and Fahrig 2017). A direct reduction in animal abundance in response to crop management has been demonstrated for birds (Wilson et al. 2017) and invertebrates (Thorbek and Bilde 2004, Bosem Baillod et al. 2017) but few examples are available for reptiles (Rotem et al. 2013), although see Pulsford et al. (2017) in a nearby grazing landscape. Reptiles have also been shown to be influenced by a lack of particular microhabitats (e.g. shaded leaf litter) required to avoid overheating and water loss (Pfeifer et al. 2017).

While the farmland may be a selective filter for some species and reduce the occurrence of uncommon species, we found several common, disturbance-tolerant species were present within farmland (although at lower levels of abundance), particularly when key habitat features (e.g. trees and shrubs) are present (discussed below). For reptile species adapted to hot and dry conditions, open spaces and edges, matrix environments may provide suitable habitat and favourable climatic conditions (Pfeifer et al. 2017).

Our results indicate that efforts to increase restoration of habitat within farmland may increase reptile abundances within the matrix for some species, but do not mitigate habitat loss for edge sensitive species (Pfeifer et al. 2017) or the necessity of maintaining and increasing the extent of remnant native vegetation within these landscapes (Michael et al. 2018).

Does spatial variation in matrix quality influence reptile species richness, abundance and cross habitat movement?

We found similar numbers of reptiles from remnant patches across edges into linear plantings, compared to significantly lower abundance and richness found across edges into other matrix types (Figures 2A and 2B). Low contrast matrix types such as linear plantings likely contain more suitable resources and microclimatic conditions for patch-dependent species compared to high contrast matrix types like crop or pasture paddocks (Laurance et al. 2011, Michael et al. 2018). Linear plantings may increase movement and dispersal of birds, mammals and invertebrates (Haddad 1999, Lindenmayer et al. 2010). However, there are few studies that show plantings increase reptile numbers in the cropping matrix (Jellinek et al. 2014a, Pulsford et al. 2017, Thompson et al. 2017). Our evidence provides a clear incentive to increase replanting efforts in agricultural landscapes (Böhm et al. 2013, Lindenmayer et al. 2016). Previous studies hypothesised that modified habitats may act as population sinks (Tilman et al. 1995, Thompson et al. 2017). Research examining recruitment and survival are needed to determine if linear plantings are sink habitat, although we found no evidence of directional bias of movement into linear plantings.

Our study represents one of the only large scale experimental studies to investigate the potential of woody mulch to attract reptiles to harvested agricultural paddocks, using a readily available material which was compatible with agricultural activities (Wanger et al. 2010, Shoo et al. 2014). Contrary to expectations (Table 1), we did not detect short-term responses to the application of fine woody debris (Figures 2A, 2B and 3). We suggest three possible explanations for the observed lack of response: (1) predation; reptiles detected and responded to debris but were removed by predators (Fischer et al. 2005); (2) reptiles detected the debris but the texture was too fine to provide shelter (Owens et al. 2008); (3) the material was not in-situ for long enough before surveying for reptiles to occupy these areas (Shoo et al. 2014), and; (4) woody mulch may only be used as egg-laying sites for some species. Indeed, in a previous study, we found elevated predation risk in edge habitats adjoining the woody debris matrix type, which may have contributed to avoidance behaviour or increased mortality of reptiles, subsequently reducing reptiles within the debris (Hansen unpublished data). While temporary woody mulch in cropped areas did not appear to benefit reptiles, the treatment does influence invertebrate fauna (Ng et al. 2017), and further studies could explore its value in linear plantings, where groundcover is sparse and takes a long time to develop (Cunningham et al. 2007, Smith et al. 2015).

Does the temporal influence of crop harvesting reduce matrix quality for reptiles?

We predicted that crops should promote a temporary increase in prey availability for reptiles, resulting in a higher abundance and richness of reptiles within crop paddocks (Table 1), and the converse after harvesting, but this was not the case (Table 1). Instead, uncommon reptile abundance declined across the whole crop transect between harvesting periods, an effect not observed across other transects (Figure 4). These results suggest high contrast habitat edges, created by crop harvest, may contribute to edge effects for uncommon species, influencing reptile’s responses in both the patch and matrix (Rotem 2012, Pfeifer et al. 2017). If changes in adjacent land use are increasing edge effected habitat and reducing core area of remnant patches available for reptiles, then the amount of habitat loss and fragmentation for patch-dependent species may be greater than that simply converted to agriculture (Ewers and Didham 2007, Pfeifer et al. 2017)

Previous studies have suggested cross-habitat movement of reptiles from patches into adjacent wheat fields may result in removal of those individuals by crop harvesting or increased predation (Todd et al. 2008), and subsequent reduction in the natural patches population size (Rotem et al. 2013). However, we did not find evidence of cross habitat movement of any uncommon reptile species into the paddock from the patch during or after harvest (Table S5). Survey techniques which allow direct tracking during harvesting of crops would be required to determine if mortality risk contributed to patterns of matrix use observed in this study.

Conservation implications and conclusions

A critical issue for the persistence of reptiles in heterogeneous and production landscapes is providing habitat and promoting cross-habitat movement (Brown et al. 2011b, Driscoll et al. 2013b, Ferrante et al. 2017). Plantings have the potential to do both in our study region. Many of the species recorded within plantings depend on tree and shrub-related habitat features (e.g. leaf litter; Cogger 2014, Michael et al. 2018) which may explain why some reptile species benefit from plantings. This implies conservation strategies need to increase and incentivise restoration efforts and establish shelterbelts within farmland, while also retaining existing native vegetation (Kay et al. 2016a, Lindenmayer et al. 2018). Priorities for future research should seek to understand if plantings act as habitat, as movement corridors, or as population sinks using direct tracking and demographic research (Munro et al. 2007, Tscharntke et al. 2012, Duflot et al. 2017, Thompson et al. 2017). Furthermore, more research is required to evaluate the threshold responses for particular groups (e.g. guild assemblages; Michael et al. 2015) reliant on resources within plantings, and other areas that may be depleted within the matrix.

Land managers could minimise the detrimental influence of the post cropping matrix by enhancing core habitat through targeted restoration programs (e.g. planting, reducing livestock grazing, increasing woody debris; Lindenmayer et al. 2018, Michael et al. 2018) and reducing microclimatic changes caused by edge conditions by widening planted buffers around patches (Ewers and Didham 2007). Management also should minimise the removal of key habitat features like trees and shrubs within paddocks (Fischer and Lindenmayer 2002, Wanger et al. 2010, Neilly et al. 2018) and around paddock margins.

Our findings highlight opportunities to support reptiles within agricultural areas by maintaining existing native vegetation and restoring native vegetation in linear plantings. The results also suggest that edge effects may have an important influence on uncommon reptile persistence within farmland, with the possibility that core habitat within patches may expand or shrink in response to short-term changes in the matrix. Our results show that plantings may be essential for the conservation of reptiles in paddocks. Land-use intensification that removes native vegetation or prohibits restoration will likely see further declines of reptile species. Conversely, given that reptiles are able to use linear plantings, there is hope that declines of reptiles in agricultural landscapes can be arrested, at least for common species. Such improvements may be possible along with intensification if gains in productivity within paddocks allow for some land to be spared around field margins for restoration.

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Table 1 Farm management types of the cropping landscape examined within the study with related predicted reptile responses

Farm management element	Predictions
1. Habitat type	
(a) Remnant native vegetation	Remnant patches have higher abundance and richness of reptiles compared to paddocks given the resemblance of patches to natural habitat (Valentine and Schwarzkopf 2009, Rotem 2012, Pulsford et al. 2017).
(b) Edges	Edges are more exposed, with minimal shelter and may form a barrier to movement (Anderson and Burgin 2008, Lasky et al. 2011) due to increased predation risk (Andrén 1995, Anderson and Burgin 2008, Pita et al. 2009), behavioural avoidance (Bowler and Benton 2005, Rittenhouse and Semlitsch 2006), and human disturbance (vegetation removal and access tracks) associated fences installed at the edges (Lasky et al. 2011), which would tend to reduce richness and abundance from the edge into the matrix. The habitat quality and intensity of disturbance within the matrix also has a great influence on anthropogenic – natural ecotones (Santos-Barrera and Urbina-Cardona 2011). Edges adjacent to matrix types with low management rates and the maintenance of natural elements (e.g. leaf litters, canopy cover) may have higher species diversity, than highly disturbed and exposed management areas (Santos-Barrera and Urbina-Cardona 2011).
(c) Matrix	Farmland will have lower reptile abundance (for particular species) and richness than remnants given the higher contrast with native vegetation and lack of extensive cover (Ribeiro et al. 2009, Rotem 2012, Michael et al. 2015). Therefore, population would not be self-sustaining (Driscoll et al. 2013b).

2. Matrix type:	
(a) Cropped paddock	Higher reptile richness and abundance in crop paddocks compared to pasture paddocks. Cropped paddocks may be capable of supporting a high number of patch-dependent reptiles periodically spilling over from the remnant patch due to increased shelter and food resources, but this response is likely to depend on the timing of harvesting of crops (Rotem et al. 2013).
(b) Linear plantings	Higher numbers and species-richness compared to than more simplified, high contrast habitat type like crops and pastures (Cunningham et al. 2007, Jellinek et al. 2014a, Triska et al. 2016).
(c) Grazed pasture or “rested” areas	Lowest numbers and richness of reptiles due to the substantial and consistent contrast in habitat attributes compared to remnant native vegetation (Pulsford et al. 2017)
(d) Woody mulch	Higher reptile numbers and richness compared to pasture due to addition of habitat, incubation sites and protection from desiccation (Davis et al. 2010, Brown et al. 2011a, Manning et al. 2013, Michael et al. 2015)
3. Crop harvesting	
(a) Pre-harvest	Crop paddocks will have higher reptile abundance and richness and directional bias of movement of reptiles from patches into cropped areas prior to harvesting compared to after harvesting when structure is available (see 1 (a); Rotem et al. 2013).
(b) Post-harvest	Crop paddocks after harvesting, and nearby areas will have lower reptile abundance and richness due to the removal of potential shelter and food resources by crop harvesting (Smart et al. 2005, López and Martín 2013, Rotem et al. 2013, Carpio et al. 2017). A directional bias in the movement of reptiles returning to the

remnant patches or linear plantings may also occur (Rotem et al. 2013, Kay et al. 2016b)

Figure headings

Figure 11 (A) Study area and study site of eleven study sites within New South Wales. (B) Study site layout showing transects extending from a remnant patch into four matrix types (coloured lines). (C - F) Example photographs of the four matrix types within each study site. (C) Woody mulch application (D) Cropping paddock. (E) Recently planted native vegetation. (F) Rested paddock.

Figure 12 (A) Significant relationships (including Tukey's post hoc analysis) for reptile abundance between treatments over distance (from remnant patch into the paddock or matrix). (B) Significant relationships (including Tukey's post hoc analysis) for reptile richness between treatments over distance (from remnant patch into the paddock or matrix). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates plotted on the original scale.

Figure 13 Uncommon reptile abundance between treatments over distance (from remnant patch into the paddock or matrix). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates plotted on the original scale.

Figure 14 Significant relationships (including Tukey's post hoc analysis) for uncommon reptile abundance between harvesting periods, over distance (from remnant patch into the paddock or matrix). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates plotted on the original scale.

Figure 15 (A) Significant relationships (including Tukey's post hoc analysis) for reptile's abundance between harvesting periods, over distance (from remnant patch into the paddock or matrix). (B) Significant relationships (including Tukey's post hoc analysis) for reptile's richness between harvesting periods, over distance (from remnant patch into the paddock or matrix). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates plotted on the original scale.

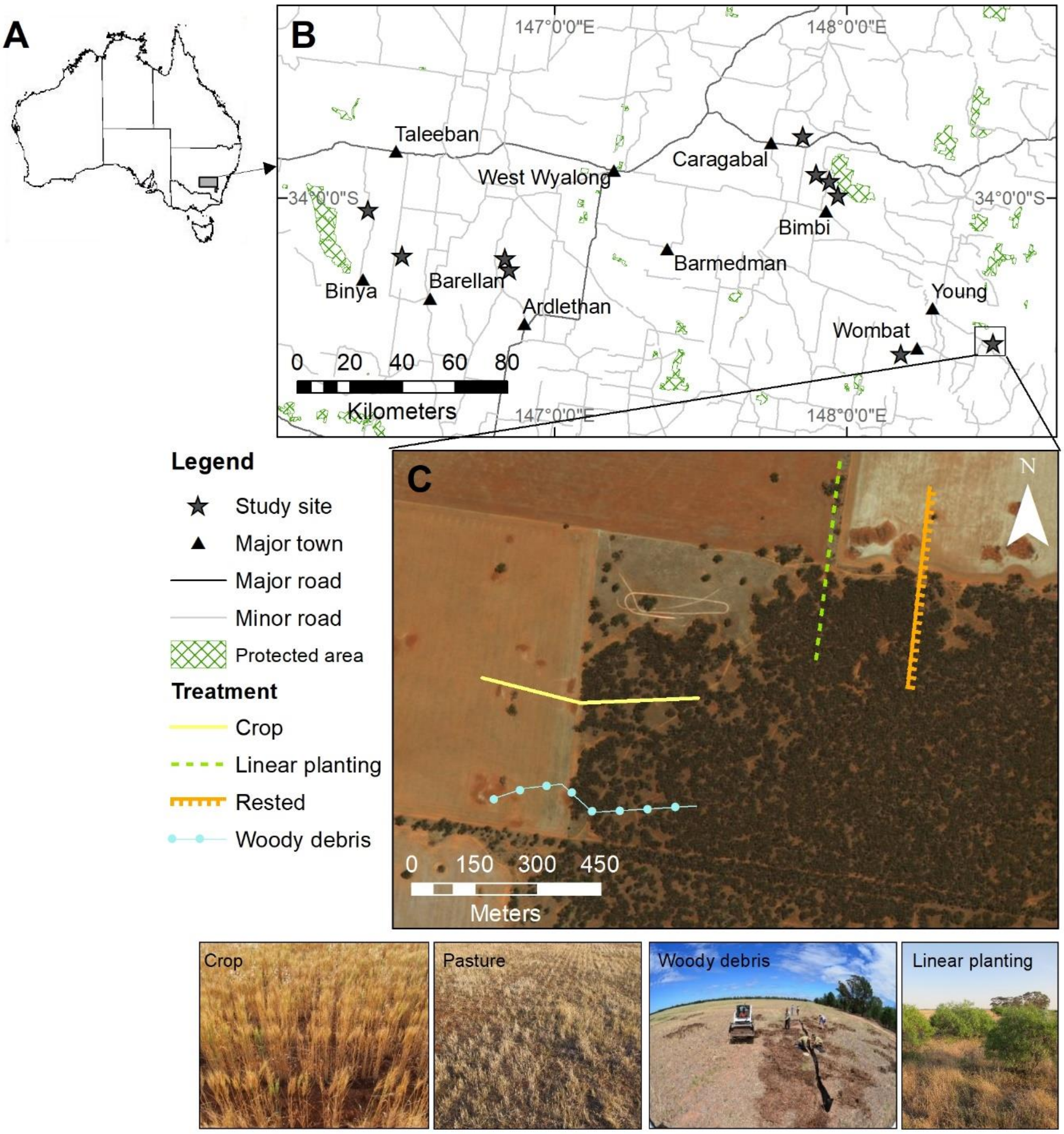
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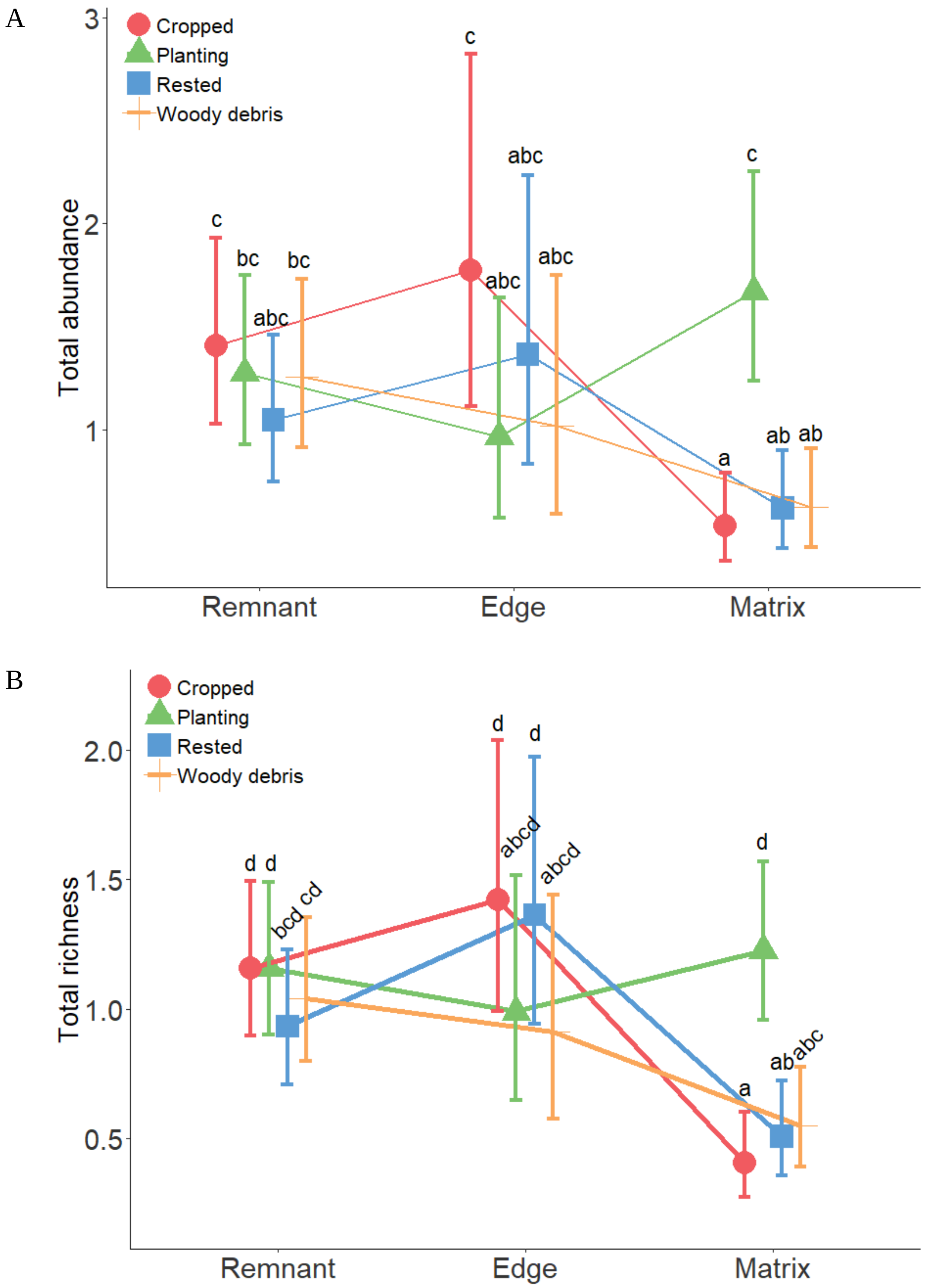
Figure 11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Woody debris
Total richness
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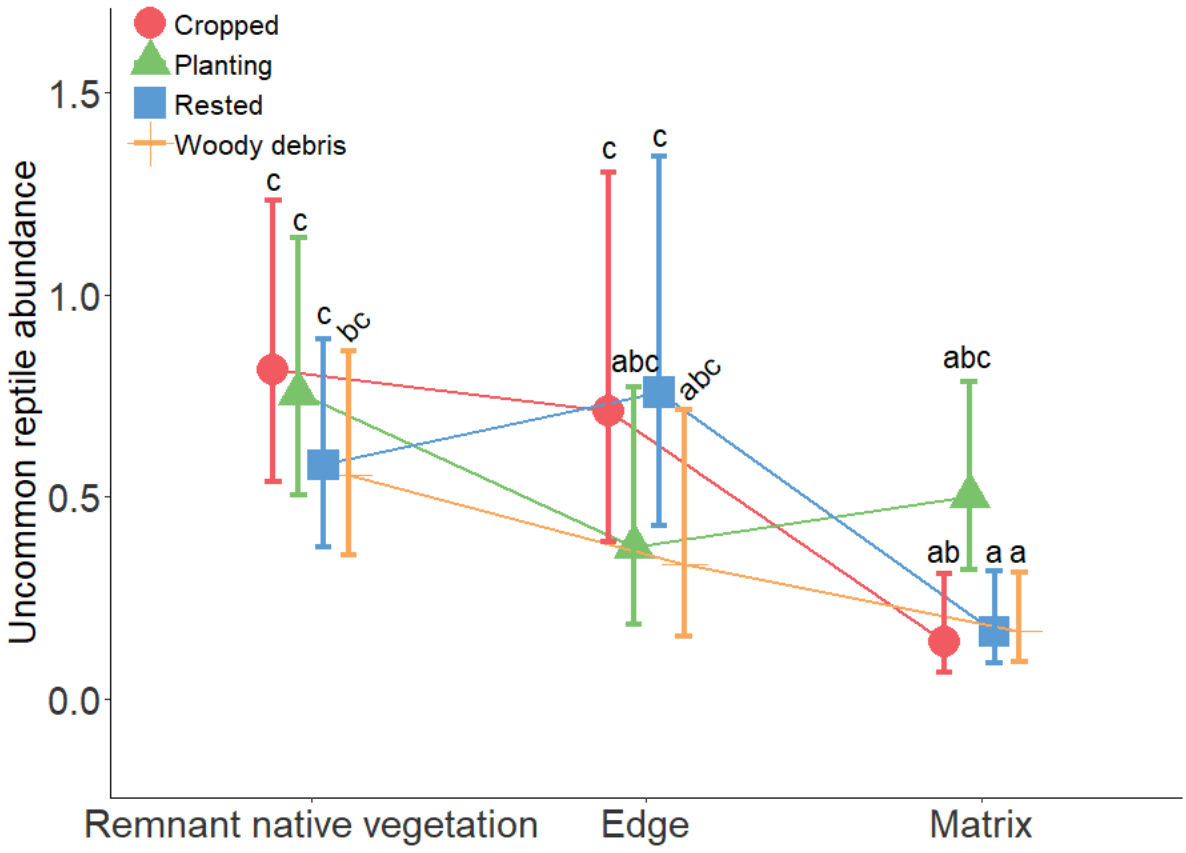
Remnant
Edge
Matrix

Figure 12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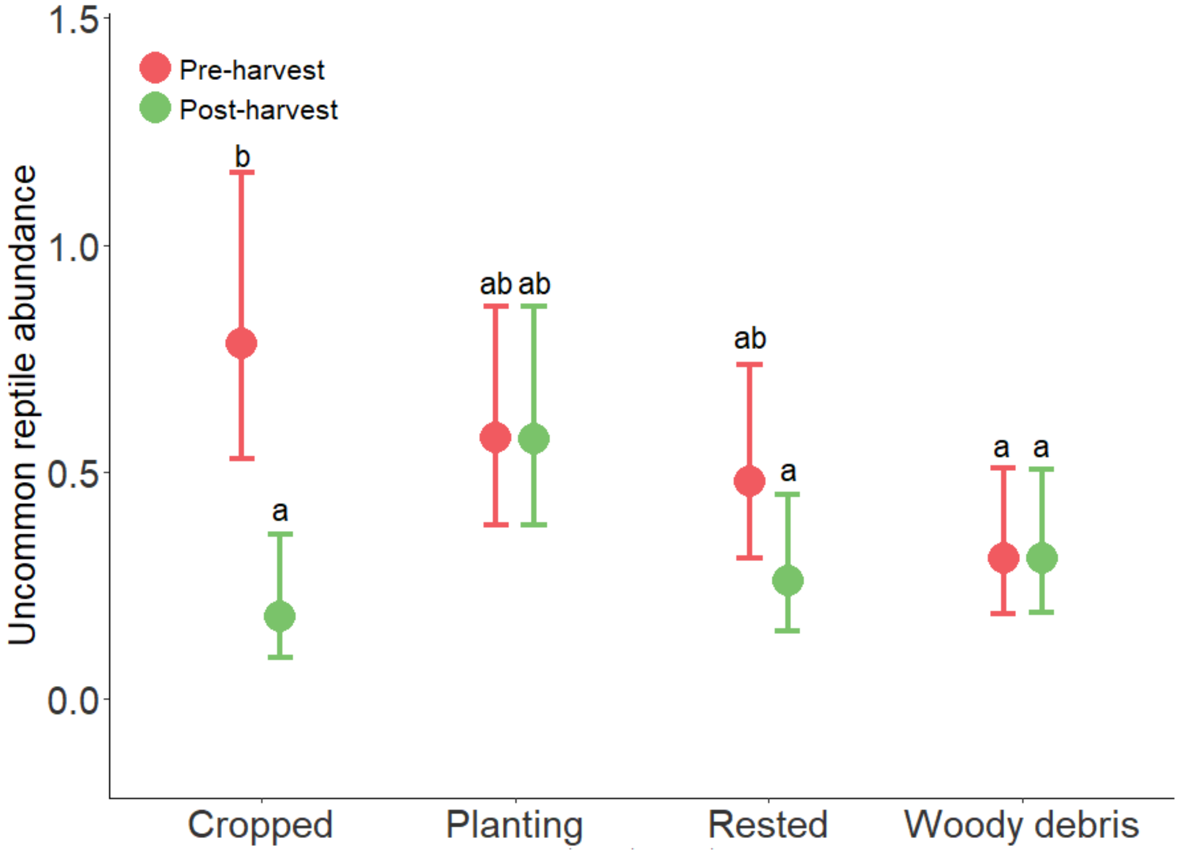
Remnant native vegetation
Edge
Matrix

Figure 13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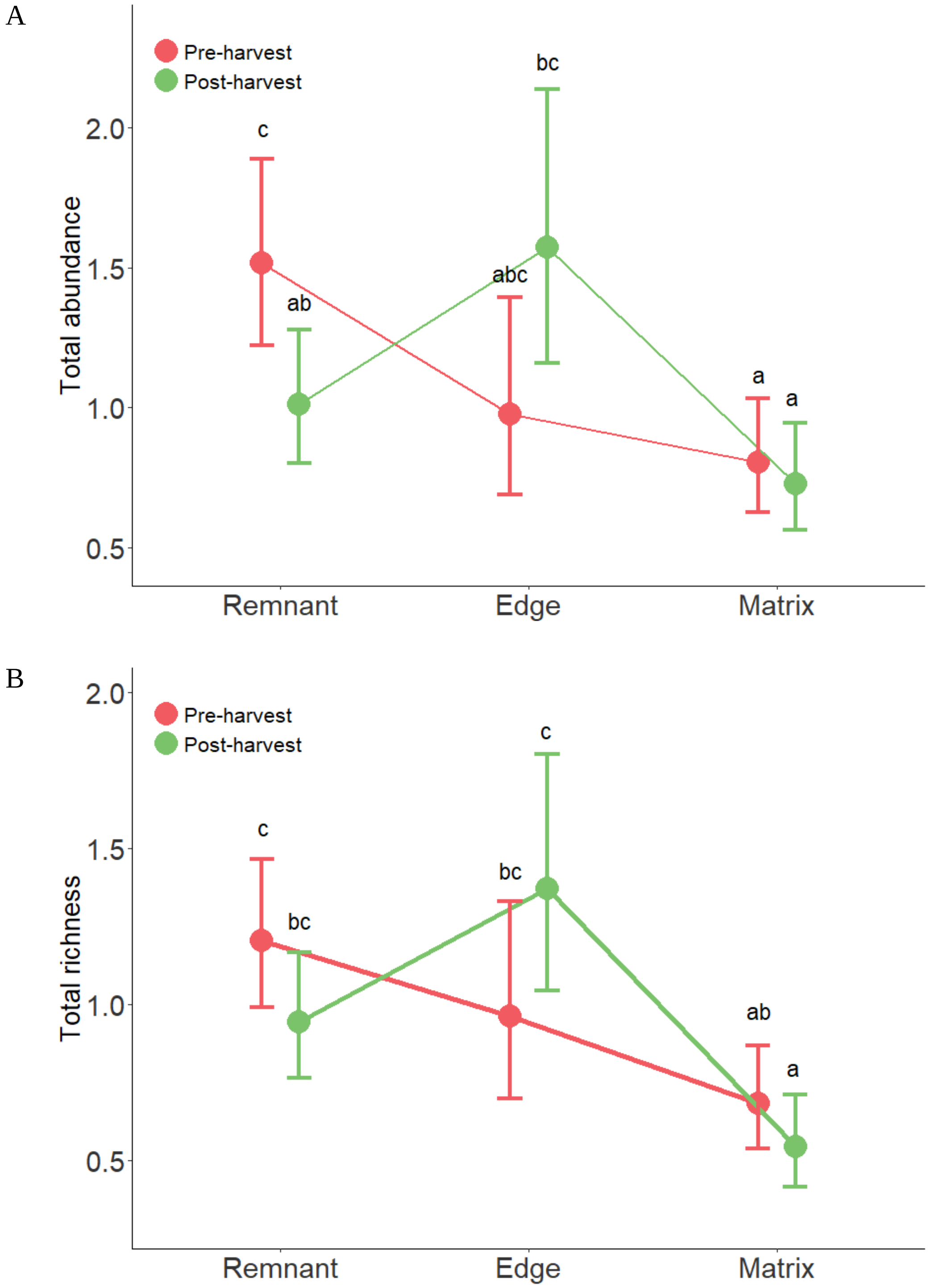
Rested
Woody debris

Figure 14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Total richness
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Figure 15

Supplementary material

Appendix S1:

Post-hoc analysis of significant interactions was calculated using the 'lsmeans' function (Lenth 2016) and the results of this test are shown on all plots.

Table S2 Broad vegetation types (using Vegetation Information System classification (Information 2003, Benson 2006) and land tenure

Location	Vegetation type	Vegetation community	Land tenure
Young			
BD	Woodland	Stringybark Black Cypress Pine Open Forest	Private land
HC1	Woodland	White Box Yellow Box Blakely's Red Gum Woodland	Private land
HC2	Woodland	White Box Yellow Box Blakely's Red Gum Woodland	Private land
Grenfell			
DR	Woodland	Pine Woodland & White Box - White Cypress Pine woodland	Forestry Corporation of New South Wales (Bimbi State Forest)
IE	Woodland	Pine Woodland	Forestry Corporation of New South Wales (Barbingal State Forest)
RR	Woodland	White Box - White Cypress Pine woodland	Private land and New South Wales National Parks and Wildlife Service (Weddin Mountains National Park)
SN	Woodland	White Box - White Cypress Pine woodland	Forestry Corporation of New South Wales (Weddin State Forest)
Ardlethan			
DF	Mallee woodland	Mallee woodlands and shrublands	Private land
GH	Mallee woodland	Mallee woodlands and shrublands	Private land
PC	Woodland	Black Cypress Pine - some mallee	New South Wales Trade & Investment Crown lands
SD	Mallee woodland	Mallee woodlands and shrublands	Private land

Table S2 The total number of reptile species detected across sites,the number of sites occupied by each species (n=11 sites) and the proportion of each species captured within each matrix type. ***(Michael et al. 2015)***

Species	**Guild/niche**	**No. of captures (%)**	**No. of sites captured (%)**	**C*(%)**	**LP*(%)**	**P*(%)**	**WD*(%)**
Morethia boulengeri (Scincidae)	Terrestrial/generalist*	247 (28.92)	11 (100)	8 (3)	**56 (22.67)**	1 (0.40)	16 (6.47)
Menetia greyii (Scincidae)	Terrestrial/generalist*	129 (15.11)	9 (81.82)	5 (3.88)	**27 (20.93)**	14 (10.85)	7 (5.43)
Ctenotus spaldingi (Scincidae)	Crytozonic/generalist*	88 (10.30)	5 (45.45)	13 (14.77)	11 (12.5)	**21 (23.86)**	16 (18.18)
Lerista timida (Scincidae)	Fossorial/generalist*	68 (7.96)	8 (72.73)	**4 (5.88)**	**4 (5.88)**	1 (1.47)	2 (2.94)
Carlia tetradactyla (Scincidae)	Terrestrial/generalist*	59 (6.91)	5 (45.45)	5 (8.47)	**10 (16.95)**	5 (8.47)	6 (10.17)
Demansia psammophis (Elapidae)	Crytozonic/generalist*	41 (4.80)	5 (45.45)	1 (2.44)	**8 (19.5)**	1 (2.44)	-
Gehyra versicolor (Gekkonidae)	Arboreal/generalist*	34 (3.98)	8 (72.73)	-	1 (2.94)	1 (2.94)	-
Cryptoblepharus pannosus (Scincidae)	Semi-arboreal/generalist*	31 (3.63)	8 (72.73)	-	1 (3.22)	-	2 (6.45)

Strophurus intermedius (Gekkonidae)	Arboreal/generalist*	22 (2.58)	4 (36.36)	**2 (9.09)**	1 (4.55)	1 (4.55)	-
Pogona barbata (Agamidae)	Semi-arboreal/generalist*	17 (1.99)	8 (72.73)	**3 (17.65)**	1 (5.88)	1 (5.88)	2 (11.76)
Christinus mamoratus (Gekkonidae)	Arboreal/generalist*	13 (1.52)	2 (18.18)	-	**3 (23.08)**	-	1 (7.69)
Diplodactylus vittatus (Gekkonidae)	Cryptozoic/specialist*	13 (1.52)	4 (36.36)	2 (15.38)	-	1 (7.69)	-
Delma inornata (Pygopodidae)	Terrestrial/generalist*	11 (1.29)	8 (72.73)	-	**4 (36.36)**	1 (9.09)	1 (9.09)
Lerista punctatovittata (Scincidae)	NA	11 (1.29)	3 (27.27)	-	-	-	-
Anilios bituberculatus (Typhlopidae)	Fossorial/specialist*	10 (1.17)	6 (54.55)	-	3 (30)	2 (20)	-
Pseudonaja textilis (Elapidae)	Terrestrial/generalist*	9 (1.05)	1 (9.09)	1 (11.11)	**2 (22.22)**	1 (11.11)	-
Parasuta dwyeri (Elapidae)	Crytozonic/generalist*	8 (0.94)	6 (54.55)	2 (25)	2 (25)	-	-
Egernia striolata (Scincidae)	Saxicolous/generalist*	7 (0.82)	4 (36.36)	-	-	-	-

Underwoodisaurus milii (Gekkonidae)	Cryptozoic/specialist*	5 (0.59)	3 (27.27)	-	-	1 (33.33)	-
Rhynchoedura ornata (Gekkonidae)	NA	4 (0.47)	1 (9.09)	-	-	-	-
Anilios nigrescens(Typhlopidae)	Fossorial/specialist*	4 (0.47)	2 (18.18)	-	-	-	-
Pogona vitticeps (Agamidae)	Semi-arboreal/generalist*	3 (0.35)	2 (18.18)	-	-	-	-
Lampropholis delicata (Scincidae)	Terrestrial/generalist*	3 (0.35)	1 (9.09)	-	-	-	-
Anilios proximus (Typhlopidae)	Fossorial/specialist*	3 (0.35)	2 (18.18)	-	-	-	-
Varanus varius (Varanidae)	Semi-arboreal/generalist*	3 (0.35)	1 (9.09)	-	-	-	-
Diporiphora nobbi (Agamidae)	Semi-arboreal/generalist*	2 (0.23)	1 (9.09)	-	-	-	-
Tiliqua scincoides (Scincidae)	Fossorial/specialist*	2 (0.23)	2 (18.18)	-	-	-	-
Pseudechis australis (Elapidae)	Terrestrial/generalist*	1 (0.12)	1 (9.09)	-	-	-	-

Pseudechis guttatus (Elapidae)	Terrestrial/generalist*	1 (0.12)	1 (9.09)	-	-	-	-
Suta suta (Elapidae)	Under log/ specialist	1 (0.12)	1 (9.09)	-	1	-	-
Vermicella annulata (Elapidae)	Cryptozoic/specialist	1 (0.12)	1 (9.09)	-	-	-	-
Morelia spilota (Pythonidae)	Cryptozoic/specialist	1 (0.12)	1 (9.09)	-	-	-	-
Tiliqua rugosa (Scincidae)	Terrestrial/generalist*	1 (0.12)	1 (9.09)	-	1	-	-
Varanus gouldii (Varanidae)	Semi-arboreal/generalist*	1 (0.12)	1 (9.09)	-	-	-	-

Note: LP = No. caught in linear planting land use type; WD=No. caught in woody debris land use type; C=No. caught in cropping land use type and P=No. caught in cropping land use type; all numbers pooled across harvesting periods

Table S3 ANOVA results for total reptile abundance and species richness and direction

Response	**Model terms**	**Chisq**	**Df**	**P**
Total reptile abundance	treatment	11.92	3	<0.01*
	habitat	18.40	2	<0.01*
	harvesting period	5.51	1	0.02*
	region	12.23	2	<0.01*
	treatment: habitat	31.38	6	<0.01*
	treatment: harvesting period	15.44	3	<0.01*
	habitat: harvesting period	20.15	2	<0.01*
	treatment: habitat:harvesting period	6.11	6	0.41
Total reptile richness	treatment	13.94	3	<0.01*
	habitat	29.93	2	<0.01*
	harvesting period	2.09	1	0.15
	region	20.83	2	<0.01*
	treatment: habitat	30.03	6	<0.01*
	treatment: harvesting period	7.81	3	0.05
	habitat: harvesting period	7.15	2	0.03
	treatment: habitat: harvesting period	3.01	6	0.81
Uncommon reptile abundance	treatment	10.26	3	0.02*
	habitat	43.09	2	<0.01*
	harvesting period	11.77	1	<0.01*
	region	4.16	2	0.12
	treatment: habitat	17.60	6	0.01*
	treatment: harvesting period	18.40	3	<0.01*
	habitat: harvesting period	2.98	2	0.22
	treatment: habitat: harvesting period	4.28	6	0.64

Uncommon reptile richness	treatment	6.18	3	0.10
	habitat	40.55	2	<0.01*
	harvesting period	2.56	1	0.11
	region	5.68	2	0.06
	treatment: habitat	18.78	6	<0.01*
	treatment: harvesting period	12.09	3	0.01*
	habitat: harvesting period	3.79	2	0.15
	treatment: habitat: harvesting period	1.91	6	0.93
Direction (richness)	harvesting period	0.00	1	0.98
	treatment	1.24	3	0.74
	habitat	0.03	2	0.98
	region	1.41	2	0.49
	harvesting period: treatment	4.09	3	0.25
	harvesting period: habitat	1.37	2	0.51
	treatment: habitat	2.89	6	0.82
	harvesting period: treatment: habitat	4.66	6	0.59
Direction (abundance)	harvesting period	0.01	1	0.92
	treatment	2.04	3	0.57
	habitat	0.13	2	0.94
	location	0.09	2	0.96
	harvesting period: treatment	6.94	3	0.07
	harvesting period: habitat	2.00	2	0.37
	treatment: habitat	2.23	6	0.90
	harvesting period: treatment: habitat	3.13	6	0.79

Table S4 Summary of the results for the best model of reptile responses (total abundance, total richness and abundance of uncommon reptiles)

Response	**Model terms**	**Estimate**	**SE**	**z value**	**P**
Total reptile abundance	(Intercept)	0.78	0.30	2.63	0.01*
	treatment (Planting)	-0.43	0.40	-1.08	0.28
	treatment (Rested)	-0.14	0.38	-0.36	0.72
	treatment (Woody debris)	-0.07	0.38	-0.18	0.86
	habitat (Matrix)	-1.56	0.37	-4.18	<0.01*
	habitat (Remnant)	-0.63	0.32	-1.96	0.05
	harvesting period (Pre-harvest)	-0.08	0.29	-0.28	0.78
	region (West)	0.05	0.20	0.22	0.82
	region (Young)	-0.69	0.23	-3.02	<0.01*
	treatment (Planting): habitat (Matrix)	1.85	0.49	3.73	<0.01*
	treatment (Rested): habitat (Matrix)	0.47	0.51	0.92	0.36
	treatment (Woody debris): habitat (Matrix)	0.83	0.50	1.66	0.10
	treatment (Planting): habitat (Remnant)	0.68	0.47	1.45	0.15
	treatment (Rested): habitat (Remnant)	-0.10	0.47	-0.21	0.83
	treatment (Woody debris): habitat (Remnant)	0.16	0.45	0.36	0.72
	treatment (Planting): harvesting period (Pre-harvest)	-0.36	0.47	-0.76	0.45
	treatment (Rested): harvesting period (Pre-harvest)	-0.24	0.43	-0.56	0.57
	treatment (Woody debris): harvesting.period (Pre-harvest)	-0.98	0.49	-2.00	0.05*
	habitat (Matrix): harvesting.period (Pre-harvest)	0.71	0.41	1.72	0.09
	habitat (Remnant): harvesting.period (Pre-harvest)	0.80	0.34	2.33	0.02*
	treatment (Planting): habitat (Matrix): harvesting period (Pre-harvest)	-0.19	0.58	-0.33	0.74
	treatment (Rested): habitat (Matrix): harvesting period (Pre-harvest)	-0.13	0.59	-0.22	0.83

	treatment (Woody debris): habitat (Matrix): harvesting period (Pre-harvest)	-0.23	0.64	-0.37	0.71
	treatment (Planting): habitat (Remnant): harvesting.period (Pre-harvest)	-0.33	0.54	-0.62	0.54
	treatment (Rested): habitat (Remnant): harvesting period (Pre-harvest)	0.12	0.51	0.24	0.81
	treatment (Woody debris): habitat (Remnant):harvesting period (Pre-harvest)	0.56	0.56	1.01	0.31
Total reptile richness	(Intercept)	0.43	0.28	1.57	0.12
	treatment (Planting)	-0.13	0.37	-0.37	0.72
	treatment (Rested)	0.17	0.34	0.50	0.62
	treatment (Woody debris)	0.06	0.35	0.16	0.87
	habitat (Matrix)	-1.57	0.40	-3.90	<0.01*
	habitat (Remnant)	-0.37	0.30	-1.23	0.22
	harvesting.period (Pre-harvest)	0.12	0.34	0.34	0.73
	region (West)	0.16	0.17	0.93	0.35
	region (Young)	-0.73	0.20	-3.63	<0.01*
	treatment (Planting): habitat (Matrix)	1.57	0.51	3.10	<0.01*
	treatment (Rested): habitat (Matrix)	0.23	0.53	0.44	0.66
	treatment (Woody debris): habitat (Matrix)	0.77	0.51	1.51	0.13
	treatment (Planting): habitat (Remnant)	0.37	0.43	0.87	0.39
	treatment (Rested): habitat (Remnant)	-0.34	0.42	-0.79	0.43
	treatment (Woody debris): habitat (Remnant)	-0.03	0.42	-0.07	0.94
	treatment (Planting): harvesting period (Pre-harvest)	-0.45	0.54	-0.85	0.40
	treatment (Rested): harvesting.period (Pre-harvest)	-0.42	0.49	-0.86	0.39
	treatment (Woody debris): harvesting.period (Pre-harvest)	-1.00	0.56	-1.78	0.08
	habitat (Matrix): harvesting.period (Pre-harvest)	0.62	0.51	1.22	0.22
	habitat (Remnant): harvesting.period (Pre-harvest)	0.34	0.41	0.83	0.41

	treatment (Planting): habitat (Matrix):harvesting.period (Pre-harvest)	-0.20	0.69	-0.28	0.78
	treatment (Rested): habitat (Matrix):harvesting.period (Pre-harvest)	0.06	0.71	0.09	0.93
	treatment (Woody debris): habitat (Matrix):harvesting.period (Pre-harvest)	-0.04	0.75	-0.06	0.96
	treatment (Planting): habitat (Remnant):harvesting.period (Pre-harvest)	-0.02	0.62	-0.04	0.97
	treatment (Rested): habitat (Remnant):harvesting.period (Pre-harvest)	0.32	0.59	0.55	0.58
	treatment (Woody debris): habitat (Remnant):harvesting.period (Pre-harvest)	0.74	0.65	1.13	0.26
Uncommon reptile abundance	(Intercept)	-1.05	0.48	-2.19	0.03*
	treatment (Planting)	-0.08	0.61	-0.14	0.89
	treatment (Rested)	0.46	0.55	0.84	0.40
	treatment (Woody debris)	0.12	0.58	0.20	0.84
	habitat (Matrix)	-2.23	0.81	-2.77	0.01*
	habitat (Remnant native vegetation)	0.11	0.47	0.24	0.81
	harvesting.period (Pre-harvest)	0.92	0.47	1.97	0.05*
	region (West)	0.63	0.33	1.92	0.06
	region (Young)	0.11	0.36	0.29	0.77
	treatment (Planting):habitat (Matrix)	2.37	0.94	2.53	0.01*
	treatment (Rested):habitat (Matrix)	0.22	1.00	0.22	0.82
	treatment (Woody debris):habitat (Matrix)	1.14	0.97	1.17	0.24
	treatment (Planting):habitat (Remnant native vegetation)	0.50	0.66	0.76	0.45
	treatment (Rested):habitat (Remnant native vegetation)	-0.47	0.62	-0.76	0.45
	treatment (Woody debris):habitat (Remnant native vegetation)	-0.16	0.66	-0.25	0.81
	treatment (Planting):harvesting.period (Pre-harvest)	-1.11	0.75	-1.48	0.14
	treatment (Rested):harvesting.period (Pre-harvest)	-0.80	0.63	-1.27	0.21

	treatment (Woody debris):harvesting.period (Pre-harvest)	-1.76	0.81	-2.17	0.03*
	habitat (Matrix):harvesting.period (Pre-harvest)	1.22	0.86	1.42	0.16
	habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.04	0.53	0.07	0.94
	treatment (Planting):habitat (Matrix):harvesting.period (Pre-harvest)	-0.93	1.08	-0.86	0.39
	treatment (Rested):habitat (Matrix):harvesting.period (Pre-harvest)	-0.25	1.11	-0.22	0.83
	treatment (Woody debris):habitat (Matrix):harvesting.period (Pre-harvest)	-0.38	1.20	-0.32	0.75
	treatment (Planting):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.13	0.83	0.15	0.88
	treatment (Rested):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.13	0.73	0.18	0.86
	treatment (Woody debris):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	1.08	0.90	1.20	0.23
Uncommon reptile richness	(Intercept)	-0.87	0.46	-1.90	0.06
	treatment (Planting)	0.15	0.55	0.28	0.78
	treatment (Rested)	0.61	0.51	1.20	0.23
	treatment (Woody debris)	0.15	0.55	0.28	0.78
	habitat (Matrix)	-2.20	0.81	-2.71	0.01*
	habitat (Remnant native vegetation)	0.00	0.47	0.00	1.00
	harvesting.period (Pre-harvest)	0.51	0.51	1.00	0.32
	region (West)	0.53	0.30	1.78	0.07
	region (Young)	-0.19	0.33	-0.57	0.57
	treatment (Planting):habitat (Matrix)	1.99	0.93	2.14	0.03*
	treatment (Rested):habitat (Matrix)	0.09	1.00	0.09	0.93
	treatment (Woody debris):habitat (Matrix)	0.95	0.98	0.96	0.34
	treatment (Planting):habitat (Remnant native vegetation)	0.21	0.63	0.34	0.73

	treatment (Rested):habitat (Remnant native vegetation)	-0.55	0.60	-0.92	0.36
	treatment (Woody debris):habitat (Remnant native vegetation)	-0.10	0.64	-0.16	0.88
	treatment (Planting):harvesting.period (Pre-harvest)	-1.07	0.81	-1.33	0.19
	treatment (Rested):harvesting.period (Pre-harvest)	-0.61	0.67	-0.90	0.37
	treatment (Woody debris):harvesting.period (Pre-harvest)	-1.36	0.86	-1.58	0.11
	habitat (Matrix):harvesting.period (Pre-harvest)	1.10	0.93	1.19	0.24
	habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.21	0.59	0.36	0.72
	treatment (Planting):habitat (Matrix):harvesting.period (Pre-harvest)	-0.60	1.17	-0.51	0.61
	treatment (Rested):habitat (Matrix):harvesting.period (Pre-harvest)	-0.09	1.18	-0.07	0.94
	treatment (Woody debris):habitat (Matrix):harvesting.period (Pre-harvest)	-0.25	1.29	-0.20	0.84
	treatment (Planting):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.12	0.91	0.13	0.90
	treatment (Rested):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.16	0.79	0.21	0.84
	treatment(Woody debris):habitat (Remnant native vegetation):harvesting.period (Pre-harvest)	0.80	0.96	0.84	0.40

Table S5 Summary of recaptured reptiles within each treatment and habitat type. An arrow (→) indicates if an individual shifted between different treatments or habitat types. The total straight-line distance moved by each individual and the number of days between first and last captures dates is also summarised. Distance travelled by recaptured individuals was examined using straight line (euclidean) distances between trap stations in ESRI Arc GIS (ESRI 2012)

Species	**Treatment**	**Habitat type**	**Total distance moved (m)**	**Time between first and last capture (days)**
Pre-harvest				
Ctenotus robustus	Cropped	Matrix	0	3
Carlia tetradactyla	Cropped	Remnant	0	4.5±2.6
Morethia boulengeri	Cropped	Remnant→Matrix→Edge	60	6
Morethia boulengeri	Planting	Matrix	0	6.93±4
Ctenotus robustus	Planting	Remnant	0	2
Egernia striolata	Pasture	Remnant	180	15
Carlia tetradactyla	Pasture→Planting	Matrix	700	3
Morethia boulengeri	Pasture→Woody debris	Remnant→Matrix	287	4
Morethia boulengeri	Woody debris	Remnant	20	3
Post-harvest				
Ctenotus robustus	Cropped	Remnant	0	5
Morethia boulengeri	Planting	Edge	0	6

Species	**Treatment**	**Habitat type**	**Total distance moved (m)**	**Time between first and last capture (days)**
Ctenotus robustus	Planting	Matrix	125	35
Morethia boulengeri	Planting	Matrix	0	14
Menetia greyii	Planting→Cropped	Matrix→Edge	250	3
Gehyra variegata	Pasture	Edge	0	31
Ctenotus robustus	Pasture	Matrix	0	2
Morethia boulengeri	Woody debris	Edge	0	15±1
Ctenotus robustus	Woody debris	Matrix	0	2
Ctenotus robustus	Woody debris	Remnant	0	2
Ctenotus robustus	Woody debris→Cropped	Matrix	294	2
Between harvesting periods				
Carlia tetradactyla	Cropped	Remnant	0	64
Carlia tetradactyla	Cropped→Pasture→Cropped	Remnant→Matrix→Remnant	798	31
Morethia boulengeri	Cropped→Woody	Matrix→Remnant	286	49
Morethia boulengeri	Planting	Remnant→Matrix	150	76
Morethia boulengeri	Woody debris	Remnant→Matrix	220	133

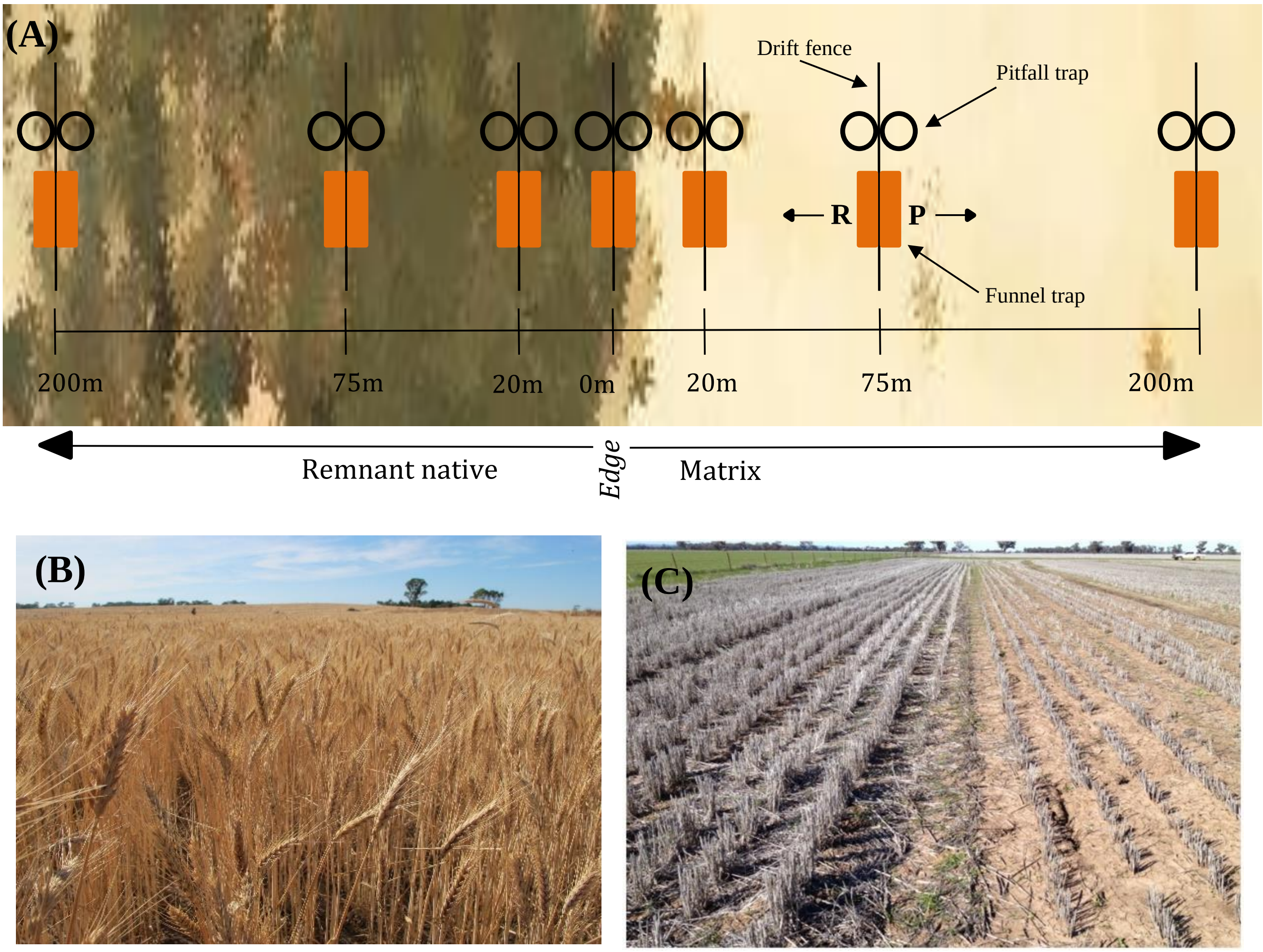

Figure S1 (A) Transect layout indicating trap arrays and the direction of travel for each captured individual (i.e. whether caught on the paddock ("P") side while moving in the direction of the remnant, or the remnant patch ("R") side while moving in the direction of the matrix) (B) Representative photo of a crop paddock prior to harvesting (C) Representative photo of a crop paddock after harvesting.

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CHAPTER THREE:

AMPHIBIANS IN AGRICULTURAL LANDSCAPES: THE HABITAT VALUE OF CROP AREAS, LINEAR PLANTINGS AND REMNANT WOODLAND PATCHES

Amphibians are the most threatened vertebrate group globally endangered by habitat loss and fragmentation (Cushman 2006, Arntzen et al. 2017, Ferrante et al. 2017). For species that have some capacity to persist in human-modified landscapes, their occurrence is often influenced by different forms of land use and the presence of remnant native vegetation. However, terrestrial habitat use by amphibians in agricultural landscapes remains poorly studied (Cushman 2006, Mendelson et al. 2006, Thompson et al. 2017). I examined the effects of different agricultural land uses, remnant vegetation patches and edges over time on frog richness, abundance and body condition and movement.

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(**https://doi.org/10.1111/acv.12437**).

Abstract

Mitigating the negative impacts of agriculture on amphibians requires knowledge of how different land uses affect species distribution and community composition. In the case of frogs, there is currently insufficient information on their use of terrestrial habitats in cropping landscapes to inform conservation planning. We examined how four different farmland types (linear plantings, cereal crops, grazing paddocks, and woody mulch) and crop harvesting influenced amphibian abundance, richness, body condition and movement. We found the abundance of frogs was significantly higher in linear plantings compared to grazing paddocks and adjacent patches of remnant woodland vegetation. However, species richness and abundance of three individual species did not vary significantly between farmland types. For the most common frog *Uperoleia laeveigata,* body condition was higher at the edges of the woody debris treatment (coupled with higher abundance) and lower in farmland with debris and linear plantings. The body condition of *Limnodynastes tasmaniensis* and *Limnodynastes interioris* was not influenced by farmland type. Frog abundance and condition was largely unaffected by crop harvesting. However, frogs were less common after harvesting at the edges of farmland and within remnant patches. Movement patterns did not suggest mass movement out of crops after harvest, where almost half of all individuals recaptured remained within the farmland. These results suggest that some generalist frog species may have an affinity for habitats within agricultural paddocks, particularly when key habitat features like plantings are present. However, we found overall frog richness was low and did not differ between remnant patches, edges and farmland which may be an indication of habitat degradation within terrestrial habitats across the landscape. Although protection of remnant native vegetation is important, conservation strategies for the protection of amphibians will be ineffective if they do not consider the variety of land uses and the relationships of different species and their microhabitats within and outside of patches.

Keywords: *body condition index, restoration, conservation, matrix, habitat quality, land-use*

Introduction

Demand for agricultural products is driving intensification and expansion of agriculture, reducing and fragmenting habitats and contributing to global biodiversity decline (Tilman et al. 2011, Thompson et al. 2017). In some cases, agricultural landscapes can support moderate to high levels of biodiversity (Mendenhall et al. 2014, Thompson et al. 2017), suggesting there are opportunities for biodiversity conservation in agroecosystems (Benton et al. 2003, Hazell et al. 2004, Donald and Evans 2006, Pita et al. 2009). Despite well documented sensitivities of many species to modified landscapes (Brotons et al. 2005, Knox et al. 2012, Gastón et al. 2016), the circumstances under which mixed farmland can provide habitat is context and species-specific (Eycott et al. 2010, Prevedello and Vieira 2010, Driscoll et al. 2013b).

In fragmented agricultural landscapes, population viability depends on functional connectivity between suitable habitat patches, with successful dispersal depending on the condition and quality of the intervening land cover types (Driscoll et al. 2013b, Youngquist et al. 2017), ecophysiological traits of a species (preferred body temperature, skin permeability and susceptibility to evaporative water loss; Cruz-Piedrahita et al. 2018, Yuan et al. 2018) and species-specific behaviour (Richter et al. 2001, Blaum and Wichmann 2007). However, quantifying species preferences for particular land cover types remains a fundamental challenge in modified landscapes as some species may disperse through and utilise habitat types that are different to preferred habitat (e.g. remnant vegetation; Driscoll et al. 2013b, Cline and Hunter 2014, Cooney et al. 2015). Further, human-modified land cover can change over time (e.g. simplification of cover by harvesting crops) reducing species dispersal between habitat patches (Kay et al. 2016b), mortality risk (Anderson and Burgin 2008, Ewers and Didham 2008) and the likelihood of emigrating from patches (Prevedello and Vieira 2010, Driscoll et al. 2013b).

Amphibians are one of the most at-risk groups of taxa in agricultural areas (Cushman 2006, Arntzen et al. 2017) due to their complex life-history and narrow habitat tolerances, which can make them susceptible to rapid changes in habitat and microclimate (Cushman 2006, Barrett and Guyer 2008, Cogger 2014). Consequently, many amphibians are threatened with extinction worldwide, more so, than any other vertebrata (Wake and Vredenburg 2008, Thompson et al. 2017). Despite the rapid decline of many species of amphibians (Mendelson et al. 2006), and the significant vulnerability of frogs to habitat modification, data on amphibian responses to land management and revegetation is lacking for many regions and species, particularly in Australia (Hazell 2003, Nowakowski et al. 2017a, Nowakowski et al. 2017b, Thompson et al. 2017).

Frog use of, and movement within, agricultural landscapes appears to be influenced by changes within the terrestrial environment (Vos and Stumpel 1996, Lamoureux and Madison 1999). While breeding habitat availability can limit frog populations (e.g. breeding habitat; Cushman 2006), suitable terrestrial habitat is also required for population persistence, and can influence movement between water sources, juvenile dispersal, foraging, over-wintering and aestivation (Feder and Burggren 1992, Hazell et al. 2001, Miaud and Sanuy 2005, Cushman 2006, Mac Nally et al. 2009)

Thus, we should expect changes within the farmland matrix (e.g. simplification of vegetation cover) to regulate amphibian movements and potentially reduce connectivity, limit dispersal, and reduce local and regional population persistence (Cushman 2006, Vos et al. 2007, Mac Nally et al. 2009).

Here, we examine frog responses to three farmland management elements that provide contrasting resources and conditions likely to influence frog body condition, abundance, richness and movement patterns in cropping landscapes. Our research questions were: (1) *Do different farmland types influence amphibian abundance, richness, body condition and movement patterns, in contrast to remnant patches and the edges between farmland and remnant patches*? and, *(2) Does crop harvesting reduce amphibian abundance, richness, body condition and movement between farmland types*?

Habitat use and the effects of landscape change on frogs in agricultural areas have received little attention in less studied regions such as Australia. Knowledge of how frogs use such mixed farming landscapes is limited to frog habitat use in relation to farm dams or constructed aquatic habitat (Hazell et al. 2001, Hazell et al. 2004). In particular, there is little research examining the use of differing modified terrestrial habitats for Australian frogs and how this has been affected by agricultural land use. This information is required to guide appropriate conservation actions based on quantified frog responses to land use change (Arntzen et al. 2017, Thompson et al. 2017).

Materials and methods

Study area

Our study area was located in central New South Wales, Australia between the following towns: Young: 34° 26' 18.723" S; 148° 10' 54.975" E, Grenfell: 33° 55' 58.249" S; 147° 53' 48.729" E, Ardlethan: 34° 10' 34.776" S; 146° 50' 7.522" E; Fig. 16). Clearing for agriculture has resulted in extensive loss of native eucalypt woodland vegetation and replacement with intensive cereal cropping (wheat, canola, lupin and barley) and livestock grazing (sheep *Ovis aries* and cattle *Bos taurus*. The dominant native vegetation types within remnant patches of woodland in the western part of our study area include mallee woodland and shrubland, with some white cypress pine (*Callitris glaucophylla*). The eastern part of our study area is dominated by patches of box gum and white cypress pine woodland, including the threatened white box (*Eucalyptus albens*), yellow box (*E. melliodora*), blakely's red gum (*E. blakelyi*) woodland and derived grasslands.

Study design

We selected ten study sites, each incorporating a single block design comprising a remnant patch of native vegetation surrounded by four contrasting farmland types (Fig. 16):

1) *Cropping* paddock: Wheat crops and some barley. All paddocks were subject to harvesting.
2) *Rested* paddock: Open paddocks with a mix of native and exotic grasses. Mostly cleared of canopy and mid-story vegetation with occasional, scattered paddock trees (Fig. 16). All paddocks were grazed by livestock either sheep or cattle.
3) *Linear planting*: Linear strip of vegetation between 15 - 30 m wide comprising primarily *Acacia* mid-storey with occasional eucalypts and a mix of exotic and native grassy groundcover. All plantings were subject to occasional grazing by sheep.
4) *Woody debris*: An experimental treatment where a linear strip of native woody mulch was patchily applied to a cereal cropping paddock at each site immediately after harvesting. Woody mulch comprised processed blue mallee (*E. polybractea*) (hereafter "woody debris"). We patchily applied between 20 and 25 tonnes of woody debris (per site) to a harvested crop paddock to examine if we could increase ground layer complexity and temporarily increase frog movement in crop paddocks (Fig. 16). Mulch material was used due to the practical limitations of larger material (e.g. logs and branches) obstructing cropping machinery.

Sampling amphibians

At each study site, seven trap arrays were spaced along 400 m transects centred on, and running perpendicularly to the edge of the remnant patch, with arrays placed at the edge (0 m) and 20 m, 75 m and 200 m in both the remnant patch and the adjacent farmland type and woody mulch treatment (Fig. 16C). Each array consisted of four traps, with two pitfall traps and two funnel traps on both sides of a 15 m long and 0.35 m high drift fence (five metre spacing between traps).

Traps were opened for six days and five nights for two periods during spring (‘pre-harvest’; before the harvesting of crops) and two periods during summer (after the harvesting of crops; Fig. 16D). Pre-harvest surveys were completed between late September and early December 2014 and coincided with mid and high growth phases of crops. Post-harvest surveys were completed between January and March 2015. A total of 1,120 trap days was completed across all sites per survey, equating to 672 trap days per site across the entire survey period.

All animals were individually marked using Visible Implant Elastomer (Smith et al. 2012) to examine movement patterns, and then measured and released ten metres from the trap array on the opposite side of where the individual was captured to reduce barriers the drift fence may represent to normal animal movement.

Analysis

We examined the effects of farmland type, habitat type and harvesting on the relative abundance and richness of frogs by fitting generalized linear mixed models (GLMM) with a Poisson distribution and a log link (McCullagh 1984, Nicholls 1989). Our response variables were total amphibian species abundance and richness. The main effects and the two and three-way interactions between treatment (four farmland types; crop, planting, pasture, and woody debris), habitat type (remnant, edge, and paddock) and harvesting period (before and after harvesting) were fitted as fixed effects. Given the spatial clustering of the sites, wide distances between clusters, and to account for broad climatic differences (e.g. climate and geographic variation), three regions (“region”) were fitted as an additive fixed effect in all models. Site number, a unique transect number, and a unique trap number were fitted as random effects to account for site variation and repeated sampling of traps.

To investigate if body condition was influenced by differences in habitat quality, we calculated a residual body condition index (hereafter BCI) following the methodology of Băncilă et al. (2010) and Scheele et al. (2014). Body weight (grams) of each species was regressed against snout-urostyle length (SUL), and where this relationship was curvilinear both were $\log_{10}$ transformed. We plotted the residuals to verify the data were normally distributed, and inspected the residual vs. fitted plots to verify the residuals were randomly distributed compared to the fitted values. We applied linear modelling after outliers were removed from the dataset (i.e. cases where body weight and SUL where clearly not credible and likely explained by a sick individual or measurement error) to individual log-scaled BCI as the response variable and the interaction between treatment, habitat and harvesting as explanatory variables. Remnant patch size (mean 5240.89 ± SE 3003.3 ha) and rainfall was found previously not to have an effect on frog species richness and abundance and thus was not considered further in this study (N. A. Hansen unpublished).

For all analyses, we calculated *P*-values using the ‘Anova’ function in the ‘car’ package to reveal significant components and interactions of the model (Bates et al. 2013). Post-hoc analysis of significant interactions was calculated using the ‘lsmeans’ function (Lenth 2016) and the results of this test are shown on all plots. All analyses were completed using R 3.3.2 (R team 2016) .

Results

We captured 410 individuals from seven species, of which six were from the Myobatrachidae family, and one species from Hylidae family (Table 3) (Fig. S1). Three species accounted for 89% of all observations: smooth toadlet, *Uperoleia laevigata*; spotted grass frog, *Limnodynastes tasmaniensis,* and giant banjo frog, *L. interioris* (Table 3). Species richness per site ranged from one to five species (mean total frog richness = 4 ± 0.4SE), and total capture rate ranged from four to 123 (mean total frogs = 41 ± 13.9SE) individuals per site.

Total frog abundance and richness was higher in the eastern region of Young compared to the other regions ($P < 0.03$) (Table S1; Fig. S2). Three frog species were captured in sufficient numbers for body condition analysis: *L. tasmaniensis, L. interioris* and *U. laevigata,* (see Table 3).

Frog responses to farmland type and crop harvesting

We found frogs within farmland were more abundant in linear plantings compared to adjacent remnant patches, rested paddocks and the edges of rested paddocks ($P < 0.01$) (Tables S1 and S3; Fig. 17A), although most species were recorded infrequently across all habitat types (Table 3 and Fig. S1). We found no association between species richness and farmland type ($P = 0.42$) (Table S1). While we found frogs were generally less common after harvesting ($P < 0.02$) (Table S1), there was no interaction between harvesting and treatment, or habitat ($P > 0.31$) (Table S1).

Of the three most common amphibian species, *U. laevigata* was not significantly associated with one farmland type over another, but was more common in linear plantings compared to adjacent remnant patches ($P < 0.01$) (Table S1 and Fig. 17B). Greater numbers of *U. laevigata,* in higher body condition, also were found at the edge of woody debris transects compared to remnant patches or within the debris and plantings (P<0.01) (Tables S2 and S4; Fig. 17B and 18B). *Uperoleia laevigata* had higher values for body condition after harvest of crops, along crop transects (P < 0.01) (Table S2 and Figure 18A) and a tendency to be in poorer condition in remnant patches before harvesting (Fig.19A).

For *L. tasmaniensis*, there was a three-way interaction of body condition between treatment, habitat and harvesting but only for one pairwise comparison, where body condition was variable across remnant patches particularly prior to harvesting (Fig. 19B) with no clear ecological interpretation.

Movement responses to farmland type and crop harvesting

Of the seven species captured (Table 3), two species were recaptured (Table S5). Twenty-five individuals from the species: *U. laevigata* (n = 19) and *L. tasmaniensis* (n = 6) were recaptured. For all individuals recaptured, *U. laevigata* moved on average 149.5 m (± 37.8SE), while *L. tasmanensis* moved on average 39.2 m (± 29.6SE). Of these recaptures, 48% (n = 12; *L. tasmaniensis* (3), *U. laevigata* (9)) remained in the farmland type in which they were first captured, 16% (n=4; all *U. laevigata*) moved from one farmland type to another, 20% (n = 5; all *U. laviegata*) moved from the farmland into the patch and 16% (n = 4; all *U. laevigata*) moved from the remnant patch into the farmland (Table S5).

Discussion

Few empirical studies have examined the relative importance of differing land uses and adjacent remnant patches for frogs in agricultural landscapes. Contrary to results from previous comparable studies (Rothermel and Semlitsch 2002, Bowen et al. 2007, Collins and Fahrig 2017), we found that while frog abundance was positively associated with linear plantings, species were generally ubiquitous throughout farmland, edge habitats and remnant patches. There also was no evidence of a significant effect of habitat or farmland type on overall frog species richness. These results reflect the dominance of the overall amphibian assemblage by a few common species, notably *L. tasmaniensis*, *L. interioris* and *U. laevigata* (Table 3), all of which are widespread habitat generalists or able to persist in disturbed environments (Cogger 2014, Ocock and Wassens in press).

By examining both remnant patches and farmland, our results suggest that highly modified agricultural paddocks probably provide habitat for generalist frog species and that some frogs can move through a range of different farmland types. The common frog species, *U. laevigata* also showed a range of responses, including higher abundance in linear plantings. Our results indicate that it may be simplistic to assume highly modified farmland types are complete barriers to dispersal for frogs (Arntzen et al. 2017) with some species using a range of habitats to persist in agricultural landscapes.

Impacts of farmland type and crop harvesting on frogs

Overall, we found most frogs exhibited limited response to farmland type and crop harvesting. This was an unexpected result given the high contrast of farmland compared to native vegetation and lack of extensive cover (Hazell et al. 2001, Urbina-Cardona et al. 2006), but likely because many of the frog species were generalist, disturbance-associated species and able to persist in a variety of habitats (Hazell et al. 2004, Cogger 2014). Agricultural practices create a dynamic environment which favour amphibian assemblages with a wider range of environmental tolerances, than specialist species with narrower habitat tolerances (Rittenhouse and Semlitsch 2006, Semlitsch et al. 2009, Youngquist and Boone 2014), which could result in reduced sensitivity to differing habitats. Moreover, similar patterns have been recorded of the spatial distribution of habitat generalist frog species in anthropogenically modified habitats overseas (D’Amore et al. 2010, Youngquist and Boone 2014, Nowakowski et al. 2018), however examples within Australia are scarce.

We found that overall frog abundance was significantly greater in linear plantings, relative to rested-pasture paddocks. Overall frog abundance (all species), and the abundance of at least one species, *U. laevigata,* also was higher in plantings compared to remnant patches. Globally, linear plantings have been shown to positively benefit other groups of native biota including reptiles (Michael et al. 2011, Jellinek et al. 2014b, Mendenhall et al. 2014, Pulsford et al. 2017, Thompson et al. 2017), birds (Lindenmayer et al. 2010, Lindenmayer et al. 2016) and small mammals (Bennett 1990, Šálek et al. 2009). Woodland cover is considered to provide important habitat for amphibians in modified environments (Laan and Verboom 1990, Hazell et al. 2004). The permanent structures and microhabitat within linear plantings probably act as important habitats for foraging (Hecnar and M'Closkey 1996, Hazell et al. 2001), overwintering (Lamoureux and Madison 1999) and refugia during drier conditions. Plantings may be providing useful shelter for non-burrowing species, such as *L. tasmaniensis* and *Uperoleia* spp., and may even facilitate their persistence in adjacent cropping areas.

Pastures have been considered as highly quality habitat for some amphibians in production landscapes because of the presence of artificial waterbodies (e.g. dams) which support reproduction and movement (Hazell et al. 2004, Mendenhall et al. 2014). However, these habitats had the lowest frog abundance, similar to the findings of Urbina-Cardona et al. (2006), and suggest pastures are not ideal habitat for the maintenance of amphibians in mixed cropping areas.

Previous studies of small-bodied amphibian species, similar to *U. laevigata* and which have terrestrial development and affinities for water, have found similar woodland and forest affiliations (Becker et al. 2007, Dixo and Metzger 2010, Mendenhall et al. 2014). Desiccation risk from high temperatures and the low canopy cover typical in cleared agricultural landscapes, may be a biological filter for these species. Larger bodies species like, *L. tasmaniensis, L. interioris,* may have a greater ability to reduce their desiccation rate and can therefore frequent multiple modified habitats. Further work is required to understand what specific characteristics pertain to a survival advantage for individuals persisting in human modified landscapes.

Contrary to our expectations (Davis et al. 2010, Manning et al. 2013), the application of fine woody mulch did not result in more frogs within paddocks. Low capture rates within woody mulch may be due to the short time frame between application of mulch and field surveys, or the high mobility of the frogs across the farmland reducing capture rate. Previous studies have found the length of time that debris is in place, and the size and shape of the debris, can influence amphibian responses to debris application (Ober and Minogue 2007, Rittenhouse 2007, LeGros et al. 2014). We found higher body condition of *U. laevigata* at the edges of the woody debris treatment in contrast to remnant patches or within the mulch but this cannot be interpreted beyond highlighting the potential importance of preferred microhabitat which may encourage frogs into farmland (Hazell et al. 2001, Manning et al. 2013, Cogger 2014). Tracking experiments (e.g. radio-tracking) would be required to determine when areas of mulch are utilised, identify any important microhabitat that it may provide, and to determine any threats frogs may be exposed to in this edge environment and within mulch (e.g. predation).

We expected that the presence of crops should provide an influx of invertebrate prey resources for frogs, which should result in higher abundance and richness in farmlands with crops (Collins and Fahrig 2017), and the converse response when resources are rapidly removed such as after cropping (Rittenhouse et al. 2009, Blomquist and Hunter Jr 2010). Our results did not suggest frogs were affected by the short-term impacts of crop harvesting and some individuals persisted in crop paddocks after harvesting (Table S5). This may be because the species recorded are known to be highly mobile, with the ability to utilise disturbed habitat including agricultural paddocks (Hazell et al. 2001, Cogger 2014, Ocock and Wassens in press). We speculate that some species also may be able to persist in farmland by intermittently using nearby permanent habitat (remnant patches and plantings; Blomquist and Hunter Jr 2010), or by hiding in deep soil cracks in paddocks (pers. obs). Therefore, it is likely that these species can opportunistically move around agricultural paddocks between harvesting periods. Thus, the patchy distribution of essential resources may have important implications for those individuals to persist in crop areas. We suggest that to fully understand the effects of mixed farming on the distribution of amphibians, there is a need for long-term monitoring of individual ranging behaviour (e.g. direct tracking; Cushman 2006) at different times during the crop growing season and after harvest (Collins and Fahrig 2017).

The presence of historical records for twelve additional frog species we failed to record in our surveys suggest that some species, including those with specialised habitat requirements, may have already been lost from our study landscape or are too rare to detect (our study area encompasses the edge of several species' ranges) (Flemons et al. 2010, OEH 2017). Two species notably absent were the threatened Sloane's froglet Cr*inia sloanei* and near-threatened Bibron’s toadlet *Psedophryne bibronii* (Table S6). Both species are likely to be strongly affected by changes in habitat and require complex ground cover and connectivity via wet areas (e.g. inundated grassland, irrigation channels, drains) to move across the landscape (Cogger 2014). The combination of the variable climate of inland Australia, and the replacement of intact native vegetation with open, exposed cropland and homogenous pastures is likely to have created unsuitable conditions for these species (Hazell et al. 2004, Hero et al. 2006). However, the low diversity of amphibians found within our study may reflect our survey focus on terrestrial environments located away from other landscapes elements such as riparian environments and water bodies. More broadly, the species we recorded (Table 3) are lentic waterbody breeders, and proximity to, and quality of, aquatic habitat could influence the occurrence and abundance of frogs within our terrestrial trap sites (Hazell et al. 2001). However, exhaustive surveys of aquatic breeding habitat were outside the scope of our study and would require a different approach due to the propensity for frogs to breed in small ephemeral ponds that are difficult to locate in our study landscape. Further work should focus on the effects of land use variation and breeding habitat availability to better understand the processes that lead to variation in amphibian composition and occurrence in human-modified landscapes.

Conclusions

The persistence of many amphibians in modified agricultural landscapes depends on their ability to traverse contrasting farmland types. The dominance of generalist species, regional scale of the study, and lack of species with specialised niche requirements may have reduced our ability to detect site-specific changes that may influence amphibian populations. However, our results suggest the influence of crop harvesting, and highly modified areas may be less detrimental, or less resource depleted, for some species than previously assumed.

Farmland areas may provide good quality habitat allowing movement, dispersal, foraging opportunities and potentially contribute to amphibian conservation (Youngquist and Boone 2014). Further, particular landscape elements like plantings may be important for facilitating maintenance, long-term persistence and movement of frogs in farmland by increasing shade cover and generating litter substrate. Several studies suggest conservation strategies for frogs should be based on protecting breeding areas, such as creating buffers around wetland, riparian and revegetated areas (Rothermel and Semlitsch 2002, Cushman 2006). While these areas are critically important habitat, our results suggest non-breeding habitat in modified farming areas also needs to be conserved.

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Table 3 The total number of amphibian species detected across sites and the number of species occupied by each site (n=10). C=crop farmland type; LP = linear planting farmland type; P= rested farmland type and WD=woody debris farmland type.

Species	**No. of captures (%)**	**No. of sites captured (%)**	**C**	**LP**	**P**	**WD**
Crinia parinsignifera (Eastern sign-bearing froglet)	2 (0.49)	2 (20)	0	0	2	0
Limnodynastes tasmaniensis (Spotted marsh frog)	153 (37.32)	7 (70)	46	28	34	45
Limnodynastes fletcheri (Long-thumbed frog)	18 (4.39)	5 (50)	3	3	11	1
Litoria caerulea (Australian green tree frog)	4 (0.98)	2 (20)	0	2	0	2
Limnodynastes interioris (Giant banjo frog)	45 (10.98)	9 (90)	13	20	3	9
Neobatrachus sudelli (Sudell's froglet)	21 (5.12)	6 (60)	9	3	6	3
Uperoleia laevigata (Smooth toadlet)	167 (40.73)	9 (90)	41	55	23	48

Figure headings

Figure 16 (A) Study region and location of ten study areas within New South Wales, Australia. (B) Site layout showing transects extending from a remnant patch into four farmland types (coloured lines). (C) Trap layout and configuration for each treatment. (D) Example of a crop paddock before and after harvesting.

Figure 17 (A) Frog abundance and the relationship between habitat type and treatment. Error bars indicate 95% confidence intervals and fitted estimates are plotted on the x axis. Letters indicate post hoc comparisons for significant interactions; (B) *U. laveigata* abundance and the relationship between habitat and treatment. Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis.

Figure 18 (A) Body condition of *U. laveigata* and the relationship between treatment and harvesting. Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis; (B) Body condition of U. laveigata between the habitat type and treatment. Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis.

Figure 19 (A) Body condition of *U. laveigata* and the relationship between habitat and harvesting. Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis; (B) Body condition of L. tasmaniensis and the three-way interaction between treatment, habitat type and harvesting. Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis.

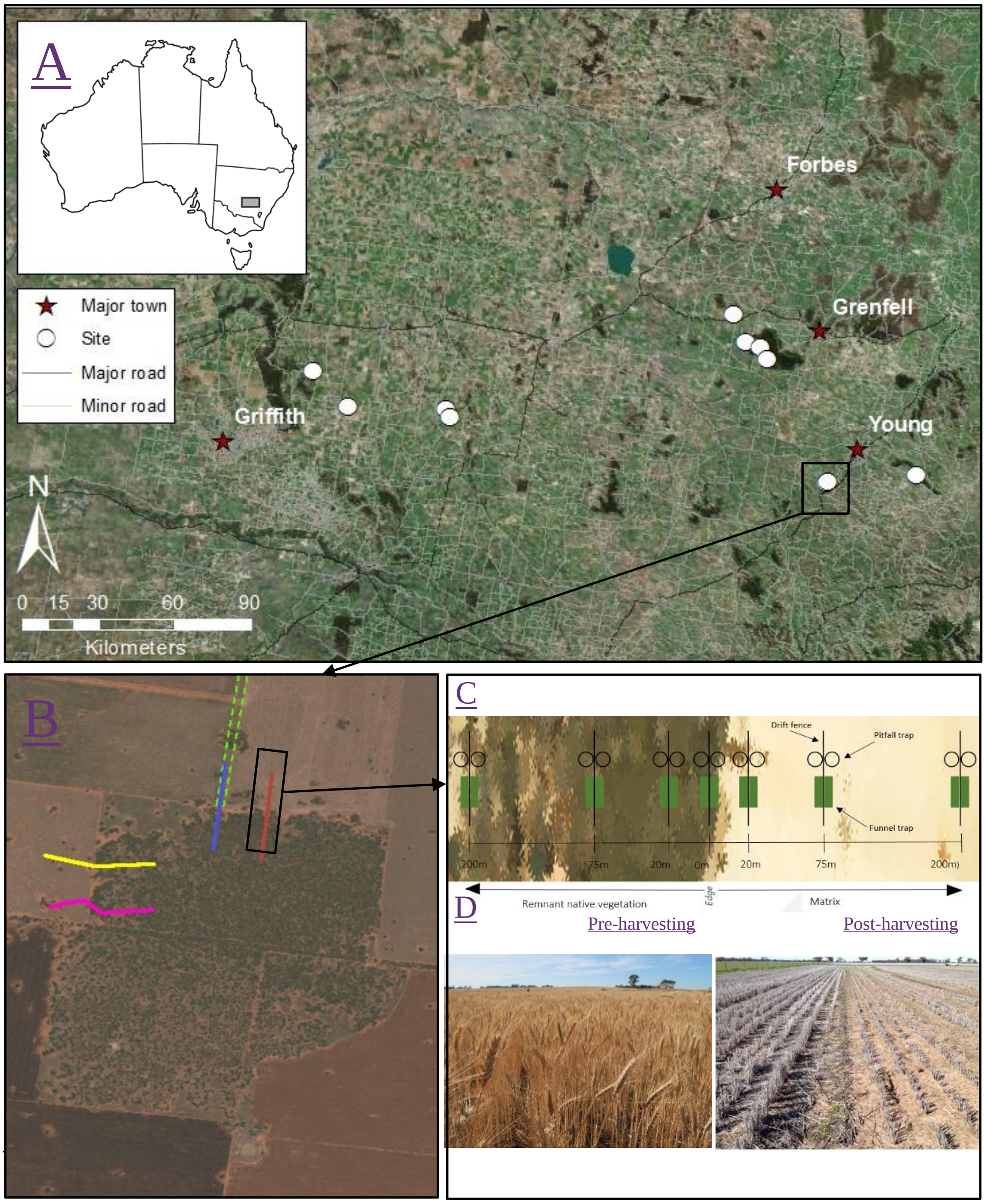
A
★ Major town
○ Site
Major road
Minor road
Forbes
Grenfell
Griffith
Young
N
0 15 30 60 90
Kilometers
B
C
Drift fence
Pitfall trap
Funnel trap
200m
75m
20m
0m
20m
75m
200m)
Remnant native vegetation
Edge
Matrix
D
Pre-harvesting
Post-harvesting

Fig. 16

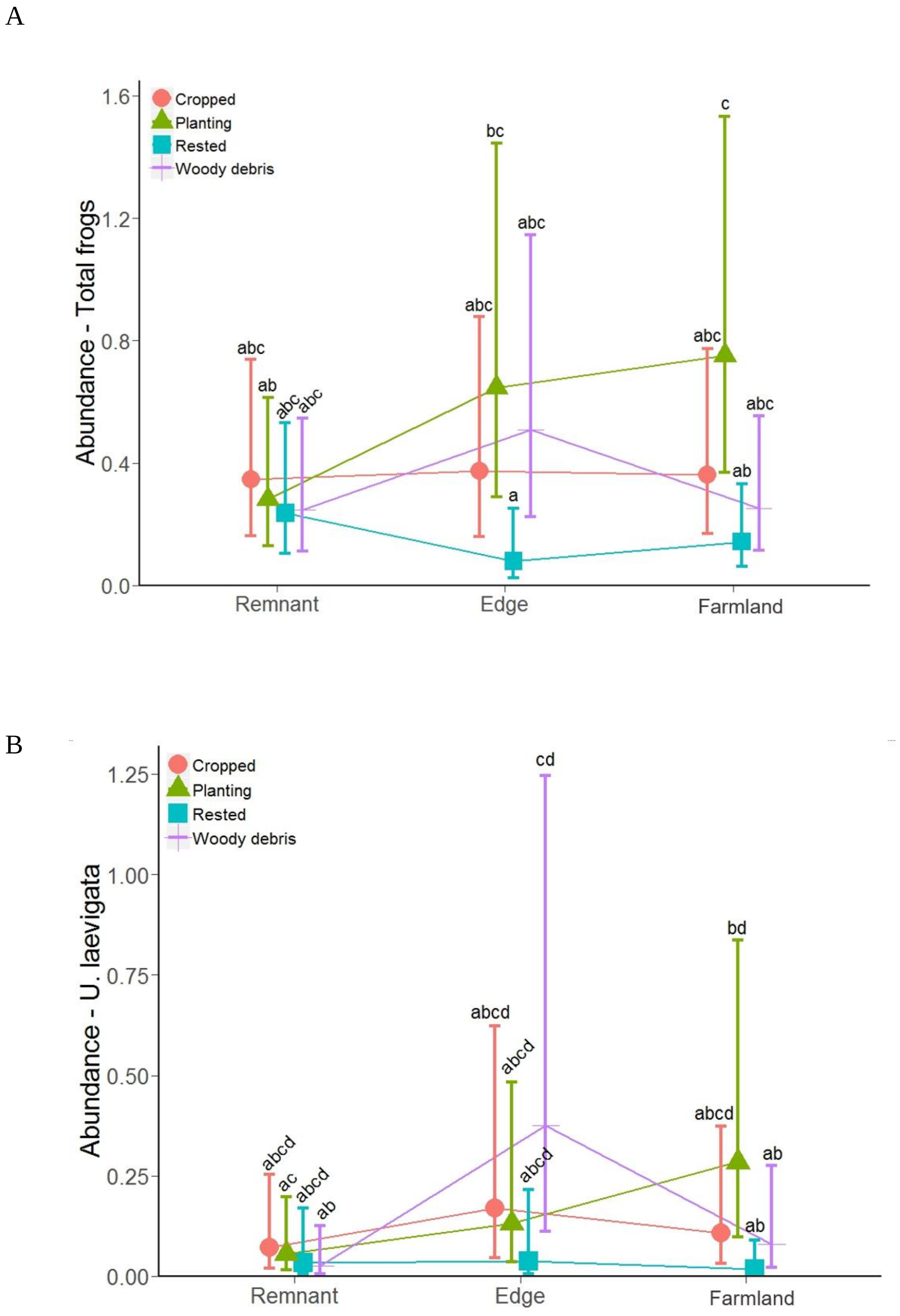
A
Cropped
Planting
Rested
Woody debris
Abundance - Total frogs
0.0
0.4
0.8
1.2
1.6
abc
ab
abc
abc
bc
abc
abc
a
c
abc
abc
ab
Remnant
Edge
Farmland
B
Cropped
Planting
Rested
Woody debris
Abundance - U. laevigata
0.00
0.25
0.50
0.75
1.00
1.25
abcd
ac
abcd
ab
cd
abcd
abcd
abcd
bd
abcd
ab
ab
Remnant
Edge
Farmland

Fig. 17

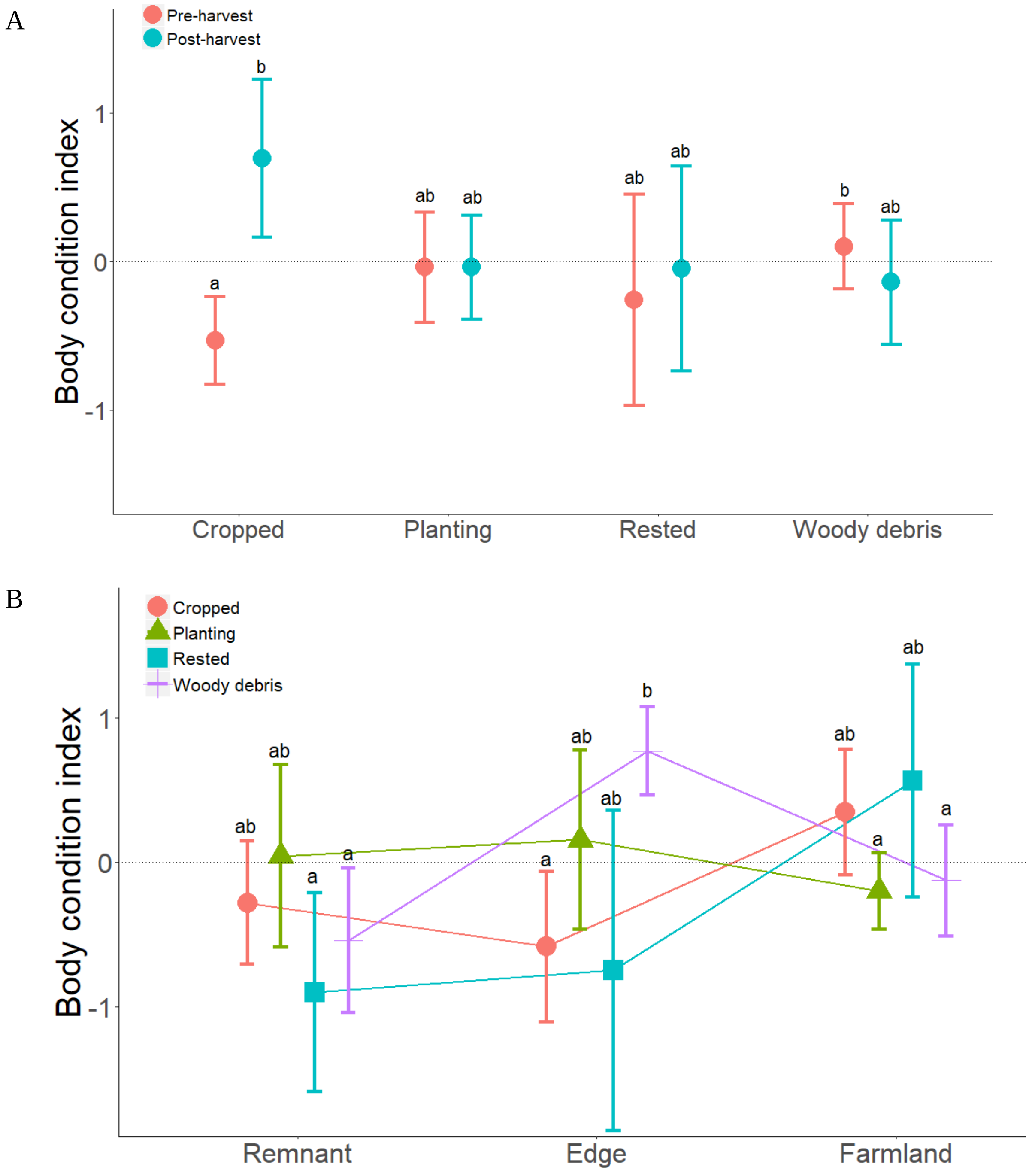
A
Pre-harvest
Post-harvest
Body condition index
1
0
-1
a
b
ab
ab
ab
ab
b
ab
Cropped
Planting
Rested
Woody debris
B
Cropped
Planting
Rested
Woody debris
Body condition index
1
0
-1
ab
ab
a
a
a
ab
ab
b
ab
ab
a
a
Remnant
Edge
Farmland

Fig. 18

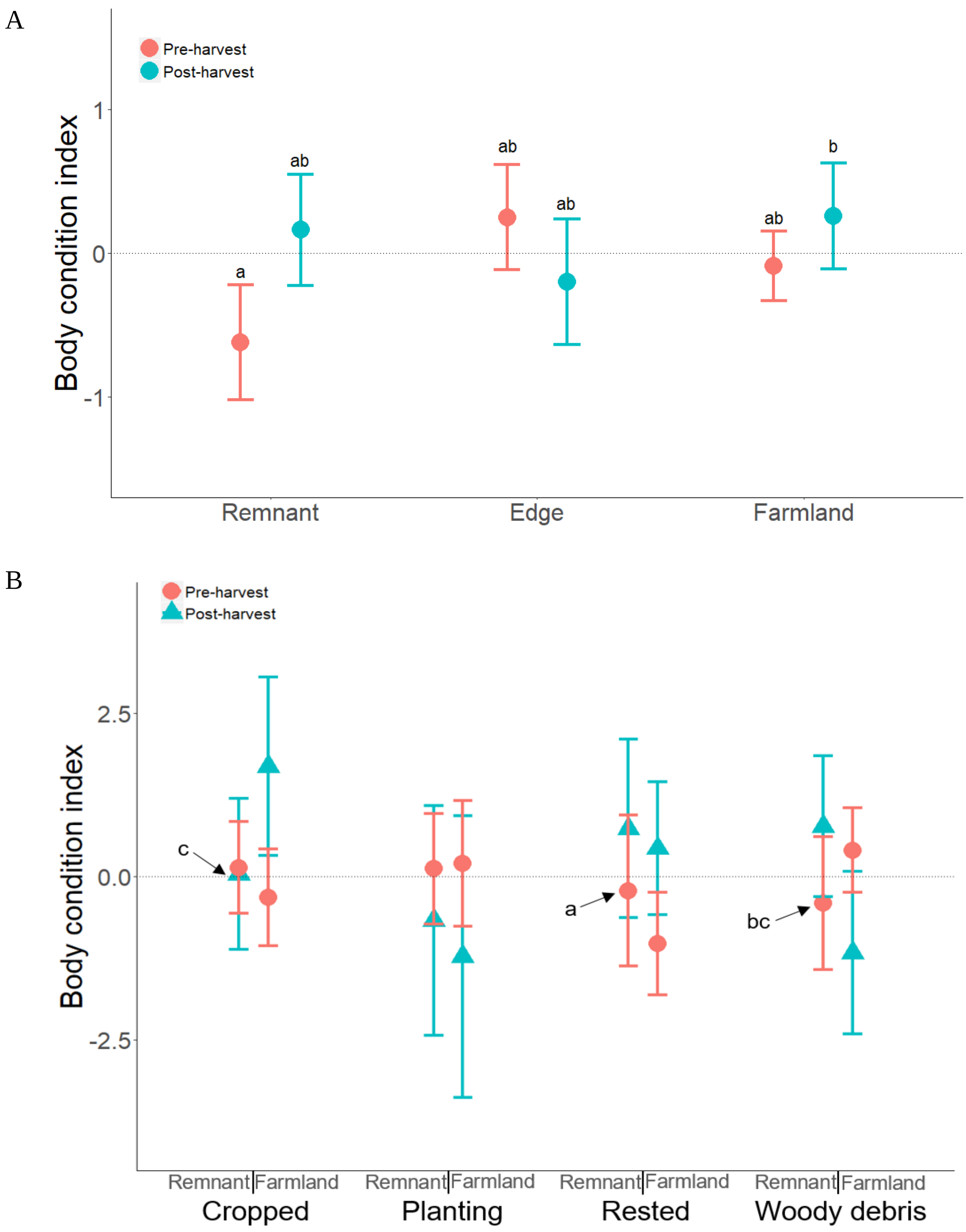
A
Pre-harvest
Post-harvest
Body condition index
1
0
-1
a
ab
ab
ab
ab
b
Remnant
Edge
Farmland
B
Pre-harvest
Post-harvest
Body condition index
2.5
0.0
-2.5
c
a
bc
Remnant
Farmland
Cropped
Remnant
Farmland
Planting
Remnant
Farmland
Rested
Remnant
Farmland
Woody debris

Fig. 19

Supplementary material

Appendix S1:

Table S1 Summary ANOVA statistics for abundance and richness

Response	**Model terms**	**Chisq**	**DF**	**P**
Total abundance	treatment*habitat*harvesting.period + region + (1|site/transect)			
	treatment	6.87	3	0.08
	habitat	3.30	2	0.19
	harvesting period	23.94	1	<0.02*
	region	7.12	2	0.03*
	treatment:habitat	32.86	6	<0.01*
	treatment:harvesting period	4.49	3	0.21
	habitat:harvesting period	4.87	2	0.09
	treatment:habitat:harvesting period	7.08	6	0.31
U. laveigata abundance	treatment*habitat*harvesting.period + region + (1|site/unique.transect.no)			
	treatment	2.03	3	0.57
	habitat	20.07	2	<0.01*
	harvesting.period	2.03	1	0.15

	region	1.92	2	0.38
	treatment:habitat	37.45	6	<0.01*
	treatment:harvesting.period	4.53	3	0.21
	habitat:harvesting.period	1.83	2	0.40
	treatment:habitat:harvesting.period	11.65	6	0.07
L. tasmanensis abundance	treatment*habitat*harvesting.period + region + (1|site/unique.transect.no)			
	treatment	1.95	3	0.58
	habitat	1.06	2	0.59
	harvesting.period	15.30	1	<0.01*
	region	5.68	1	0.02*
	treatment:habitat	5.49	6	0.48
	treatment:harvesting.period	4.52	3	0.21
	habitat:harvesting.period	3.33	2	0.19
	treatment:habitat:harvesting.period	3.90	6	0.69
L. interiosis abundance	treatment*habitat*harvesting.period + region + (1|site/unique.transect.no)			
	treatment	7.19	10	0.71
	habitat	2.46	8	0.96
	harvesting.period	1.60	8	0.99

	region	5.09	2	0.08.
	treatment:habitat	1.45	8	0.99
	treatment:harvesting.period	0.81	5	0.98
	habitat:harvesting.period	0.34	4	0.99
	treatment:habitat:harvesting.period	0.31	6	1.00
Total richness	treatment*habitat*harvesting.period + region + (1|site/unique.transect.no)			
	treatment	9.16	3	0.03*
	habitat	2.55	2	0.28
	harvesting.period	0.76	1	0.38
	region	9.03	2	0.01*
	treatment:habitat	6.00	6	0.42
	treatment:harvesting.period	0.94	3	0.82
	habitat:harvesting.period	4.07	2	0.13
	treatment:habitat:harvesting.period	5.47	6	0.49

Table S2 Summary ANOVA statistics for Body Condition Index

Response	**Model terms**	**Sum Sq**	**Df**	**F value**	**P**

U. laveigata BCI	treatment	3.28	3.00	1.60	0.19
	habitat	5.54	2.00	4.06	0.02
	harvesting.period	4.51	1.00	6.61	0.01
	treatment:habitat	19.62	6.00	4.79	<0.01
	treatment:harvesting.period	9.20	3.00	4.49	<0.01
	habitat:harvesting.period	5.34	2.00	3.91	0.02
	treatment:habitat:harvesting.period	7.01	6.00	1.71	0.12
L. tasmanensis BCI	treatment	3.94	3.00	0.55	0.65
	habitat	0.93	1.00	0.39	0.53
	harvesting	4.35	1.00	1.83	0.18
	treatment:habitat	2.07	3.00	0.29	0.83
	treatment:harvesting	20.96	3.00	2.94	0.04
	habitat:harvesting	0.18	1.00	0.07	0.79

	treatment:habitat:harvesting	27.28	3.00	3.83	0.01
L. interiosis BCI	treatment	382.4	3	0.5266	0.6681
	habitat	67.8	1	0.2802	0.60
	harvesting.period	843.6	1	3.4842	0.07.
	treatment:habitat	261.2	3	0.3596	0.78
	treatment:harvesting.period	730.6	2	1.5089	0.24
	habitat:harvesting.period	134.1	1	0.5539	0.46
	treatment:habitat:harvesting.period	557.3	2	1.1509	0.33

Table S3 Summary significant ANOVA contrasts for abundance and richness interactions

Response	**Model terms**	**Estimate**	**SE**	**z ratio**	**p value**
Total abundance	Cropped,Edge - Planting,Edge	-0.55	0.48	-1.13	0.99
	Cropped,Edge - Rested,Edge	1.55	0.64	2.43	0.39
	Cropped,Edge - Woody debris,Edge	-0.31	0.48	-0.63	1.00
	Cropped,Edge - Cropped,Matrix	0.03	0.30	0.11	1.00
	Cropped,Edge - Planting,Matrix	-0.70	0.44	-1.57	0.92
	Cropped,Edge - Rested,Matrix	0.96	0.49	1.95	0.73
	Cropped,Edge - Woody debris,Matrix	0.39	0.47	0.83	1.00
	Cropped,Edge - Cropped,Remnant	0.08	0.30	0.26	1.00
	Cropped,Edge - Planting,Remnant	0.28	0.47	0.60	1.00
	Cropped,Edge - Rested,Remnant	0.46	0.48	0.96	1.00
	Cropped,Edge - Woody debris,Remnant	0.41	0.47	0.87	1.00
	Planting,Edge - Rested,Edge	2.10	0.63	3.36	0.04

Planting,Edge - Woody debris,Edge	0.24	0.46	0.52	1.00
Planting,Edge - Cropped,Matrix	0.58	0.44	1.32	0.98
Planting,Edge - Planting,Matrix	-0.15	0.26	-0.58	1.00
Planting,Edge - Rested,Matrix	1.51	0.48	3.17	0.07
Planting,Edge - Woody debris,Matrix	0.94	0.45	2.09	0.63
Planting,Edge - Cropped,Remnant	0.62	0.44	1.42	0.96
Planting,Edge - Planting,Remnant	0.83	0.30	2.75	0.20
Planting,Edge - Rested,Remnant	1.01	0.46	2.18	0.56
Planting,Edge - Woody debris,Remnant	0.96	0.45	2.12	0.61
Rested,Edge - Woody debris,Edge	-1.86	0.62	-2.99	0.11
Rested,Edge - Cropped,Matrix	-1.52	0.61	-2.50	0.34
Rested,Edge - Planting,Matrix	-2.25	0.60	-3.77	0.01
Rested,Edge - Rested,Matrix	-0.59	0.49	-1.21	0.99

Rested,Edge - Woody debris,Matrix	-1.16	0.61	-1.90	0.76
Rested,Edge - Cropped,Remnant	-1.48	0.61	-2.43	0.38
Rested,Edge - Planting,Remnant	-1.27	0.62	-2.05	0.66
Rested,Edge - Rested,Remnant	-1.09	0.48	-2.30	0.48
Rested,Edge - Woody debris,Remnant	-1.14	0.61	-1.86	0.79
Woody debris,Edge - Cropped,Matrix	0.34	0.44	0.77	1.00
Woody debris,Edge - Planting,Matrix	-0.39	0.42	-0.93	1.00
Woody debris,Edge - Rested,Matrix	1.27	0.47	2.70	0.23
Woody debris,Edge - Woody debris,Matrix	0.70	0.25	2.75	0.20
Woody debris,Edge - Cropped,Remnant	0.38	0.44	0.87	1.00
Woody debris,Edge - Planting,Remnant	0.59	0.45	1.30	0.98
Woody debris,Edge - Rested,Remnant	0.76	0.45	1.68	0.88
Woody debris,Edge - Woody debris,Remnant	0.72	0.26	2.76	0.20

Cropped,Matrix - Planting,Matrix	-0.73	0.40	-1.84	0.80
Cropped,Matrix - Rested,Matrix	0.93	0.45	2.06	0.66
Cropped,Matrix - Woody debris,Matrix	0.36	0.42	0.84	1.00
Cropped,Matrix - Cropped,Remnant	0.04	0.22	0.20	1.00
Cropped,Matrix - Planting,Remnant	0.25	0.43	0.59	1.00
Cropped,Matrix - Rested,Remnant	0.43	0.44	0.98	1.00
Cropped,Matrix - Woody debris,Remnant	0.38	0.43	0.89	1.00
Planting,Matrix - Rested,Matrix	1.66	0.44	3.80	0.01
Planting,Matrix - Woody debris,Matrix	1.09	0.41	2.67	0.24
Planting,Matrix - Cropped,Remnant	0.77	0.40	1.96	0.72
Planting,Matrix - Planting,Remnant	0.98	0.24	4.16	0.00
Planting,Matrix - Rested,Remnant	1.16	0.42	2.75	0.20
Planting,Matrix - Woody debris,Remnant	1.11	0.41	2.70	0.23

Rested,Matrix - Woody debris,Matrix	-0.57	0.46	-1.25	0.98
Rested,Matrix - Cropped,Remnant	-0.88	0.45	-1.96	0.72
Rested,Matrix - Planting,Remnant	-0.68	0.47	-1.45	0.95
Rested,Matrix - Rested,Remnant	-0.50	0.25	-2.03	0.67
Rested,Matrix - Woody debris,Remnant	-0.55	0.46	-1.19	0.99
Woody debris,Matrix - Cropped,Remnant	-0.31	0.42	-0.74	1.00
Woody debris,Matrix - Planting,Remnant	-0.11	0.44	-0.24	1.00
Woody debris,Matrix - Rested,Remnant	0.07	0.44	0.16	1.00
Woody debris,Matrix - Woody debris,Remnant	0.02	0.24	0.10	1.00
Cropped,Remnant - Planting,Remnant	0.21	0.43	0.49	1.00
Cropped,Remnant - Rested,Remnant	0.38	0.44	0.88	1.00
Cropped,Remnant - Woody debris,Remnant	0.34	0.43	0.79	1.00
Planting,Remnant - Rested,Remnant	0.17	0.45	0.39	1.00

	Planting,Remnant - Woody debris,Remnant	0.13	0.44	0.29	1.00
	Rested,Remnant - Woody debris,Remnant	-0.05	0.45	-0.10	1.00
Uperoleia laveigata abundance	Cropped,Edge - Planting,Edge	0.25	0.84	0.30	1.00
	Cropped,Edge - Rested,Edge	1.49	1.00	1.49	0.94
	Cropped,Edge - Woody debris,Edge	-0.80	0.78	-1.02	1.00
	Cropped,Edge - Cropped,Matrix	0.44	0.49	0.90	1.00
	Cropped,Edge - Planting,Matrix	-0.52	0.76	-0.69	1.00
	Cropped,Edge - Rested,Matrix	2.24	0.94	2.39	0.42
	Cropped,Edge - Woody debris,Matrix	0.75	0.80	0.95	1.00
	Cropped,Edge - Cropped,Remnant	0.85	0.51	1.68	0.88
	Cropped,Edge - Planting,Remnant	1.10	0.82	1.33	0.98
	Cropped,Edge - Rested,Remnant	1.61	0.95	1.70	0.87
	Cropped,Edge - Woody debris,Remnant	1.85	0.93	2.00	0.70

Planting,Edge - Rested,Edge	1.24	1.02	1.22	0.99
Planting,Edge - Woody debris,Edge	-1.05	0.80	-1.31	0.98
Planting,Edge - Cropped,Matrix	0.19	0.82	0.23	1.00
Planting,Edge - Planting,Matrix	-0.77	0.44	-1.77	0.84
Planting,Edge - Rested,Matrix	1.98	0.95	2.08	0.64
Planting,Edge - Woody debris,Matrix	0.50	0.82	0.62	1.00
Planting,Edge - Cropped,Remnant	0.60	0.83	0.73	1.00
Planting,Edge - Planting,Remnant	0.84	0.55	1.54	0.93
Planting,Edge - Rested,Remnant	1.36	0.96	1.41	0.96
Planting,Edge - Woody debris,Remnant	1.60	0.94	1.70	0.87
Rested,Edge - Woody debris,Edge	-2.29	0.96	-2.39	0.41
Rested,Edge - Cropped,Matrix	-1.05	0.98	-1.07	1.00
Rested,Edge - Planting,Matrix	-2.02	0.95	-2.13	0.60

	Rested,Edge - Rested,Matrix	0.74	0.79	0.94	1.00
	Rested,Edge - Woody debris,Matrix	-0.74	0.97	-0.76	1.00
	Rested,Edge - Cropped,Remnant	-0.64	0.99	-0.65	1.00
	Rested,Edge - Planting,Remnant	-0.40	1.00	-0.40	1.00
	Rested,Edge - Rested,Remnant	0.12	0.80	0.15	1.00
	Rested,Edge - Woody debris,Remnant	0.35	1.08	0.33	1.00
	Woody debris,Edge - Cropped,Matrix	1.24	0.75	1.65	0.89
	Woody debris,Edge - Planting,Matrix	0.28	0.71	0.39	1.00
	Woody debris,Edge - Rested,Matrix	3.03	0.89	3.41	0.03
	Woody debris,Edge - Woody debris,Matrix	1.55	0.36	4.36	0.00
	Woody debris,Edge - Cropped,Remnant	1.65	0.76	2.17	0.57
	Woody debris,Edge - Planting,Remnant	1.89	0.78	2.43	0.38
	Woody debris,Edge - Rested,Remnant	2.41	0.90	2.68	0.24

Woody debris,Edge - Woody debris,Remnant	2.64	0.59	4.50	0.00
Cropped,Matrix - Planting,Matrix	-0.96	0.73	-1.33	0.98
Cropped,Matrix - Rested,Matrix	1.79	0.91	1.96	0.72
Cropped,Matrix - Woody debris,Matrix	0.31	0.77	0.41	1.00
Cropped,Matrix - Cropped,Remnant	0.41	0.46	0.89	1.00
Cropped,Matrix - Planting,Remnant	0.65	0.80	0.82	1.00
Cropped,Matrix - Rested,Remnant	1.17	0.92	1.27	0.98
Cropped,Matrix - Woody debris,Remnant	1.40	0.90	1.56	0.92
Planting,Matrix - Rested,Matrix	2.76	0.88	3.15	0.07
Planting,Matrix - Woody debris,Matrix	1.28	0.73	1.76	0.84
Planting,Matrix - Cropped,Remnant	1.37	0.73	1.87	0.78
Planting,Matrix - Planting,Remnant	1.62	0.40	4.06	0.00
Planting,Matrix - Rested,Remnant	2.14	0.89	2.41	0.40

Planting,Matrix - Woody debris,Remnant	2.37	0.86	2.75	0.20
Rested,Matrix - Woody debris,Matrix	-1.48	0.91	-1.64	0.90
Rested,Matrix - Cropped,Remnant	-1.39	0.92	-1.51	0.94
Rested,Matrix - Planting,Remnant	-1.14	0.94	-1.22	0.99
Rested,Matrix - Rested,Remnant	-0.62	0.72	-0.87	1.00
Rested,Matrix - Woody debris,Remnant	-0.39	1.02	-0.38	1.00
Woody debris,Matrix - Cropped,Remnant	0.10	0.78	0.12	1.00
Woody debris,Matrix - Planting,Remnant	0.34	0.80	0.43	1.00
Woody debris,Matrix - Rested,Remnant	0.86	0.92	0.94	1.00
Woody debris,Matrix - Woody debris,Remnant	1.09	0.61	1.79	0.83
Cropped,Remnant - Planting,Remnant	0.24	0.80	0.30	1.00
Cropped,Remnant - Rested,Remnant	0.76	0.93	0.82	1.00
Cropped,Remnant - Woody debris,Remnant	1.00	0.91	1.10	0.99

	Planting,Remnant - Rested,Remnant	0.52	0.95	0.55	1.00
	Planting,Remnant - Woody debris,Remnant	0.75	0.92	0.82	1.00
	Rested,Remnant - Woody debris,Remnant	0.23	1.03	0.23	1.00

Table S4 Summary significant ANOVA contrasts for Body Condition Index interactions

Response	**Model terms**	**Estimate**	**SE**	**t ratio**	**p value**
Uperoleia laevigata body condition	(Intercept)	-0.07	0.09	-0.84	0.40
	treatmentPlanting	-0.04	0.12	-0.36	0.72
	treatmentRested	0.03	0.14	0.24	0.81
	treatmentWoody debris	0.17	0.10	1.69	0.09
	habitatMatrix	0.24	0.12	1.98	0.05
	habitatRemnant native vegetation	0.22	0.10	2.14	0.03
	harvesting.periodPre-harvest	-0.03	0.10	-0.24	0.81
	treatmentPlanting:habitatMatrix	-0.09	0.15	-0.58	0.56
	treatmentRested:habitatMatrix	-0.08	0.18	-0.44	0.66
	treatmentWoody debris:habitatMatrix	-0.41	0.15	-2.77	0.01
	treatmentPlanting:habitatRemnant native vegetation	-0.02	0.15	-0.16	0.87
	treatmentRested:habitatRemnant native vegetation	-0.36	0.21	-1.70	0.09

	treatmentWoody debris:habitatRemnant native vegetation	-0.34	0.13	-2.57	0.01
	treatmentPlanting:harvesting.periodPre-harvest	0.22	0.15	1.44	0.15
	treatmentRested:harvesting.periodPre-harvest	-0.09	0.21	-0.42	0.68
	treatmentWoody debris:harvesting.periodPre-harvest	0.04	0.12	0.32	0.75
	habitatMatrix:harvesting.periodPre-harvest	-0.14	0.14	-0.99	0.32
	habitatRemnant native vegetation:harvesting.periodPre-harvest	-0.31	0.13	-2.37	0.02
	treatmentPlanting:habitatMatrix:harvesting.periodPre-harvest	-0.17	0.19	-0.93	0.35
	treatmentRested:habitatMatrix:harvesting.periodPre-harvest	0.21	0.27	0.78	0.44
	treatmentWoody debris:habitatMatrix:harvesting.periodPre-harvest	0.19	0.17	1.11	0.27
	treatmentPlanting:habitatRemnant native vegetation:harvesting.periodPre-harvest	0.02	0.20	0.09	0.93
	treatmentRested:habitatRemnant native vegetation:harvesting.periodPre-harvest	0.53	0.27	1.92	0.05

	treatmentWoody debris:habitatRemnant native vegetation:harvesting.periodPre-harvest	0.20	0.17	1.19	0.24
Limnodynastes tasmaniensis body condition	(Intercept)	0.02	0.05	0.43	0.67
	treatmentPlanting	-0.07	0.10	-0.68	0.49
	treatmentRested	0.11	0.08	1.37	0.17
	treatmentWoody debris	0.07	0.07	0.95	0.34
	habitatRemnant native vegetation	0.11	0.08	1.29	0.20
	harvestingPre-harvest	0.00	0.06	0.02	0.98
	treatmentPlanting:habitatRemnant native vegetation	-0.16	0.16	-1.01	0.31
	treatmentRested:habitatRemnant native vegetation	-0.26	0.11	-2.32	0.02
	treatmentWoody debris:habitatRemnant native vegetation	-0.33	0.11	-2.89	0.00
	treatmentPlanting:harvestingPre-harvest	0.05	0.11	0.47	0.64
	treatmentRested:harvestingPre-harvest	-0.13	0.10	-1.30	0.19
	treatmentWoody debris:harvestingPre-harvest	-0.11	0.09	-1.24	0.22
	habitatRemnant native vegetation:harvestingPre-harvest	-0.15	0.10	-1.56	0.12

	treatmentPlanting:habitatRemnant native vegetation:harvestingPre-harvest	0.21	0.18	1.17	0.24
	treatmentRested:habitatRemnant native vegetation:harvestingPre-harvest	0.20	0.14	1.41	0.16
	treatmentWoody debris:habitatRemnant native vegetation:harvestingPre-harvest	0.41	0.14	3.05	0.00

Table S5 Summary of recaptured individuals over the entire survey period. An arrow (→) indicates if an individual shifted between different treatments or habitat types. The total straight-line distance moved by each individual and the number of days between first and last captures dates is also summarised.

Species	Harvesting period	Treatment	Habitat type	Total distance moved (m)	Time between first and last capture
Limnodynastes tasmanensis	Pre-harvest-->Post-harvest	Rested	Patch	180	80
	Pre-harvest	Cropped	Matrix	0	2
	Pre-harvest	Rested	Edge	0	2
	Pre-harvest	Rested	Patch	0	2
	Post- harvest	Cropped	Matrix	55	2
	Post- harvest	Rested	Patch	0	3
Uperoleia laveigata	Pre-harvest-->Post-harvest	Cropped-->Rested-->Cropped	Matrix-->Patch	350	29
	Pre-harvest-->Post-harvest	Woody debris-->Cropped	Patch	0	110
	Pre-harvest -->Post-harvest	Cropped	Matrix-->Patch	40	105
	Pre-harvest -->Post-harvest	Planting	Remant	55	115
	Pre-harvest	Cropped	Edge-->Matrix	150	58

	Pre-harvest	Planting -->Crop-->Planting	Matrix-->Patch-->Matrix	440	52
	Pre-harvest	Woody debris	Matrix-->Edge	20	4
	Pre-harvest	Woody debris	Edge	0	4
	Pre-harvest	Cropped-->Woody debris-->Cropped	Matrix-->Edge-->Patch	400	29
	Pre-harvest	Woody debris	Edge	0	4
	Pre-harvest	Woody debris	Edge	0	2
	Pre-harvest	Woody debris	Matrix-->Edge	150	4
	Pre-harvest	Planting-->Woody debris	Matrix	400	5
	Pre-harvest	Woody debris	Edge-->Matrix	75	2
	Post- harvest	Planting	Matrix-->Remnant	150	4
	Post- harvest	Planting	Remant-->Matrix	150	2
	Post- harvest	Woody debris	Matrix-->Edge	20	2
	Post- harvest	Woody debris-->Planting	Edge-->Matrix	420	24
	Post- harvest	Woody debris	Matrix-->Edge	20	2

Table S6 Historical records of frogs within the study area. Note: *sourced from IUCN (2017) database, **sourced from OEH (2018) database.

Species	IUCN Status*	Population status*	Number of records/ last known record (year)**
Crinia parinsignifera (Eastern Sign-bearing Froglet)	Least concern	Unknown	90/ 2015
Limnodynastes interioris (Giant Banjo Frog)	Least concern	Stable	70/2016
Litoria caerulea (Green Tree Frog)	Least concern	Stable	13/2012
Limnodynastes fletcheri (Long-thumbed Frog)	Least concern	Stable	81/1995
Uperoleia laevigata (Smooth Toadlet)	Least concern	Stable	10/2012
Limnodynastes tasmaniensis (Spotted Grass Frog)	Least concern	Stable	194/2016
Neobatrachus sudelli (Sudell's Frog)	unlisted	Stable	11/2007
Limnodynastes salmini (Salmon Striped Frog)	Least concern	Stable	2/1985
Crinia sloanei (Sloane's Froglet); list as vulnerable under Australian threatened species legislation	data deficient	Data deficient	2/2004

Species	IUCN Status*	Population status*	Number of records/ last known record (year)**
Litoria peronii (Peron's Tree Frog)	Least concern	Stable	101/2016
Pseudophryne bibronii (Bibron's Toadlet)	Near-threatened	Decreasing	10/2007
Litoria latopalmata (Broad-palmed Frog)	Least concern	Stable	3/2007
Limnodynastes peronii Brown-striped Frog)	Least concern	Increasing	1/1995
Crinia signifera (Common Eastern Froglet)	Least concern	Stable	28/2016
Notaden bennettii (Crucifix Frog)	Least concern	Stable	2/2003
Litoria rubella (Desert Tree Frog)	Least concern	Stable	2/2015
Limnodynastes dumerilii (Eastern Banjo Frog)	Least concern	Stable	11/2005
Uperoleia rugosa (Wrinkled Toadlet)	Unlisted	Stable	14/2016

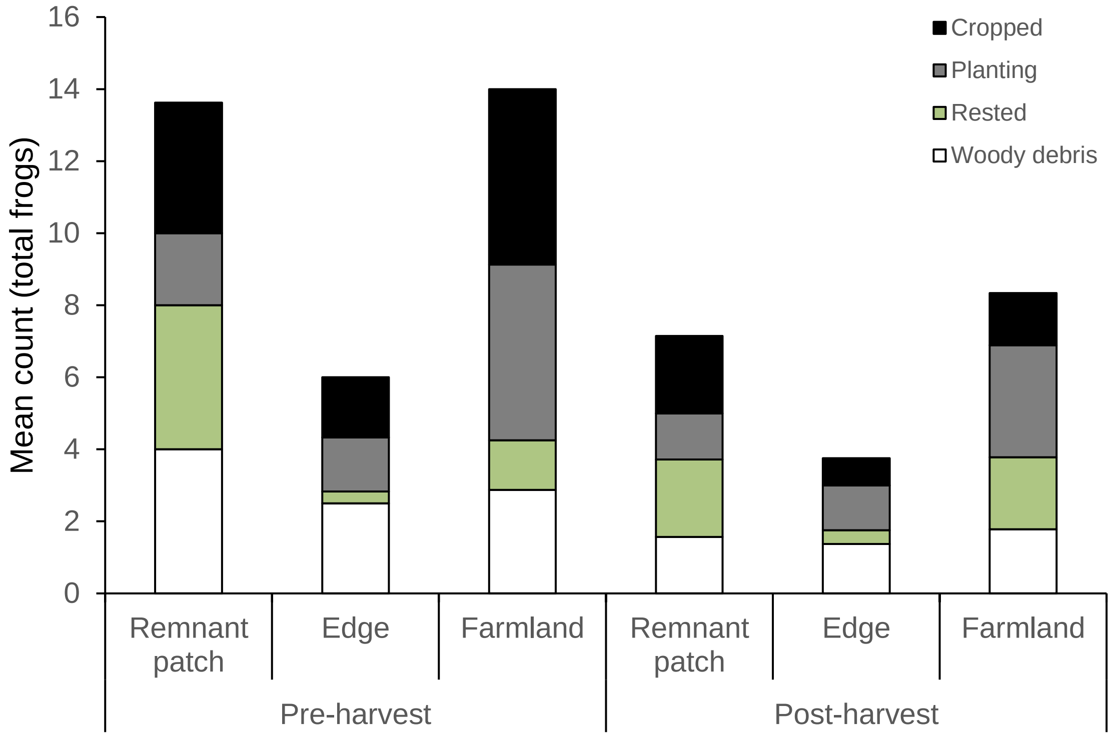

Fig. S1 Mean number of amphibians within each habitat type (remnant patch, edge and farmland), between treatments (cropped, planting, rested and woody debris) and harvesting periods (pre-harvesting and post-harvesting).

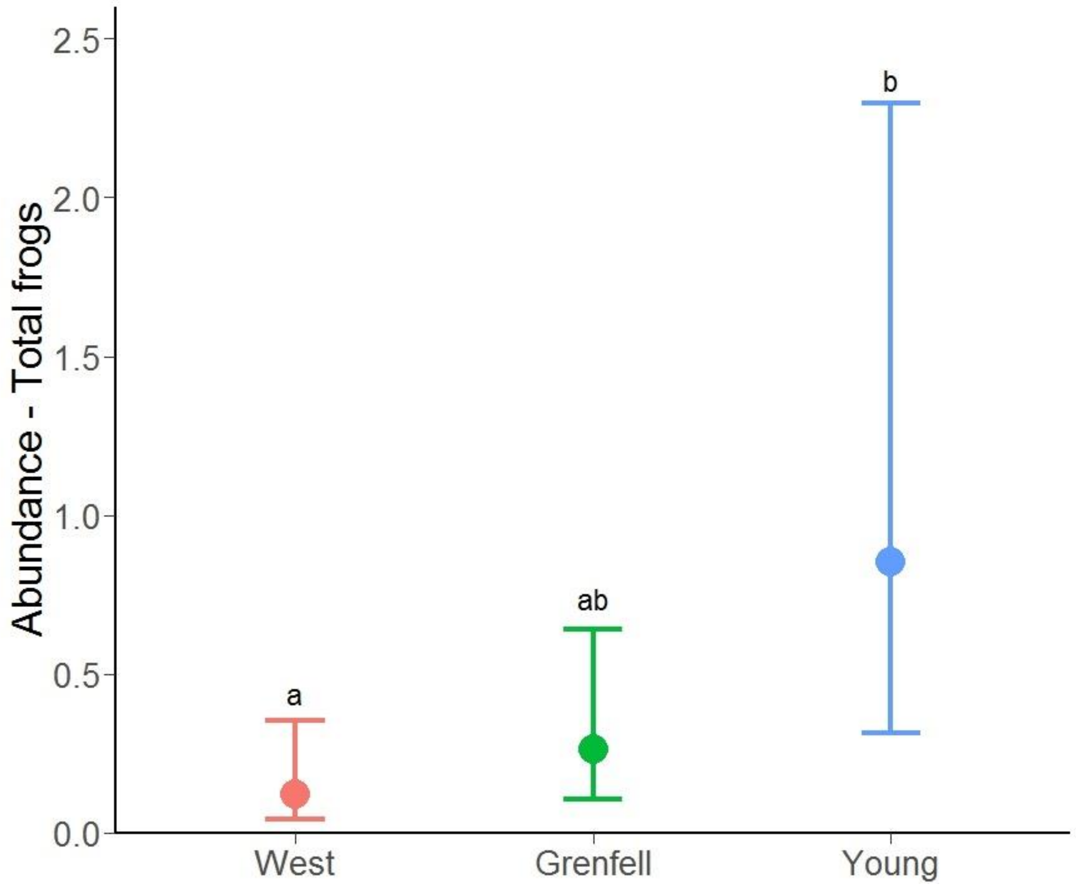

Fig. S2. Total abundance of frogs within each region across a gradient from west (West) to east (Grenfell and Young)

CHAPTER FOUR:

PREDATION RISK FOR REPTILES IS HIGHEST AT REMNANT EDGES IN AN AGRICULTURAL LANDSCAPE

Many of the mechanisms affecting reptile occurrence in farming landscapes including predation, are poorly understood and rarely empirically tested. This is despite the worldwide decline of reptiles in agricultural areas (Gibbons et al. 2000, Wanger et al. 2010, Böhm et al. 2013, Jellinek et al. 2014a), and the potential impact of predation risk on reptile movement and habitat selection (Anderson and Burgin 2008, Sato et al. 2014). To address this important knowledge gap, I examined how a range of farm management practices influence predation risk.

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Abstract

1. Preventing biodiversity loss in fragmented agricultural landscapes is a global problem. The persistence of biodiversity within remnant vegetation can be influenced by an animal's ability to move through the farmland matrix between habitat patches. Yet, many of the mechanisms driving species occurrence within these landscapes are poorly understood, particularly for reptiles.
2. We used scented and unscented plasticine lizard models and wildlife cameras to (1) estimate predation risk of reptiles in four farmland types (crop field, pasture paddock, restoration tree planting and areas with applied woody mulch) relative to the patch edge and remnant vegetation, and (2) examine how predation risk was influenced by temporal change in the matrix (crop harvesting).
3. Birds (55.1%), mammals (41.1%), reptiles (3.4%) and invertebrates (0.5%) attacked models, 87% of which were native species. Mammalian predators were 60.2% more likely to attack scented models then unscented models.
4. We found predator attacks on models were highest at edges, irrespective of adjacent farmland type, with a reduced risk within farmland and remnant patches ($P<0.01$). Both mammal and bird predators contributed to high numbers of predation attempts at edges. Predation attempts occurred across all surveyed habitats. This result reflects the range of generalist predators occurring in our study area, and the extent to which natural habitat has been modified throughout the study area.
5. Removal of crops did not increase predation attempts in crop fields or other farmland types. However, numbers of predation attempts were higher in edge habitats, particularly prior to harvesting.
6. *Synthesis and applications.* Reptiles are at risk of predation by birds and mammals in both remnant patches and the farmland matrix, particularly in edge habitat. Edge habitats in our study area are open with minimal shelter, and likely provide only limited refuge from predation. Thus, the risk of mortality at edges may be a key mechanism that could reduce cross-habitat movement by reptiles if they perceive these areas as high risk, low quality habitat. This has important implications for management targeting reptile conservation, particularly if predation risk acts as a potential barrier to movement through

agricultural landscapes. We are not aware of any studies specifically investigating the use of edges by predators and the consequences for reptile populations in these systems, and we identify this as a priority area for research.

Key words: corridor, edge-effects, farming, gecko, lizard, matrix, mortality, odour, predation risk

Introduction

Habitat loss and fragmentation resulting from intensive agricultural production is a major threat to global biodiversity (Ellis and Ramankutty 2008, Venter et al. 2016, Thompson et al. 2017). Habitat patches can be surrounded by a highly-modified agricultural matrix (defined as an extensive, non-native land cover type which cannot sustain some species dependent on patches of remnant native vegetation; Driscoll et al. 2013b) comprised of different farmland types. The long-term persistence of fauna populations within these landscapes can depend on the ability of animals to move between remnant patches of habitat (Sarre et al. 1995, Kay et al. 2016b, Pulsford et al. 2017). However, some matrix environments could represent a barrier to movement (Prevedello and Vieira 2010, Pulsford et al. 2017), particularly if there is high mortality risk during dispersal (Anderson and Burgin 2008, Daly et al. 2008). Despite increasing research on the impact of matrix heterogeneity on some fauna species (Watling et al. 2011, Driscoll et al. 2013b, Cline and Hunter 2014), empirical data on the mechanisms explaining reduced use of some matrix types is lacking in agroecosystems (Driscoll et al. 2013b).

The risk of elevated mortality, such as individuals being killed by harvesting machinery (Rotem 2012), increased risk of desiccation (Cosentino et al. 2011), or predation (Schtickzelle and Baguette 2003, Schneider et al. 2013), at different times and within different matrix environments may be an important driver of matrix use by fauna in agricultural areas (Storch et al. 2005, Ewers and Didham 2006, Pita et al. 2007, Driscoll et al. 2013b). Predation is one of the most important factors influencing mortality (Castilla and Labra 1998) and population persistence (Suhonen et al. 1994, Purger et al. 2008). Predation risk may reduce an individual's willingness to emigrate (Stevens et al. 2006), their likelihood of reaching a new patch (Pita et al. 2009) and their safe return from exploratory forays into the matrix (Ewers and Didham 2006, Rotem 2012). These factors increase the effective isolation of remnant patches (Pita et al. 2009). Yet, agricultural lands can vary markedly in spatial and temporal vegetation structure. This can affect the ability of predators to traverse and forage between several habitat types and, in turn alter the exposure of prey to predation (Storch et al. 2005, Cosentino et al. 2011, Driscoll et al.

2013b). Predator responses to habitat edges also may vary depending on the species, landscape type and scale (Lidicker 1999, Rand et al. 2006, Driscoll et al. 2013b).

The effects of habitat structure on predation risk has been reasonably well explored for birds (Whittingham and Evans 2004, Storch et al. 2005, Purger et al. 2008), and mammals (Norrdahl and Korpimäki 1998, Pita et al. 2009). However, knowledge of the influence of predation risk on reptiles within agricultural areas is limited (Daly et al. 2008, Driscoll et al. 2013b, Sato et al. 2014). Most reptile species have limited dispersal abilities when compared to birds and mammals, and depend on specific microhabitat features to avoid predation (Manning et al. 2013, Michael et al. 2015). Reptiles also have specific thermal requirements that make them dependent on basking opportunities, exposing them to predation risk (Anderson and Burgin 2008, Sato et al. 2014). Therefore, predation risk may be a key ecological driver which may impact reptile movement and habitat selection in agricultural landscapes, and in turn, influence the effectiveness of management approaches aimed at improving reptile persistence (Vandermeer and Carvajal 2001, Driscoll et al. 2013b).

Since the understanding of predation risk on reptiles in agroecosystems is limited, we used scented and unscented plasticine models of a patch-dependent gecko species, *Gehyra versicolor*, to test if predation risk varied between differing types of farmland, at different distances from edges and before and after crop harvesting. *G. versicolor* is a small, nocturnal, arboreal and saxicolous species and occurs widely throughout eastern Australia (Michael and Lindenmayer 2010, Cogger 2014). This species can be relatively common in fragmented agricultural landscapes and is strongly associated with woodland remnants, rocky outcrops, logs and shrubs (Gruber and Henle 2004, Cogger 2014). Previous studies found that *G. versicolor* (syn. *G. variegata*) exhibits good dispersal through natural habitat, but poor dispersal in agricultural landscapes (Sarre et al. 1995, Sarre 1998).Using a landscape-scale field experiment we addressed two specific questions:

<u>(1) Does differing farmland type (cropped paddocks, pasture paddocks, linear plantings and applied woody mulch) influence predation risk in contrast to the adjacent edge ecotone and remnant patch?</u> We hypothesised that predation rates would be greater in the farmland matrix and edge habitats. Many empirical studies have documented increased avian and insect

predation rates near patch edges and within farmland for a suite of taxa (Ries et al. 2004, Storch et al. 2005, Driscoll et al. 2013b). We postulated that structurally simplified farmland types (crops and paddocks) would have higher rates of predation (Storch et al. 2005, Purger et al. 2008, Stoate et al. 2009b), compared to structurally complex linear plantings and woody debris treatments. This was because lizards in such areas would be more exposed and visible to predators (Wilson et al. 2005, Michael et al. 2015). Previous studies have supported the idea that the potential food subsidies provided by crops may increase generalist predators within paddocks, resulting in elevated predation rates and reducing prey populations within agricultural habitats (Andren 1992, Rand et al. 2006, Rotem 2012) Furthermore, while temporary vegetation cover (e.g. cereal crop, pasture grasses) may conceal prey from visual predators (e.g. corvids, raptors), the cover afforded may increase predation by animals which use olfactory cues such as mammals (Wilson et al. 2005, Stoate et al. 2009b).

In agricultural environments, edge habitats may be inhabited by a large suite of mammalian and avian predators using edges as hunting areas, movement corridors or transitory zones to cross-forage between patches and farmland, which in turn, increases predation risk (Huhta et al. 1996, Sewell and Catterall 1998, Anderson and Burgin 2008). These mechanisms may increase hunting opportunities for these predators in edge areas compared to core remnants (Storch et al. 2005, Anderson and Burgin 2008). While the impact of these predators on reptile prey is well known (Barrows and Allen 2007, Anderson and Burgin 2008), the contribution of edge habitats to predation risk for reptiles in agroecosystems is unclear.

<u>(2) Does crop harvest increase predation risk?</u> Harvesting may influence predation rates in all farmland types as predators may move opportunistically to new foraging habitat (spill-over effects) (Storch et al. 2005), or compensatory shifts due to the prey source being killed during the mechanical harvesting of crops (Thorbek and Bilde 2004, Rotem et al. 2013). For example, rodent predators increased in habitat surrounding crop fields after crop harvesting due to the decline in resource availability within cropped fields (Jacob et al. 2004). Therefore, we tested if attacks on reptile models would be higher in crop paddocks prior to harvesting, due to an increase in prey abundance (Rand et al. 2006), with the converse effect after harvesting due to the rapid removal of resources (Rotem et al. 2013). Consequently, we expected predators to

spillover or shift to nearby habitats and farmland types in search of foraging opportunities (e.g. linear planting and woody debris; Thorbek and Bilde 2004, Sinclair et al. 2005, Storch et al. 2005). We also expected the addition of woody mulch to a bare crop paddock would provide additional shelter for reptiles (i.e. models) after harvesting, therefore reducing exposure of models to predators and reducing attacks on models.

Methods

Study species

Gehyra versicolor is a medium-sized (mean SVL = 55 mm) nocturnal, arboreal and saxicolous gecko in the family Gekkonidae (Gruber and Henle 2004). Currently its population status is unknown due to recent taxonomic reclassification (Duckett et al. 2013). This species may alter its habitat use in response to availability of food and shelter resources, antagonistic behaviour, mating opportunities (Henle et al. 2004) and uses the matrix ecotone (observed from a previous study; N A. Hansen unpublished data).

Study areas

Our study area is located within western New South Wales, Australia and is bounded by the coordinates 33° 55' 58.249" S; 147° 53' 48.729" E (Grenfell) and 34° 10' 34.776" S; 146° 50' 7.522" (Ardlethan; Fig. 1A and 1B). Mixed farming dominates the landscape, characterized by intensive cereal cropping (wheat, canola, lupins and barley) and grazing by sheep (*Ovis aries*) and cattle (*Bos taurus*). The dominant native vegetation types within the remnant patches in the western part of our study area include mallee woodland and shrubland with some White Cypress Pine (*Callitris glaucophylla*). The eastern part of our study area is dominated by patches of Box Gum and White Cypress Pine woodland, including threatened White Box (*Eucalyptus albens*) woodland, Yellow Box (*Eucalyptus melliodora*) woodland, Blakely's Red Gum (*Eucalyptus blakelyi*) woodland and derived grasslands.

Gecko models

Plasticine models are useful for estimating rates of predation (Daly et al. 2008, Sato et al. 2014). We created a prototype model of *G. versicolor* using non-toxic sculpting clay (Chavant NSP

Hard Clay). The models were based on mean morphological measurements taken from adult specimens previously recorded in the field (N A. Hansen unpublished data). We used a prototype to create silicon molds for mass model production. We then painted the models with non-toxic paint to mimic the body color of *G. versicolor* (Fig. S1 A). We deployed a total of 540 models.

Several studies have used plasticine models to estimate predation rates, typically targeting visual predators like diurnal birds or mammals (Daly et al. 2008, Purger et al. 2008, Sato et al. 2014, Bateman et al. 2016). However, *G. versicolor* is a nocturnal species (Gruber and Henle 2004, Cogger 2014) and predation of this species is largely by nocturnal predators (Henle 1990). Therefore, to evaluate potential impacts of predators that use olfaction for hunting such as nocturnal mammals and reptile predators, we synthesized and applied *G. versicolor* odour to one of the two models at each plot (n = 10 models per transect). We synthesized odour by fermenting skin, faeces and bedding from captive *G. versicolor* individuals in water, for at least four weeks. We then strained the liquid and soaked plasticine models overnight in the mixture to produce a scented model. Separate latex gloves were used for each model to ensure no human scent was transferred on to models, or cross contamination of gecko scent between scented and unscented models.

Experimental design and survey protocol

We established a blocked experiment with seven replicate study locations (Fig. 1B and 1C). Each location comprised a remnant patch of native vegetation surrounded by a matrix of three different farmland types: (1) “cropping”: a cereal crop paddock (largely wheat and some barley), (2) “linear plantings”: a linear strip of fenced restoration vegetation, predominantly *Acacia* midstorey with occasional eucalypt species, grassy ground cover, occasionally subject to disturbance by sheep grazing, (3) “grazed pasture”: a rotationally grazed paddock, cleared of midstorey and canopy cover with the occasional paddock tree (Fig. 1C). We created a fourth experimental farmland type by apply a native woody mulch (hereafter “woody debris”) to a cropped paddock after crop harvest to examine if we could temporarily provide shelter and protection for reptiles in the cropping farmland type. Forest cover across the study area is < 11% and remnant patch size range between 64.89 ha and 23,073 ha (mean patch size = 6759.94 ± SE 4212.50 ha). The dominant predators recorded (Table 1) are widespread generalists found throughout farmland patches and matrix alike so, patch size is unlikely to influence the main of predators recorded (Storch et al. 2005, Anderson and Burgin 2008, Daly et al. 2008, Arthur et al. 2010).

At each location, we located five paired sets of plasticine models along 400 metre transects centred on, and running perpendicularly to, the edge of a remnant patch. We placed model sets at the edge (0 metres), and at 20 metres and 200 metres into both the remnant patch and the adjacent farmland type (Fig.1D). We positioned models near to, but not completely obscured by, ground cover (e.g. crop row, mulch or grasses). To examine how harvesting influenced predation risk, we deployed a new set of models before and after crops were harvested (“harvesting”). We placed a single camera trap (Scout Guard SG560K-8mHD; Gotcha Traps Pty Ltd) at each plot (i.e. 0 m, 20 m and 200 m into a remnant patch, 20 m and 200 m into a paddock; Fig 1D) to identify species of predators near the models over a four-day period. Access constraints prevented one pasture treatment at one location from being surveyed.

We considered a predation attempt to be the displacement of the model from its original position, complete removal, or visible signs of attack (bite, claw or scratch marks; Fig. S1 B and C). We also considered investigation of a model by a reptile predator, captured by camera footage, as a predation attempt. For each model, we recorded: whether the model had been attacked, the evidence for predation (visible signs, attached hairs, displacement), where on the model the visible signs of attack were located, and the type of predator attacking the model.

Statistical analysis

We examined the effect of changes within the matrix environment on predation risk by fitting generalized linear mixed models (GLMM; Bolker et al. 2009) assuming a binomial distribution with a logit-link function. We included the condition of the plasticine models (attacked vs. not attacked) as the response variable, fitting separate GLMMs for three groups of predators: all predators, mammal predators and bird predators. We modelled the interaction of treatment (four farmland types: planting, pasture, woody debris and crop), harvesting period (before and after harvesting) and habitat (remnant, edge and matrix) as fixed effects. Physical structure of the 20 m and 200 m points were not found to substantially differ and were pooled into each respective habitat types (remnant and matrix) for analysis. We included model type (scented and unscented) as an additive fixed effect. ‘Camera trap number’ was nested within location (sites were clustered into east and west) as random effects to account for regional variation across the geographical gradient of sites, repeated sampling units and camera trap differences within the data. To examine if scent influenced predation attempts between predators, we fitted separate GLMMs with the plasticine models (scented vs unscented) as the response variable and all predators and predator groups as fixed effects.

We calculated *P*-values using the ‘Anova’ function in the ‘lme4’ package to reveal significant effects and interactions of the model (Bates et al. 2013). We conducted a post-hoc analysis of significant interactions using the ‘lsmeans’ function (Lenth 2016).

We conducted all analyses using R 3.4.0 (R Core Team 2017).

Results

Of the 540 models we deployed, 186 models were attacked and investigated by 21 species, 15 of which are considered potential gecko predators (Table 1). We identified predation attempts by model attacks (30 %; n = 55), camera identification (41 %; n = 77) or both (29 %; n = 54). Animals investigating or attacking the models included birds (55.1 % of attacks; n = 114), mammals (41.1 % of attacks; n = 85), reptiles (3.4 % of attacks; n = 7) and invertebrates (0.5 % of attacks; n = 1). Three species dominated the predation events: White-winged Chough *Corcorax melanorhamphos* (n = 61 predation events), Red Fox *Vulpes vulpes* (n = 28 predation events) and Australian Magpie *Cracticus tibicen* (n = 20 predation events) (Table 4). Predation markings from bird and mammals were predominantly located on the head, tail, or hind limbs, suggesting that the predators perceived models as potential prey (Daly et al. 2008, Sato et al. 2014). Nearly all the predator species were native (86.7 % of attacks, n = 13) with the remainder exotic (13.3 % of attacks, n = 2) (Table 1).

Effect of farmland type on predation risk in contrast to the adjacent edge ecotone and remnant patch

We did not find significant interactive effects of ‘treatment’, ‘habitat’ and ‘harvesting’ on predation risk of lizard models ($P = 0.08$) (Table 2). We did not detect any significant differences in total predation attempts ($P = 0.33$), or predation of models by birds ($P = 0.61$) or mammals ($P = 0.18$) between farmland types (Table 2).

Instead, we found models located in edge habitats suffered higher predation (all predators)than in the matrix or remnant patches ($P = 0.02$) (Table 2; Fig. 3A). Avian predation attempts were similarly highest at the edge (36 % of attacks; mean 6.43 ± 1.09SE attacked models) compared to matrix (30 % of attacks; mean 5.29 ± 1.02SE attacked models) and remnant patches (34 % of attacks; mean attacked models 6.00 ± 1.40SE) ($P < 0.01$) (Table 2; Fig. 3B). Predation attempts by mammals were similar across habitat types, with 40 % of attacks in remnant patches (mean attacked models = 4.43 ± 0.92SE), 29 % of attacks in edge habitat (mean attacked models = 3.29 ± 0.48SE), and 31 % of attacks (mean attacked models = 3.43 ± 0.84SE) in matrix habitats ($P = 0.23$) (Tables 2 and S1).

Effect of crop harvest on predation risk

We found no interactive effect of ‘treatment’, ‘habitat’ and ‘harvest’, suggesting removal of crops did not increase predation attempts by predators or between groups of predators within crop paddocks ($P < 0.08$) (Table 2). Instead, we found predation attempts by (all) predators were significantly lower along the crop transect after harvesting, compared to the woody debris transect ($P = 0.02$). Predation by birds was highest at the edge prior to harvesting compared to the remnant patches and matrix ($P = 0.04$) (Tables 2 and S1; Fig. 5A). Similarly, predation attempts by mammals were higher at the edge prior to crop harvesting, compared to the matrix ($P < 0.01$) (Figure 5B). However, we found no significant contrasts after harvesting (Table S1; Fig. 5B).

Other responses

Scented models were attacked in higher numbers (60 % of total attacks; n = 50) by mammal predators compared to unscented models (40 % of total attacks; n = 33) ($P = 0.05$) (Figure S2).

Predation attempts by both predators (all predators) and bird predators were not influenced by scent (all predators: P = 0.10 birds: P = 0.17 respectively). Sample sizes of reptile predator attacks on models were too small to analyse (n= 7 scented; n= 3 unscented).

Discussion

We sought to evaluate how a range of farm management practices influence predation risk and consequently develop new insights into the avoidance of particular farmland types by reptiles. Our findings reveal habitat type (remnant patches, edge and farmland) and temporal changes (between harvesting periods) were the most important factors influencing predation risk, with highest frequency of predation attempts of models at habitat edges, particularly prior to harvesting. We also found the harvesting of crops did not result in significantly increased predation attempts on models in the crop fields, or other farmland types. Predation risk within edge habitats may act as a potential barrier to movement of lizards into the matrix, and we argue that it may contribute to the decline in the abundance of reptiles from edges into some farmland habitats observed within a previous study (Hansen 2018) . Based on this information, we can begin to build an improved capacity for managing predation risk and enhance reptile conservation in human-natural linked agricultural systems.

The influence of farmland type, in contrast to the edge and remnant patches, on predation risk

A key finding of this study was that edge habitats are “risker” than the matrix for lizards, with both mammal and bird predators contributing to predator attacks along edges. We found elevated predation risk at the edge irrespective of adjacent farmland type. Further, both matrix-generalist predators, such as the Red Fox *Vulpes vulpes*, and the Australian Raven *Corvus coronoides*, and forest-specialist predator species such as Yellow-footed antechinus *Antechinus flavipes* contributed to predation attempts at the edge (Table 1).

Our findings are partially congruent with our prediction that edges would result in higher predation risk (Introduction, question 1). This is consistent with previous studies showing increased predation in edge habitat, particularly by mammalian and avian predators (Keyser et al. 1998, Šálek et al. 2010). Higher rates of predation at edges could be due to a combination of predators using edges as movement corridors between landscape elements (consuming prey along the way; Piper et al. 2002, Storch et al. 2005, Anderson and Burgin 2008), generalist predators crossing edge habitat when penetrating patches from adjacent modified habitats (Andrén 1995, Huhta et al. 1996, Thompson et al. 2008) and forest-specialist predators spilling over opportunistically from patch into edge habitats (Storch et al. 2005). Higher diversity of forest-specialist and farmland generalist predators at edges may increase predation risk because a greater variety of predators are present (Andrén 1995, Piper et al. 2002), resulting in more models being found. In our study area, reptile models were likely more exposed in open, edge habitats which were cleared dirt tracks and fence lines and subsequently more visible to predators compared to farmland and remnant patches.

Some of the bird species observed within our study (e.g. Laughing Kookaburra *Dacelo novaeguineae*, Australian Ravens *Corvus coronoides*, Pied Butcherbirds *Cracticus nigrogularis*, Australian Magpies *Cracticus tibicen*; Table 1) are known to take advantage of the elevated perching opportunities associated with human-made structures like fence posts at edges (Sewell and Catterall 1998, Bergin et al. 2000, Vander Haegen et al. 2002, Anderson and Burgin 2008) and forage in both remnant patches and adjacent modified areas (Anderson and Burgin 2008). Mammalian predators may take advantage of the concealment provided by adjacent woodland habitat, using edges as travel corridors (Andren 1992, Bergin et al. 2000). Previous studies also have suggested some mammalian predators (e.g. Red Foxes *Vulpes vulpes*, mustelids; Table 1) show a preference for habitat edges compared to forest and farmland interiors (Šálek et al. 2009, 2010). Our findings demonstrate both the matrix and remnant patches are subject to similar levels of elevated predation risk. These results likely reflect the foraging strategies of the generalist predator species observed and the degree of disturbance throughout the remnant patches within our study area. Remnant patches close to farmland edges are vulnerable to spill over of associated predator communities benefiting from crop systems (Andren 1992, Vander Haegen et al. 2002, Rand et al. 2006) and is a process identified as a key driver of species decline within remnants (Saunders et al. 1991, Matthews et al. 1999). Surprisingly, we could not find published studies on the implications of spill over of predators from farmland on reptiles using patches, or adjacent matrix and suggests this is an area of fragmentation research that warrants critical attention.

The influence of crop harvest on predation risk

There are strong ecological reasons (Introduction, question 2) to expect harvesting of crops to increase predation attempts on models within crop fields (Thorbek and Bilde 2004, Purger et al. 2008, Cosentino et al. 2011, Rotem et al. 2013) and adjacent habitats (Schneider et al. 2013). We observed a trend for a decline in predation attempts after harvesting along the crop transect and an increase in the woody debris transect, leading to a significant difference between crops and woody debris after harvest (Figure 4). There may have been a transitory shift of predator populations into nearby woody mulch and remnant areas due to the rapid removal of resources in the crop paddock.

We found both mammalian and bird predators contributed to the high number of predation attempts on models in edge habitats prior to harvesting compared to the matrix, and compared to the lower attacks on models in the matrix and remnant patches after harvesting (bird predators only). We suggest predator breeding season – particularly for bird predators – may have intensified predation on lizard models within and nearby the agricultural matrix before harvesting. Our pre-harvesting surveys corresponded with the breeding period for many passerines within Australia (September-January; Howe 1984). Previous studies attribute increased predation by birds on reptiles to the high density and opportunistic foraging behavior of adults during the breeding season which may lead to reduced rates of predation when the breeding season ends and individuals move to other areas in the landscape (Castilla and Labra 1998, Padilla et al. 2007). We are unaware of any studies that causally link increased predation risk in edge habitat with avian breeding season, or if predator young of predators produced during the year contribute to observed trends, and suggest the mechanisms behind avian predatory responses to changes in edge-farmland composition and landscape structure need to be further tested. However, the patterns of mammalian predator activity in modified landscapes are more likely related to abundances and distribution of main prey, rather than breeding season (Tattersall et al. 2002, Miller et al. 2006, Šálek et al. 2010).

Other responses: use of scent on predators of replica models

The use of replica models is an important method for understanding potential risk of predation as treatments and sample size can be standardised, without compromising live specimens (Daly et al. 2008, Thompson et al. 2008). However, the detectability of plasticine models, particularly by mammals that rely on olfactory cues or those with a nocturnal foraging strategy, may be reduced because of their unnatural scent, or lack of scent (Major and Kendal 1996, Bayne and Hobson 1999). We attempted to counteract this possible bias by applying a natural gecko scent to a proportion of models, and testing whether an increase in the variety of predators could be detected. Our findings suggest the application of a natural gecko scent increases the detectability of plasticine models for olfactory-searching predators, including nocturnal foraging species such as the Yellow-footed Antechinus *Antechinus flavipes* and the Common Dunnart *Sminthopsis murina*. Both species were observed on camera footage, and attacked only the scented models. The scent likely increased the detectability of the model. However, some mammals are also neophilic and attracted to new or unusual scents (O'Connor et al. 2005, Bytheway et al. 2016). Determining whether the responses we observed were a realistic predatory response to natural prey, or to a novel object would be a necessary next step to understanding the methodological accuracy for estimating predation risk.

Management implications and future research

Understanding mechanisms underpinning the avoidance of particular habitat by reptiles can help identify habitats that may influence dispersal efficiency or movement (Whittingham and Evans 2004, Driscoll et al. 2013b) and inform management decisions to facilitate the persistence of reptiles in fragmented agricultural landscapes (Barton et al. 2015, Kay et al. 2016b). Our study suggests predation risk – a key ecological driver of reptile movement (Daly et al. 2008, Sato et al. 2014) – can be significantly influenced by anthropogenic land use changes. Predation risk may further reduce the suitability of habitat for reptiles in agricultural areas (Driscoll et al. 2013b, Sato et al. 2014). Our results show predation, from multiple predators, are highest at edges. These areas are already subject to extreme simplification and provide limited shelter from predators. Thus, reptiles may perceive these areas as high risk, low quality habitat and avoid them or, removal of individuals may reduce patch occupancy (Gehring and Swihart 2003, Pita et al. 2007). Therefore, targeted management of edge habitats could influence species movements and potentially increase connectivity for some reptiles within agricultural areas. In a previous study, we found reptile abundances to be highest in some of these edge habitats, and lowest within the adjacent farmland (N. A. Hansen, unpublished data). Based on this information, if reptiles accumulate at edges, and higher predation risk at edges may result in a population sink, then actions to reduce mortality risk within farmland may be important.

Vulnerability to predation may be increased by a lack of shelter within edge habitats increasing visibility of reptiles to predators (Anderson and Burgin 2008, Sato et al. 2014). Reducing the hostility of edges by providing shelter (rocks, logs litter and grasses) will offer refuge and provide stepping stones for reptiles between remnant patches and farmland (Michael et al. 2011, Manning et al. 2013). Other studies have found that the lower stratum vegetation cover can provide shelter for reptiles from predators (Fischer et al. 2003, Michael et al. 2015). We also suggest increasing the ratio of interior area to edge in areas where dispersal might be important (e.g. by widening linear plantings) could reduce penetration of predators and improve the occurrence of reptiles within farmland (Laurance and Yensen 1991, Graham et al. 2013).

By providing new insights into why a target species might avoid a particular matrix type, our findings highlight important future research priorities. Dispersal and movement of a patch-dependent species between habitat patches may be altered by perceived predation risk in the matrix (Amo et al. 2007, Driscoll et al. 2013b, Sato et al. 2014). A necessary next step is to examine if perceived predation risk influences an animal’s willingness to move between patches or opportunistically utilise the matrix (Ewers and Didham 2006, Rotem et al. 2013).Further, if lizards are attracted to edges because of basking opportunities and supplementary prey food resources from the adjacent farmland (Anderson and Burgin 2008, Rotem et al. 2013), and as a result, are exposed to increased predation pressure, could edges act as a sinks and influence movement from patches?

Additionally, we are not aware of any studies specifically investigating the use of edges by predators and the consequences reptile populations in agroecosystems. We therefore suggest an important area of research is the need to establish the relative impacts of both native and exotic predators on reptile use of agricultural landscapes. For example, what is the impact of predation risk on reptile survival? Do mitigation measures to reduce predation risk in edge habitat (e.g. pest control of feral predators, or additional cover) improve reptile abundance in farmland? How far do predator’s forage from edges (patch vs farmland)? Is the effectiveness of plantings as habitat and for movement and the quality of remnant patches reduced due to predation risk at edges? Answering these questions will have consequences for the size and design of restoration areas and the management of remnant patches in croplands.

Conclusions

Habitat fragmentation and loss has contributed to the decline of many reptile species worldwide. Our study demonstrates that edge habitats are potentially “risky” for lizards, more so than the matrix. We suggest increasing shelter opportunities for lizards and to reducing the size of edges particularly where dispersal may be important (such as between remnants and linear plantings).

Authors contributions

N.A.H designed the study and methodology, collected the data, performed the lead writing and analysis. C.F.S designed the study and edited. D. R.M and D.B.L edited. D.A.D designed the study, assisted with the analysis and edited.

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Table 4. Summary of species captured on camera or identified by attack marks. Note: ˆpotential predator of *Gehyra versicolor*; **known to include reptiles as prey.

Group	Scientific name	Common name
Invertebrate	*Iridomyrmex sp.*	Meat-eating ants**
Bird	*Aquila audax*	Wedge-tailed Eagle** (Brooker and Ridpath 1980)
	Corcorax melanorhamphos	White-winged chough** (Anderson and Burgin 2008)
	Corvus coronoides	Australian Raven**(Sato et al. 2014)
	Cracticus tibicen	Australian Magpie**(Anderson and Burgin 2008)
	Cracticus torquatus	Grey butcherbird**(Anderson and Burgin 2008)
	Dacelo novaeguineae	Laughing Kookaburra**(Anderson and Burgin 2008)
	Dromaius novaehollandiae	Emu**
	Grallina cyanoleuca	Magpie-lark
	Pomatostomus temporalis	Grey crowned babbler
	Struthidea cinerea	Apostle bird**(Chapman 2001)
Mammal	*Vuples vulpes*	Red Foxˆ** (Henle 1990)
	Macropus giganteus	Eastern Grey Kangaroo
		Swamp/rock wallabies
	Trichosurus vulpecula	Brush-tail Possum (How and Hillcox 2000)
	Mus musculus	House mouseˆ** (Henle 1990)
	Lepus europaeus	European hare
	Sminthopsis murina	Common Dunnart**
		Livestock (cow, sheep)
	Capra hircus	Feral goat
	Antechinus flavipes	Yellow-footed antechinus**
Reptile	*Varanus gouldii*	Sand monitorˆ** (Henle 1990)
	Varanus varius	Lace monitorˆ** (Henle 1990, Guarino 2001)
	Tiliqua Scincoides	Eastern Blue- tongue lizard

Table 5. GLMM results for harvest (pre-harvesting vs. post-harvesting), treatment (four farmland types: planting, pasture, woody debris and crop) and habitat (remnant native vegetation, edge and matrix) on predation rates on gecko models. Note: model type = scented vs. unscented.

Response	**Model terms**	***X*2**	**Df**	**P**
All predator	treatment*habitat*harvest + model.type + (1|location/camera trap number)			
	treatment	3.79	3	0.29
	habitat	8.09	2	0.02
	harvest	0.62	1	0.43
	model.type	2.51	1	0.11
	treatment:habitat	6.86	6	0.33
	treatment:harvest	9.88	3	0.02
	habitat:harvest	0.55	2	0.76
	treatment:habitat:harvest	11.26	6	0.08
Bird predator	treatment+habitat+harvest + treatment:habitat+ treatment:harvest+harvest:habitat+(1|location/camera trap number)			
	treatment	5.35	3	0.15
	habitat	19.20	2	<0.01
	harvest	3.22	1	0.07.
	treatment:habitat	4.50	6	0.61
	treatment:harvest	6.74	3	0.08
	habitat:harvest	6.38	2	0.04
Mammal predator	treatment + habitat + harvest + model.type+ treatment:harvest + harvest:habitat + treatment:habitat+(1|location/camera trap number)			
	treatment	0.91	3	0.82
	habitat	2.94	2	0.23
	harvest	1.65	1	0.20
	treatment:harvest	4.40	3	0.22
	habitat:harvest	9.17	2	0.01
	treatment:habitat	8.93	6	0.18

Figure headings

Figure 1 (A) The geographical location of the study area in New South Wales, Australia. (B) The approximate locations of study locations (represented by the open circles). (C) Location layout for each block design; coloured lines indicate each transect (or treatment) examined during the study. Each treatment extends from the remnant into four farmland types (planting, pasture, woody debris and crop). (D) Configuration of models and cameras for each treatment.

Figure 2 Examples of predation on gecko models from camera footage. From top left to right clockwise: Australian Magpie *Cracticus tibicen*, Laughing Kookaburra Dacelo novaeguineae, Wedge-tailed Eagle *Aquila audax,* Grey Butcherbird Cracticus torquatus, Red Fox *Vulpes vulpes* and Lace monitor *Varanus varius*.

Figure 3 Significant interaction between habitat types and (A) all predators and (B) bird predators. Letters indicate post-hoc pairwise contrasts. Different letters symbolize when contrasts are significantly different and error bars indicate 95 % confidence intervals with fitted estimates plotted on the x-axis.

Figure 4 Significant relationships between habitat (A), harvesting and treatment (B) and the three-way interaction between treatment, habitat and harvesting for predation attempts by all predators on plasticine models. Letters indicate post-hoc pairwise contrasts. Different letters symbolize when contrasts are significantly different and error bars indicate 95 % confidence intervals with fitted estimates plotted on the x-axis. R = remnant patch, E = edge and M = matrix.

Figure 5 Significant interaction of habitat and harvesting from (A) bird predators and (B) mammal predators on gecko models. Letters indicate post hoc contrasts and error bars indicate 95 % confidence intervals with fitted estimates plotted on the x axis.

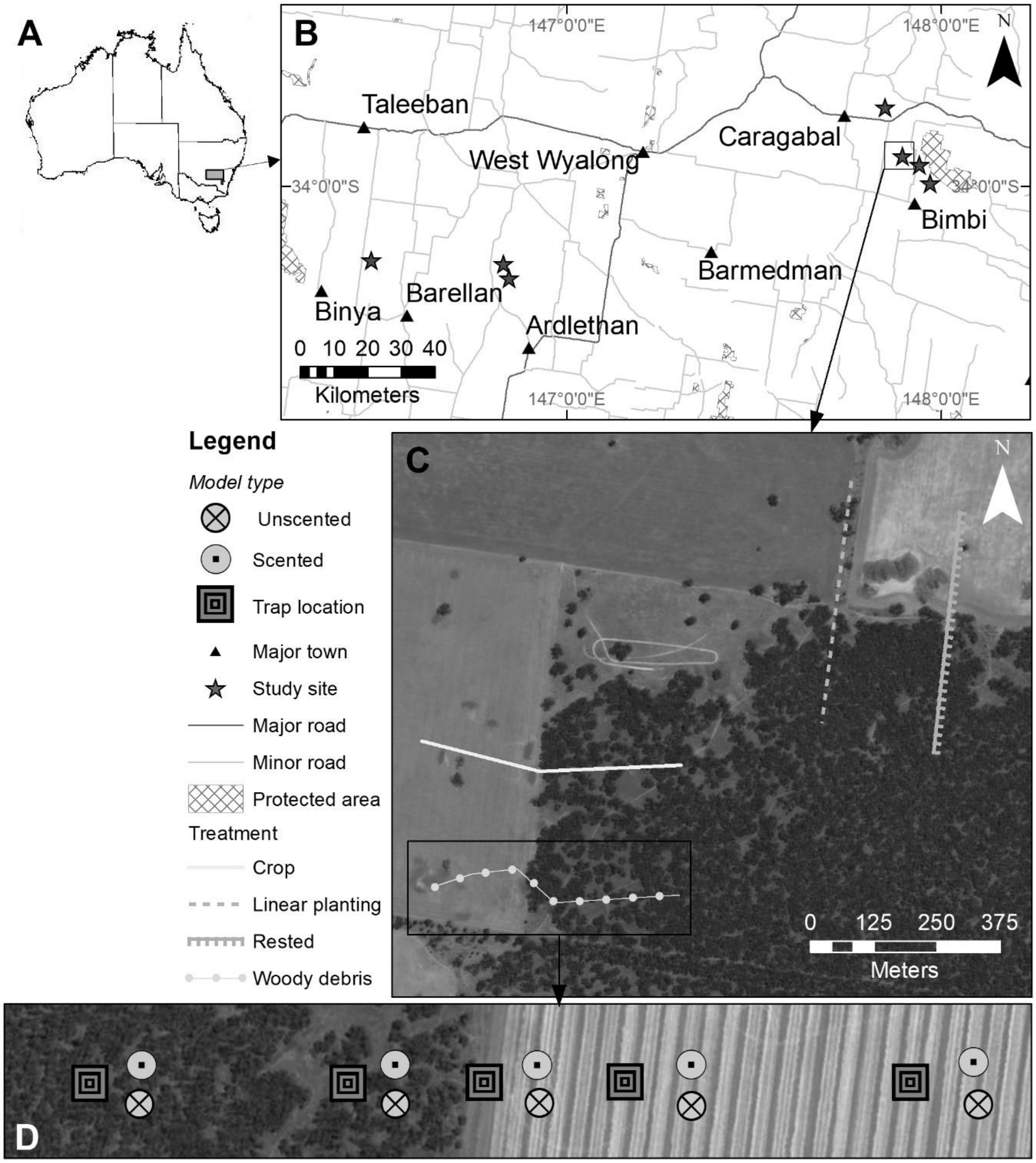

A
B
147°0'0"E
148°0'0"E
N
Taleeban
Caragabal
West Wyalong
34°0'0"S
34°0'0"S
Bimbi
Barmedman
Barellan
Binya
Ardlethan
0 10 20 30 40
Kilometers
147°0'0"E
148°0'0"E
Legend
Model type
Unscented
Scented
Trap location
Major town
Study site
Major road
Minor road
Protected area
Treatment
Crop
Linear planting
Rested
Woody debris
C
N
0 125 250 375
Meters
D

Fig.1


2015.11.03 17:00:51
2015.11.
2015.10.07
2016.01.31 08:02:38
2015.11.11 01:16:03
2016.02.1

Fig. 2

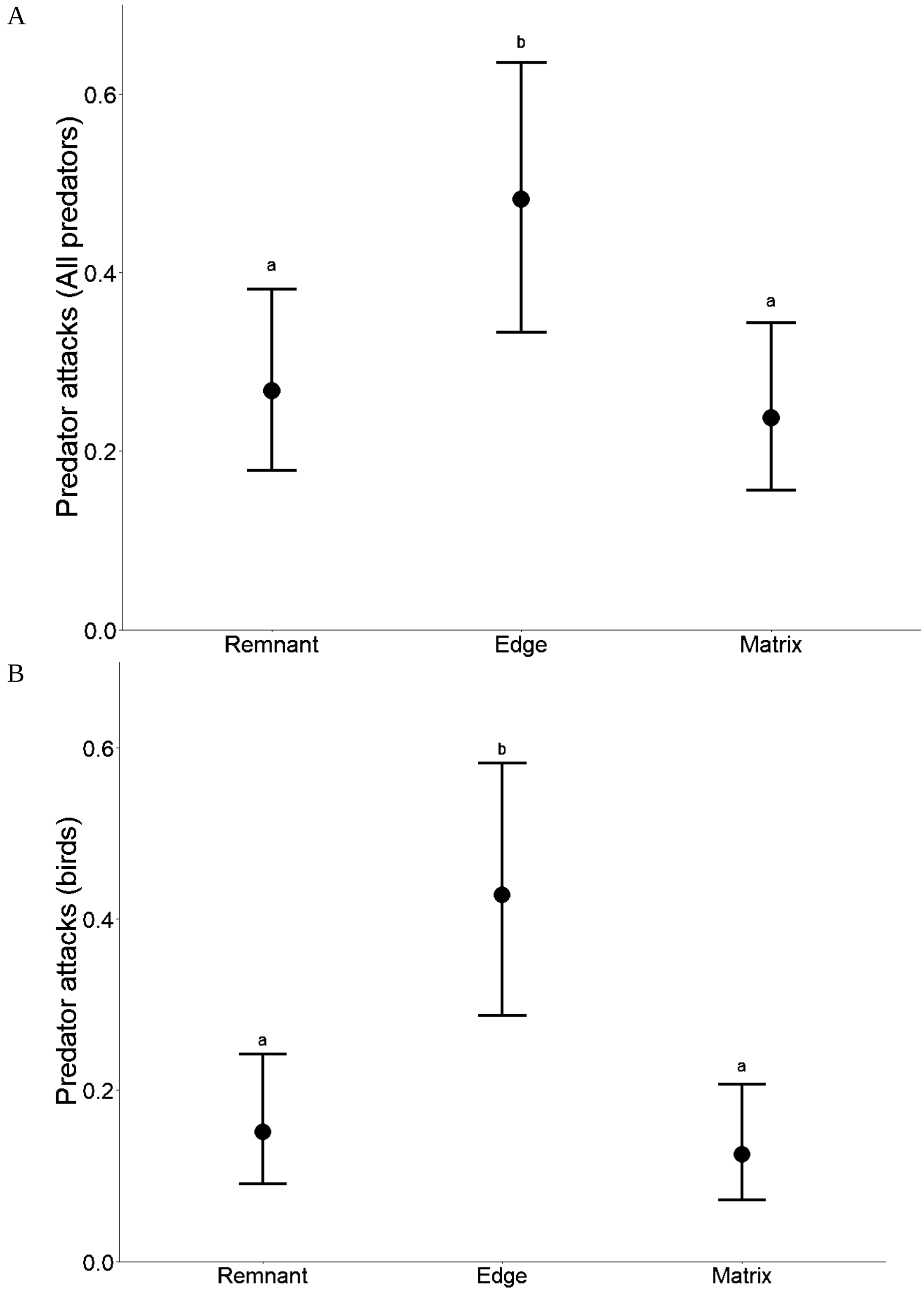
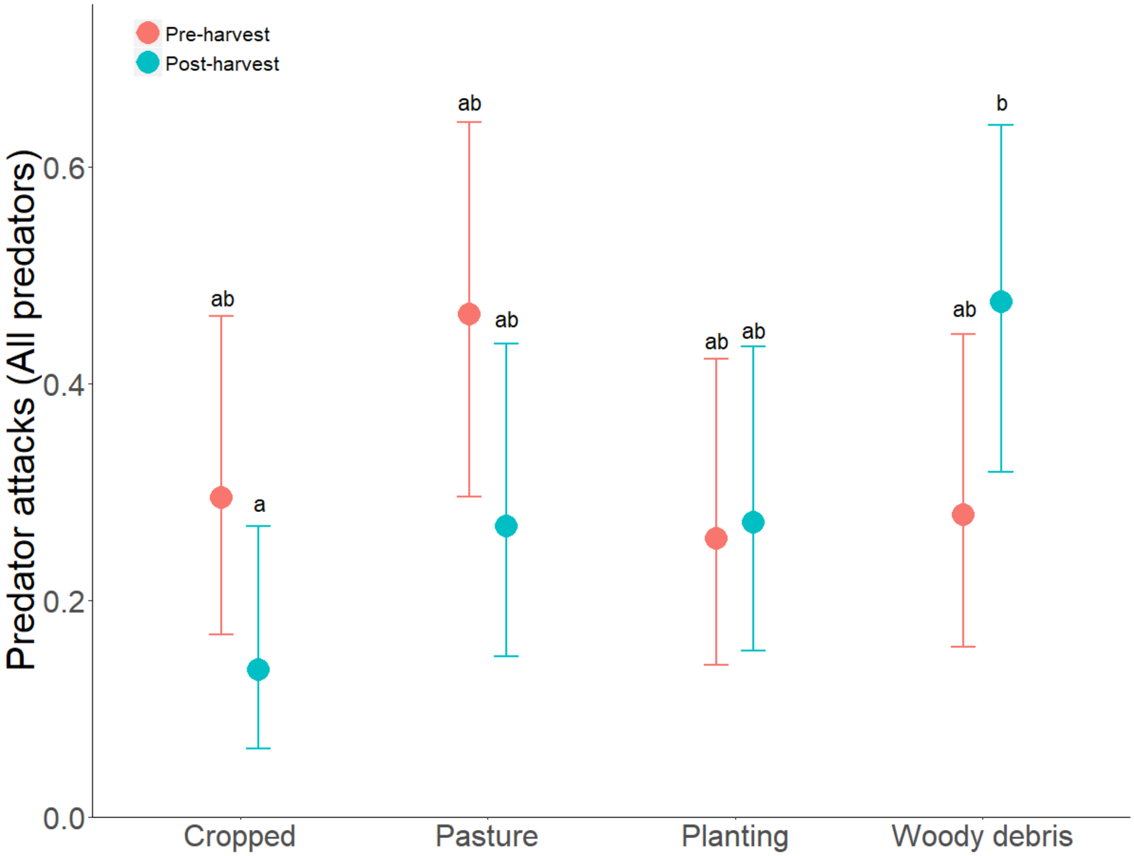

A
Predator attacks (All predators)
0.0
0.2
0.4
0.6
a
b
a
Remnant
Edge
Matrix
B
Predator attacks (birds)
0.0
0.2
0.4
0.6
a
b
a
Remnant
Edge
Matrix

Fig.3



● Pre-harvest
● Post-harvest
Predator attacks (All predators)
0.0
0.2
0.4
0.6
ab
a
ab
ab
ab
ab
ab
b
Cropped
Pasture
Planting
Woody debris

Fig. 4

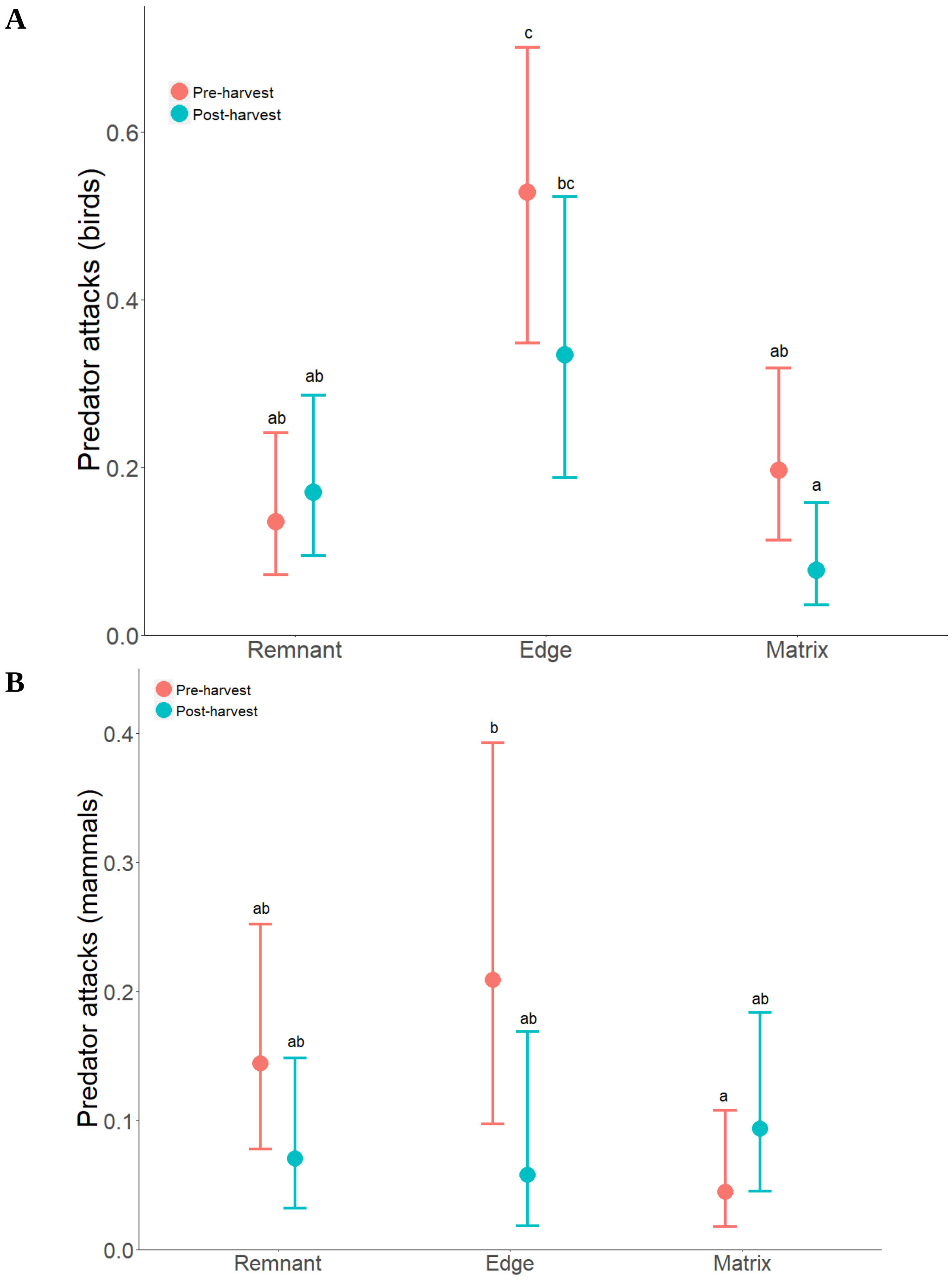

A
Pre-harvest
Post-harvest
Predator attacks (birds)
0.0
0.2
0.4
0.6
ab
ab
c
bc
ab
a
Remnant
Edge
Matrix
B
Pre-harvest
Post-harvest
Predator attacks (mammals)
0.0
0.1
0.2
0.3
0.4
ab
ab
b
ab
a
ab
Remnant
Edge
Matrix

Fig. 5

Supplementary material

Table S1. Summary of the GLMM results for predation rates from all predators, birds and mammals as predicted by interactions between harvesting (before and after harvesting), treatment (crop, woody debris, planting and pasture) and habitat (remnant patches vs. edge vs. matrix) fitted as fixed effects. Given the spatial clustering of the sites, we included the 'Site' and 'Trap number' as random effects to account for site variation, repeated sampling units and trap differences within the data. Note: model type= scented vs. unscented.

Response	**Model terms**	**Estimate**	**SE**	**z value**	**P**
All predator	(Intercept)	0.11	0.73	0.15	0.88
	treatmentPasture	-1.30	1.09	-1.19	0.23
	treatmentPlanting	0.07	0.99	0.07	0.94
	treatmentWoody debris	0.06	0.99	0.06	0.96
	habitatMatrix	-2.06	0.95	-2.17	0.03
	habitatRemnant	-2.43	1.00	-2.44	0.01
	harvestPre-harvest	-0.31	0.86	-0.36	0.72
	model.typeUnscented	-0.33	0.21	-1.59	0.11
	treatmentPasture:habitatMatrix	2.43	1.37	1.77	0.08.
	treatmentPlanting:habitatMatrix	0.72	1.29	0.56	0.58
	treatmentWoody debris:habitatMatrix	1.71	1.27	1.34	0.18
	treatmentPasture:habitatRemnant	2.94	1.41	2.08	0.04
	treatmentPlanting:habitatRemnant	1.26	1.32	0.96	0.34
	treatmentWoody debris:habitatRemnant	2.54	1.31	1.94	0.05
	treatmentPasture:harvestPre-harvest	1.19	1.31	0.91	0.36
	treatmentPlanting:harvestPre-harvest	0.99	1.21	0.82	0.41
	treatmentWoody debris:harvestPre-harvest	1.04	1.22	0.85	0.40
	habitatMatrix:harvestPre-harvest	0.59	1.16	0.51	0.61
	habitatRemnant:harvestPre-harvest	2.62	1.17	2.25	0.02
	treatmentPasture:habitatMatrix:harvestPre-harvest	-0.61	1.66	-0.37	0.71
	treatmentPlanting:habitatMatrix:harvestPre-harvest	-1.05	1.58	-0.67	0.51
	treatmentWoody debris:habitatMatrix:harvestPre-harvest	-2.29	1.58	-1.45	0.15

	treatmentPasture:habitatRemnant:harvestPre-harvest	-2.66	1.66	-1.61	0.11
	treatmentPlanting:habitatRemnant:harvestPre-harvest	-4.06	1.62	-2.51	0.01
	treatmentWoody debris:habitatRemnant:harvestPre-harvest	-4.87	1.61	-3.03	<0.01
Mammal predator	(Intercept)	-2.75	0.90	-3.06	<0.01
	treatmentPasture	-2.34	1.52	-1.54	0.12
	treatmentPlanting	1.24	1.08	1.15	0.25
	treatmentWoody debris	0.77	1.08	0.71	0.48
	habitatMatrix	0.14	1.04	0.13	0.90
	habitatRemnant	0.43	0.99	0.44	0.66
	harvestPre-harvest	1.89	0.77	2.45	0.01
	treatmentPasture:harvestPre-harvest	0.27	0.84	0.32	0.75
	treatmentPlanting:harvestPre-harvest	-0.67	0.81	-0.83	0.40
	treatmentWoody debris:harvestPre-harvest	-1.23	0.73	-1.68	0.09.
	habitatMatrix:harvestPre-harvest	-2.24	0.80	-2.80	0.01
	habitatRemnant:harvestPre-harvest	-0.67	0.74	-0.91	0.36
	treatmentPasture:habitatMatrix	2.95	1.61	1.83	0.07.
	treatmentPlanting:habitatMatrix	-1.28	1.31	-0.98	0.33
	treatmentWoody debris:habitatMatrix	0.24	1.28	0.19	0.85
	treatmentPasture:habitatRemnant	1.66	1.55	1.07	0.29
	treatmentPlanting:habitatRemnant	-2.05	1.23	-1.68	0.09.
	treatmentWoody debris:habitatRemnant	-0.17	1.19	-0.14	0.89
Bird predator	(Intercept)	-0.92	0.66	-1.39	0.17
	treatmentPasture	-0.88	0.92	-0.95	0.34
	treatmentPlanting	0.58	0.84	0.69	0.49
	treatmentWoody debris	1.05	0.84	1.25	0.21
	habitatMatrix	-2.37	0.86	-2.74	0.01
	habitatRemnant	-1.54	0.81	-1.89	0.06
	harvestPre-harvest	1.09	0.63	1.72	0.09.
	treatmentPasture:habitatMatrix	1.71	1.09	1.57	0.12
	treatmentPlanting:habitatMatrix	0.46	1.03	0.45	0.66
	treatmentWoody debris:habitatMatrix	0.26	1.03	0.26	0.80
	treatmentPasture:habitatRemnant	1.79	1.07	1.67	0.09.
	treatmentPlanting:habitatRemnant	0.19	1.03	0.18	0.86
	treatmentWoody debris:habitatRemnant	0.75	1.01	0.75	0.45
	treatmentPasture:harvestPre-harvest	0.59	0.72	0.82	0.41
	treatmentPlanting:harvestPre-harvest	-0.61	0.71	-0.85	0.39
	treatmentWoody debris:harvestPre-harvest	-1.00	0.69	-1.45	0.15
	habitatMatrix:harvestPre-harvest	0.27	0.61	0.45	0.65
	habitatRemnant:harvestPre-harvest	-1.07	0.59	-1.81	0.07.

Fig. S1 (A) Gecko model used in the experiment with an attack mark (highlighted in the square) (to scale). (B) Close-up evidence of teeth marks on the tail of the model from

Antechinus flavipes (highlighted by dotted line). (C) Example footage of A. flavipes detected on camera;

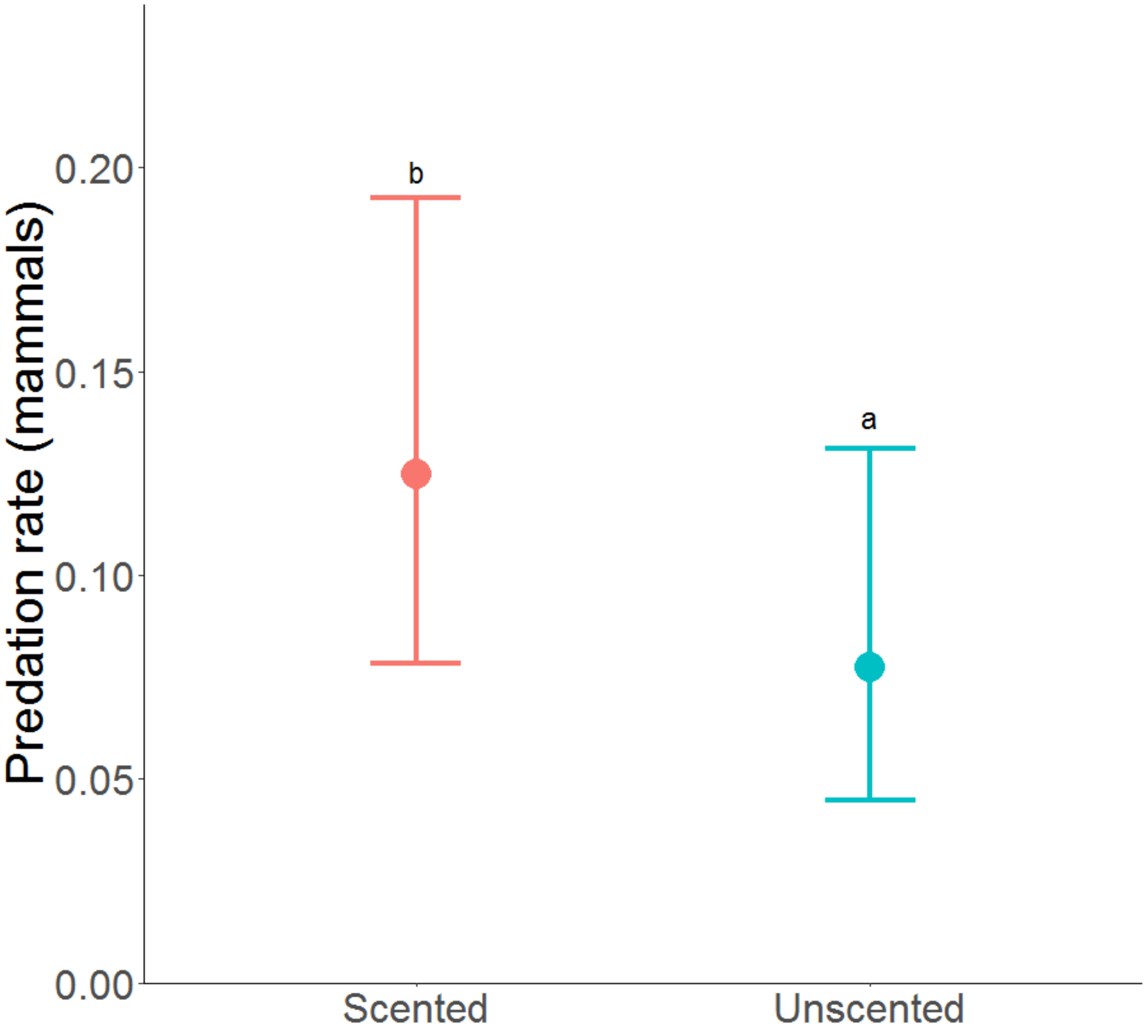

Predation rate (mammals)
0.20
0.15
0.10
0.05
0.00
b
a
Scented
Unscented

Fig. S2

CHAPTER FIVE:

MOVEMENT PATTERNS OF AN ARBOREAL SPECIES *GEHYRA VERISCOLOR* IN FRAGMENTED AGRICULTURAL LANDSCAPES REVEAL MATRIX AVOIDANCE

Movement strategies of a patch-dependent species in response to modified habitats have implications for the maintenance of functional connectivity, and local and meta- population persistence, across a fragmented landscape (Connette and Semlitsch 2013, Driscoll et al. 2013b, Kay et al. 2016b). Examining movement behaviour in response to differing habitat types is critical for identifying barriers to movement and dispersal in relation to particular landscape elements (Hoehn et al. 2007, Rotem 2012, Driscoll et al. 2013b). I quantified the fine-scale movement behaviour of a patch dependent gecko, *Gehyra versicolor,* in remnant patches, three different matrix types (crop, pasture and linear plantings) and at varying distances from the edge using fluorescent powder tracking and radio-telemetry.

A version of this chapter is *in press* in the Animal Conservation journal.

Abstract

Animal movement through agricultural landscapes is critical for population persistence of species within fragmented native vegetation patches. However, perceived habitat quality and the structural changes between differing land uses within such landscapes can reduce an animal's willingness to move. Understanding when animal movement behaviour varies in response to differing habitat types is necessary for identifying barriers to movement between habitat patches. We quantified the homing success and fine-scale movement behaviour of a patch-dependent gecko, *Gehyra versicolor*, in remnant patches, three different matrix types (crop, pasture and linear plantings), and at varying distances from the edge using fluorescent powder tracking, radio-telemetry and experimental displacement. We found displaced geckos in pasture environments orientated more strongly and moved farther into farmland after being released and, away from their home ranges in remnant patches. In contrast, we found strong homing ability of displaced animals in plantings and crop matrix types, with animals moving towards remnant patches and away from farmland. Importantly, from the 48 individuals radio-tracked, none moved into farmland, including pastures, despite 16 individuals approaching edge habitat. Because radio-tracked geckos did not move into pastures, or any other matrix type, movement further into pasture by displaced animals likely represents limited orientation capacity in pasture rather than preference for pasture. We conclude geckos behaviourally avoided the farmland, irrespective of the presence of complex habitat (e.g. linear plantings). Our findings suggest that, despite efforts to improve farmland quality by planting, farmland is not generally preferred compared to remnant native vegetation. Understanding habitat-specific movement behaviour is crucial to effectively identifying barriers to animal movement and will improve our efforts to conserve regional populations of patch-dependent species.

Keywords: ***functional connectivity, dispersal, land use, reptiles, movement behaviour, matrix permeability***

Introduction

Globally, expanding agricultural practices are fragmenting landscapes, with previously continuous native vegetation becoming embedded within a matrix of crops, pastures and habitat edges (Alexandratos and Bruinsma, 2012, Pfeifer *et al.*, 2017). Anthropogenic habitat change threatens species persistence, alters ecosystem processes, and erodes biodiversity (Pfeifer *et al.*, 2017, Saunders *et al.*, 1991). The persistence and occupation of native habitat specialists within fragments depends on an individual's ability to disperse through modified habitats and between patches as well as cope with rapid changes to their habitat (Connette and Semlitsch, 2013, Rittenhouse and Semlitsch, 2006, Sarre *et al.*, 1995). Thus, movement patterns of patch-dependent animals in response to habitat edges, and to the perceived habitat quality of the adjacent matrix, can be important determinants of functional connectivity across landscapes (Baguette and Van Dyck, 2007, Connette and Semlitsch, 2013, Doherty and Driscoll, 2018).

Matrix quality can vary greatly and, for some species, can represent a genuine barrier, whereas for others it facilitates animal movement (Driscoll *et al.*, 2013, Ferrante *et al.*, 2017, Kay *et al.*, 2016b). Behavioural responses of individuals to habitat alteration can occur if there are abrupt differences in habitat type and composition (Connette and Semlitsch, 2013, Hawkes, 2009, Schtickzelle and Baguette, 2003), or if there is increased mortality or energetic costs associated with movement (Sato *et al.*, 2014, Schneider *et al.*, 2013). For example, a patch-dependent animal may avoid crossing habitat edges, or its movement pattern may vary in distance or orientation, depending on the quality of the adjacent matrix (Cooney *et al.*, 2015, Long *et al.*, 2005, Rittenhouse and Semlitsch, 2006). Thus, identifying which species are sensitive to habitat modification has important implications for management, as well as advancing ecological concepts about the matrix (Doherty and Driscoll, 2018, Driscoll *et al.*, 2013).

Reptiles are sensitive to habitat loss and modification due to their association with specific microhabitats (Manning *et al.*, 2013, Michael *et al.*, 2018, Triska *et al.*, 2017), and are undergoing severe declines in agricultural landscapes worldwide (Gibbons *et al.*, 2000, Thompson *et al.*, 2017). The orientation and movement decisions of reptile species in response to particular landscape features is likely to have profound impacts on conservation strategies aimed at mitigating the impacts of fragmentation for reptiles, such as restoration of farmland through linear plantings, or the protection of core remnant habitat. Our understanding of reptile movement has focused primarily on longer distance movement of larger reptiles (Smith *et al.*, 2009, Whitaker and Shine, 2003), home range use rather than understanding barriers to movement (Craig *et al.*, 2011, Gerner *et al.*, 2008, Stevens *et al.*, 2010) or experimental translocations into modified environments (Kay *et al.*, 2016b). However, knowledge of the movement behaviour of reptiles, particularly small species, within isolated patches and during that initial cross-habitat dispersal movement from patches, into the adjacent matrix, remain poorly understood.

In this study, we selected *Gehyra versicolor* as a model species to test the degree to which farmland condition functions as a barrier to woodland because this species has limited dispersal capability and a strong preference for native woody vegetation (Gruber and Henle, 2004, Michael and Lindenmayer, 2010, Sarre, 1998). Previous studies found that *G. versicolor* (syn. *G. variegata*) disperses well through natural habitat, but poorly in agricultural landscapes (Sarre *et al.*, 1995, Sarre, 1998). Displacement experiments are an ideal approach to test orientation ability in reptiles (Betts *et al.*, 2015, Kay *et al.*, 2016b) and therefore we tested two hypotheses to determine if differing farmland-woodland edges influenced movement behaviour and cross-habitat movement in *G. versicolor*:

Hypothesis 1. *Low contrast farmland environments (linear plantings) promote directional movement of displaced geckos into farmland, compared to high contrast farmland* *environments (pastures and crops*). Given the species preferred habitat of trees, logs and fallen timber (Cogger, 2014, Gruber, 2004), we hypothesised that displaced geckos would move straighter (e.g. longer segments, and linear tracks) in high contrast, low quality environments such as crops and pastures (Kay *et al.*, 2016b). Conversely, given the similarity of plantings to preferred habitats within remnant patches (e.g. trees, shrubs), we predicted the familiarity of habitats (Davis and Stamps, 2004, Roe *et al.*, 2010, Tuberville *et al.*, 2005) would result in shorter distance movements (e.g. shorter length segments, less linear tracks) in and, orientated towards, low contrast, high quality farmland types such as plantings (Roe *et al.*, 2010, Smith and Ballinger, 2001).

Hypothesis 2. *Geckos do not perceive woodland-farmland edges as a barrier to movement. G. versicolor* is known to occasionally use disturbed habitats (Hoehn *et al.*, 2007). We predicted if radio-tracked geckos crossed woodland-farmland edges, they would be more likely to detect and cross habitat edges adjacent to low contrast matrix environments (Gruber and Henle, 2004, Roe *et al.*, 2010, Tuberville *et al.*, 2005), such as linear plantings or crop paddocks prior to harvest, compared to high contrast matrix environments such as crop paddocks after harvest and pasture paddocks.

Understanding animal movement patterns is increasingly recognised as important to predicting fine-scale species responses to particular landscape features and quantifying the impact of habitat loss in human-modified systems (Connette and Semlitsch, 2013, Crane *et al.*, 2014, Kay *et al.*, 2016b). However, few empirical studies have explored the kinds of changes within the matrix that can facilitate cross-habitat movement through farming landscapes and their consequences for populations of native species. With growing pressure to intensify agricultural production (Garnett *et al.*, 2013), it is a global priority to determine the connectivity and habitat needs of fauna in these complex and changing human commodity production systems (Driscoll *et al.*, 2013, Glamann *et al.*, 2017, Tanentzap *et al.*, 2015). Our research provides important insights in understanding how farm management influences suitability of habitat for patch-dependent native species.

Materials and methods

Study species

Gehrya versicolor is a small (snout vent length = 47 mm), nocturnal (although see Bustard, 1967), arboreal and saxicolous species found throughout the temperate woodlands of south-eastern Australia (Cogger, 2014, Michael and Lindenmayer, 2010).

Study area

Our investigation encompassed four study sites located in the agricultural landscape of western New South Wales, Australia (Figure 20). This landscape is characterised by intensive cereal cropping (wheat, canola, lupin and barley) and livestock grazing (sheep *Ovis aries* and cattle *Bos taurus*) systems interspersed with patches of native vegetation. The dominant native vegetation types within remnant patches in the western part of our study area include mallee woodland (*Eucalyptus viridis*), with some white cypress pine (*Callitris glaucophylla*). The eastern part of our study area is dominated by patches of box gum and white cypress pine woodland, including the threatened white box (*Eucalyptus albens*), yellow box (*E. melliodora*), blakely's red gum (*E. blakelyi*) woodland and derived native grasslands.

Gecko collection

We hand-collected adult *G.vericolor* at night using a spotlight to search available habitat, and from pitfall and funnel traps situated along the edges of three farmland types (linear plantings, pastures and crop paddocks), and up to 200 metres into remnant patches. We fed captured geckos that were held in clear plastic containers (18cm x 12cm x 10cm) with a damp cloth, bark and leaf litter until conditions were ideal for release, which were defined as within 48 hrs of capture, and after sunset.

Displacement Experiment

To test hypothesis 1, we displaced a subset of geckos (n = 47) into three farmland enviroments (linear plantings, crops and pasture paddocks), while the remaining animals (n = 145) were released within remnant patches at their original capture locations, as a control condition. Displaced animals were initially captured in remnant patches and moved at least 300 metres from their original location in a covered container to reduce the likelihood of homing to their territories.

We marked geckos using fluroescent powder (pigments F002, F008, F016, F019 Abralux Colori Beghè srl, Italy). Each individual was marked with a different colour to avoid confusion should individuals crossed paths. We covered the ventral half of a gecko with fluroescent powder before release. The release positon of the geckos was kept consistent (due west to the matrix). Animals were released within an hour of sunset and on evenings with clear conditions (e.g. no rain or wind) to reduce confounding weather effects.

We followed fluorescent powder trails by illuminating the fallen powder by ultra violet light following the methdologies by and Sozio *et al.* (2013). Tracks were recorded until no additional powder could be found. We used GPS devices to mark the start and end points of a track. We used a a measuring tape and compass bearings to measure each step length and turning angle within a track. Each track segment (bearing and length) for an individual was transcribed into ArcMap using Geodesic in Data Management Tools and merged to create a complete track.

Telemetry

To test hypothesis 2, we radio-tagged a subset of captured geckos (n = 48) from their original point of capture within woodland patches. The maximum weight limit for tags for this species, as indicated from previous studies (Hansen et al. unpub), was between 7.5% and 8%

of their body weight (Beaupre *et al.*, 2004, Gerner *et al.*, 2008, Yet, 2014). Therefore, only adult individuals weighing more than 5.84 grams were used in this study. Miniature 0.38g, 151-MHz radio transmitters (Model PIP3 AD337, Sirtrack Pty Ltd) were mounted with superglue as other glues were unlikely to last the duration of the survey (Gruber and Henle, 2004). Tagged geckos were returned within 48 hr to their capture location.

Individuals were tracked daily for the life of the transmitter (~ 6 days) between September and November 2015 (pre- crop harvesting). We then tracked a new set of individuals from January – March 2016 (after harvesting). All relocations were determined by triangulation and homing-in methods (Stevens *et al.,* 2010). Each animal was located every hour throughout the evening and night (up to eight fixes per night; 17h, 18h, 19h, 20h, 21h, 22h, 23h and 24h) and once during the day for five consecutive days and nights. We obtained visual sighting of the tagged animals 75% of the time. All GPS locations were imported into ArcView (version 10.5).

Data analysis

To examine whether geckos exhibited different movement behaviour in response to edges, we characterised the orientation of each individual gecko by subdividing a complete track (e.g. the complete path from the release point to final detection) into steps (e.g. the distance between two change-points; see Figure 2; Edelhoff *et al.*, 2016). We corrected each step length to have the same position relative to the edge (e.g. segments in the east were reflected to the west). We then calculated the distance (in metres) of each step from the edge of the remnant patch using the “Distance”; Near Tool (ArcGIS).To test if increasing distance from both sides of the farmland-woodland edge influenced movement behaviour, we calculated the turning angle (e.g. change in direction; Edelhoff *et al.*, 2016) of each step and assigned a binary response of towards the edge (0) or away from the edge (1) for each segment length (or the "direction" response variable). Many studies analyse orientation data using circular statistical packages (Connette and Semlitsch, 2013, Kay *et al.*, 2016b, Obleser *et al.*, 2016, Sinsch and Kirst, 2016). However, limitations in features sufficient for fitting generalized linear mixed models (GLMM) such as a probability distribution, multiple interactions of fixed effects, random effects (e.g. individual variation between and within tracks) and predictive modelling are not available (Kamisan *et al.*, 2010, Kovach, 2011).

We tested whether geckos were orientating towards the edge, and relative to distance normalising and rescaling (Becker *et al.*, 1988) from the edge, in different habitat types (remnant versus matrix), within different matrix environments (or treatments: crop, pasture or linear plantings) by GLMM with a binomial distribution and a log link. Sex and site were fitted as additive effects. Variation between individual tracks and individual segments was accounted for by fitting 'individual segment' as random effect in all models.

We then compared straightness (total path length divided by net displacement), total distance travelled (sum of all straight-line distances between turns for an individual) and mean step length of movement paths between individuals moving in different habitats (remnant and matrix), matrix environments and seasons (spring and summer) as explanatory variables. We log-transformed linearity, total distance and mean step length to meet model assumptions and performed a three-way ANOVA to compare each movement parameter between habitats, matrix types and seasons. When ANOVA results were significant, we used Least Squares Means and Tukey's HSD test for significant post-hoc pairwise comparisons. We used R (RStudio Team, 2016) for all statistical analyses.

Results

We captured and released 192 individuals (n = 144 fluroescent powder tracked; n = 48 radio-tracked): 145 (n = 81 females; n = 64 males) in remnant patches and 47 individuals (31 females; 16 males) for the displacement experiment. The mean track length was 8.85 m (min: 0.54 m; max: 62.39 m) for fluroescent powder tracked individuals, and 9.38 m (min: 0.03 m; max: 100.71 m) for radio-tracked individuals.

Hypothesis 1. Low contrast farmland environments (linear plantings) promote directional movement of displaced geckos into farmland, compared to high contrast farmland environments (pastures and crops).

We found significant interactive effects of ‘distance’, ‘treatment’, ‘habitat’ and ‘year’ on the orientation of fluroescent powder tracked geckos to edges ($P < 0.01$) (Table 6). Geckos released in pastures moved away from patches during summer when they were more than 40m from the edge (Figure 22; Table S3), while the converse response was observed for those within remnant patches ($P < 0.01$) (Tables 1 and S1; Figure 22). Displaced geckos also were more likely to orientate towards remnant patches in crops and plantings in summer, compared to those indiviudals released in pastures ($P < 0.01$) (Figure 22; Table S2).

Mean step length and the total length of fluroescent powder tracked geckos differed significantly between ‘treatment’, ‘habitat’ and ‘year’($P < 0.05$) (Table 7). Pairwise differences showed that mean step length of displaced geckos was significantly longer in pasture matrix environments and adjacent remnant patches in spring, than geckos released in pasture, planting and cropped matrix environments in summer (Table 7; Figure 24).

The total distance moved differed significantly between treatment types for fluroescent powder tracked individuals ($P < 0.01$) with geckos moving further in crop treatments (mean total track length = 9.12 m ± 0.81SE) compared to planting treatments (mean total track length = 6.11 m ± 0.69SE), although there was no significant interaction with habitat type (P = 0.8) (Table 7).

Hypothesis 2. Geckos do not perceive woodland-farmland edges as a barrier to movement.

We found that radio-tracked geckos moving within remnant patches showed no significant orientation patterns towards edges (P > 0.27) (Table 6; Figure 23). We also found no radio-tracked individuals moved into the farmland. We found that 16 radiotracked individuals reached the patch - matrix interface and moved along the habitat edge, but did not enter the matrix.We also did not find differences in mean step length of radio-tracked individuals moving within patches in relation to different adjacent farmland types (Table 8). During radio-tracking, radio-tagged indiviiduals were observed utilising mature trees with exfolidating bark (particularly Callitris species) and dead standing trees, or moving and foraging across open ground (with little groundcover) between logs and stumps.

Total distance moved by radio-tracked geckos differed significantly across treatment and years (*P = 0.03*) (Table 7). Pairwise differences showed geckos moved farther adjacent to pastures in spring, than plantings in summer (Figure 25).

The movement paths of displaced and resident geckos did not differ in straightness between treatment, habitat type or seasons (Table 8).

Discussion

How an animal moves or behaves in particular habitat types is important for understanding potential barriers limiting dispersal (Cooney et al., 2015, Driscoll et al., 2013, Rittenhouse and Semlitsch, 2006). Our study adds new information on the influence of farmland and season on the cross-habitat movement of reptiles in fragmented landscapes. Our findings suggest that *Gehyra versicolor* is woodland-dependent in the study system and behaviourally avoids anthropogenic matrices including linear plantings. This conclusion is supported by the results of previous studies of this species (Gruber and Henle, 2004, Sarre *et al.*, 1995, Sarre, 1998) which contain evidence of the negative impact of mixed farming land use on reptile movement.

However, dispersal and colonisation ability is context dependent (Driscoll *et al.*, 2013, Guerry and Hunter Jr, 2002) and other authors have reported this species uses human infrastructure (Hutchinson *et al.*, 2014, Tan and Schwanz, 2015). We suggest that in heavily modified landscapes, crops and plantings may act as sinks due to a lack of key microhabitat attributes. However, if there are buildings, rocks or mature trees adjacent to remnant native vegetation, then this species may be able to disperse easier (Guerry and Hunter Jr, 2002, Kurz *et al.*, 2014). Our findings highlight the importance of remnant native vegetation and stress the significant challenges of maintaining functional connectivity relevant to particular taxa in an intensivly used agricultural system (Driscoll *et al.*, 2013, Guerry and Hunter Jr, 2002, Kurz *et al.*, 2014).

Test of hypothesis 1: That low contrast farmland environments promote directional movement of displaced geckos into farmland.

Contrary to our initial predictions, we found no directional bias of individuals moving further into matrix environments with low structural contrast, such as the linear plantings. This result was unexpected given habitats within plantings (trees and shrubs) and some associated microhabitats are similar to those within remnant patches. We therefore expected higher site fidelity, compared to high contrast environments (see Hypothesis 1, Introduction). Instead, we found following displacement, the homing ability of geckos in plantings and harvested crop paddocks was higher as individuals orientated more strongly to remnant patches, compared to individuals in pastures. The reason for this finding remains unclear given we expected greater ingress into plantings compared to bare crop paddocks. Instead, we found similar species responses to structually dissimilar matrix environments. Previous studies have suggested farm management may negatively influence the occurence of reptiles within habitats adjacent to crop harvesting activities (e.g. chemical and herbicide application, crop harvesting and ploughing; Cunningham *et al.*, 2007, Rotem *et al.*, 2013). An alternative explanation might be that geckos are using olfactory habitat cues, or changes within vegetation structure within plantings and bare crop paddocks to increase their ability to detect remnant patches (Connette and Semlitsch, 2013, Kay *et al.*, 2016a). For example, structures within plantings may offer vantage points (e.g. by climbing trees and shrubs) to assist with navigation to remnant patches, or shelter opportunities while moving through unfamilar habitat, while the homing success of a gecko may be higher in a bare crop paddock due to a clear line of sight to patches.

When released within pastures, we found that displaced geckos orientated directly into pastures the farther away an individual was from an edge (> 25m; Figure 3). This is theopposite pattern to other farmland types, and it suggests either: (1) pastures are not a complete barrier during movement for geckos or, (2) animals have poor homing ability in pastures the farther they are from woodland patches (e.g. pastures may reduce habitat detection to geckos finding remnant patches). In support of (1), Kay *et al.* (2016b) have shown short (mean height < 10 cm), grazed pastures assist another arboreal gecko species, *Christinus marmoratus*, move decisively in a similar agricultural system and, illicited directed movements towards habitat for this species (e.g. paddock trees). Nevertheless, short pastures provide little ecological benefit for an arboreal gecko like *G. veriscolor*, and have been found to have a negative impact on their occurance as a result of reduced leaf litter, trampling, homogenous and simplified vegetation structure (Carvajal-Cogollo and Urbina-

Cardona, 2015, Gruber and Henle, 2004, Howland *et al.*, 2014, Sarre *et al.*, 1995, Sato *et al.*, 2014).

However, while pastures may appear useful for individuals orientating and moving through the farmland, we suggest given radio-tracked geckos did not enter pastures (see Figure S1), or any other matrix type in the short-term, geckos may be unwilling to enter such environment. Reduced movement of radio-tracked individuals into pastures also may represent a strategy to reduce exposure, for example low vegetation could cause desiccation and increase predation risk (Connette and Semlitsch, 2013, Hoehn *et al.*, 2007, Sato *et al.*, 2014).

Test of hypothesis 2: Geckos do not perceive woodland-agriculture edges as a barrier to movement.

Radio-telemetry revealed some directional bias towards habitat edges, but an unwillingness of *G. versicolor* to move into the matrix. This result is noteworthy as it has been suggested that the species can use open, modified habitat (Cogger, 2014, Gruber and Henle, 2004, Sarre, 1998). Thus, it may be assumed to be less affected by local habitat level changes. Behavioural avoidance of farmland generally by geckos, irrespective of matrix type, may be a greater barrier to animal movement than the physical structure of differing matrix types. Our results highlight the importance of remnant native vegetation, particularly with mature microhabitat features such as large trees trees with exfolitating bark and dead standing trees, for preserving reptile populations in modified cropping landscapes (Brown *et al.*, 2008, Lindenmayer *et al.*, 2018, Michael *et al.*, 2018). Our findings also highlight the likely negative consequences of habitat loss and degredation for native biota (Baguette *et al.*, 2013, Bonte *et al.*, 2012, Prevedello and Vieira, 2010).

Management implications

Intensively managed farmland may reduce cross-habitat movements and have negative impacts on species reliant on woodland habitat. While plantings may provide habitat for some reptile species (Lindenmayer *et al.*, 2010, Michael *et al.*, 2018, Munro *et al.*, 2007), our results suggest plantings may not mitigate the negative effects of broader habitat loss in agricultural areas, especially for species reliant on microhabitat features associated within mature native vegetation (Cunningham *et al.*, 2007, Neilly *et al.*, 2018). Our data indicated that radio-tracked, resident geckos did not incorporate plantings into their home ranges, and orientation and movement patterns suggest avoidance of this habitat in favour of patches. These findings hightlight that plantings are not readily interchangeable for remnant habitats, and are unlikely to be readily recolonised by habitat-specialist reptiles, a finding also supported by the results of other investigations (Cunningham *et al.*, 2007, Jellinek *et al.*, 2014, Pulsford *et al.*, 2017). Previous studies have suggested the presence of available shelter in the form of exfolitating bark, mature paddock trees, stumps and logs is the main determinant of recolonisation of disturbed areas by reptile species requiring particular habitats (Cunningham *et al.*, 2007, Nichols and Grant, 2007, Urbina-Cardona *et al.*, 2006).

If patch-dependent reptile species are not attracted to restored areas, novel management interventions may be required. These may include translocating animals into restored habitat, provided appropriate microhabitats are available (Christie *et al.*, 2011, Jellinek *et al.*, 2014, Michael *et al.*, 2018). Increasing leaf litter and introducing rocks, course woody debris and including mature trees as part of plantings may help improve the quality of plantings for geckos (Michael *et al.*, 2018, Neilly *et al.*, 2018).

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Table 6 ANOVA results for orientation and treatment, habitat and season.

Model terms	Chisq	DF	Pr (>Chisq)
Fluorescent powder			
Direction ~ site + sex + distance*treatment*habitat*season + (1|individual segment)			
site	6.57	3.00	0.09
sex	4.49	2.00	0.11
distance	0.24	1.00	0.63
treatment	0.98	2.00	0.61
habitat	2.40	1.00	0.12
year	0.74	1.00	0.39
distance:treatment	2.13	2.00	0.34
distance:habitat	0.39	1.00	0.53
treatment:habitat	0.78	2.00	0.68
distance:year	1.82	1.00	0.18
treatment:year	0.84	2.00	0.66
habitat:year	2.40	1.00	0.12
distance:treatment:habitat	9.37	2.00	0.01
distance:treatment:year	1.90	2.00	0.39
distance:habitat:year	2.76	1.00	0.10
treatment:habitat:year	6.20	2.00	0.05*
distance:treatment:habitat:year	12.19	2.00	<0.01*
Radio-tracking			

Direction ~ sex + site + distance*treatment*season + (1|individual segment)			
sex	0.01	1.00	0.94
site	1.15	2.00	0.56
distance	1.32	1.00	0.25
treatment	0.76	2.00	0.68
year	0.00	1.00	0.96
distance:treatment	0.01	2.00	0.99
distance:year	0.37	1.00	0.54
treatment:year	2.98	2.00	0.23
distance:treatment:year	2.63	2.00	0.27

Table 7 ANOVA results for mean total distance, step length and linearity for fluorescent powder geckos

Model terms	**Sum Sq**	**Df**	**F value**	**Pr (>F)**
Total length				
treatment	1.04	2	4.92	0.01*
habitat	0.03	1	0.31	0.58
year	0.01	1	0.08	0.78
site	1.03	3	3.27	0.02*
sex	0.12	1	1.16	0.28
treatment:habitat	0.05	2	0.23	0.79
treatment:year	0.14	2	0.67	0.52
habitat:year	0.05	1	0.47	0.49
treatment:habitat:year	0.03	2	0.14	0.87
Linearity				
treatment	0.04	2	0.64	0.53
habitat	0.01	1	0.19	0.67
year	0.04	1	1.43	0.23
site	0.01	3	0.14	0.93
sex	0.07	1	2.31	0.13
treatment:habitat	0.08	2	1.37	0.26
treatment:year	0.01	2	0.05	0.95
habitat:year	0.004	1	0.16	0.69
treatment:habitat:year	0.03	2	0.44	0.64
Mean step length				

treatment	0.51	2	3.13	0.05*
habitat	0.06	1	0.71	0.40
year	6.59	1	81.35	<0.01*
site	0.38	3	1.59	0.20
sex	0.001	1	0.02	0.89
treatment:habitat	0.03	2	0.16	0.86
treatment:year	0.13	2	0.79	0.45
habitat:year	0.001	1	0.01	0.91
treatment:habitat:year	0.48	2	3.00	0.05*

Table 8 ANOVA results for Mean total distance, step length and linearity for radio-tracked geckos

Model terms	**Sum Sq**	**Df**	**F value**	**Pr (>F)**
Total length				
treatment	1.14	2.00	0.91	0.41
year	1.64	1.00	2.62	0.11
site	1.21	2.00	0.97	0.39
sex	2.31	1.00	3.70	0.06.
treatment:year	4.62	2.00	3.70	0.03*
Linearity				
treatment	0.37	2.00	0.41	0.67
year	0.04	1.00	0.09	0.77
site	0.90	2.00	0.99	0.38
sex	2.80	1.00	6.14	0.02*
treatment:year	0.16	2.00	0.18	0.84
Mean step length				
treatment	1.16	2.00	1.18	0.32
year	0.71	1.00	1.46	0.23
site	1.05	2.00	1.07	0.35
sex	0.25	1.00	0.50	0.48
treatment:year	1.95	2.00	2.00	0.15

Figure headings

Figure 20 Location of the four study sites used for fluorescent powder tracking and radio-tracking of Gehyra versicolor.

Figure 21 Visualisation of a complete track for an individual released in farmland, the segmentation of a track (into steps) distinguished by a change point and turning angle/bearing to estimate the direction of each step.

Figure 22 The predicated probability of fluorescent powder tracked geckos orientating towards (0%) or away (100%) with rescaled and normalised distance from the edge, between treatments, habitat types and season plotted with 95% confidence intervals. Dots represent the spread of the data points.

Figure 23 The predicated probability of radio- tracked geckos orientating towards (0%) or away (100%) with rescaled and normalised distance (metres) from the edge, between treatments, and season plotted with 95% confidence intervals. Dots represent the spread of data points.

Figure 24 Mean step length of fluorescent powder tracked individuals and the significant relationship between treatment (cropped, pasture and planting), habitat (remnant patch and matrix) and year (spring and summer). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis.

Figure 25 Total length of radio-tracked individuals and the significant relationship between treatment (cropped, pasture and planting) and year (spring and summer). Letters indicate post hoc contrasts and error bars indicate 95% confidence intervals with fitted estimates are plotted on the x axis.

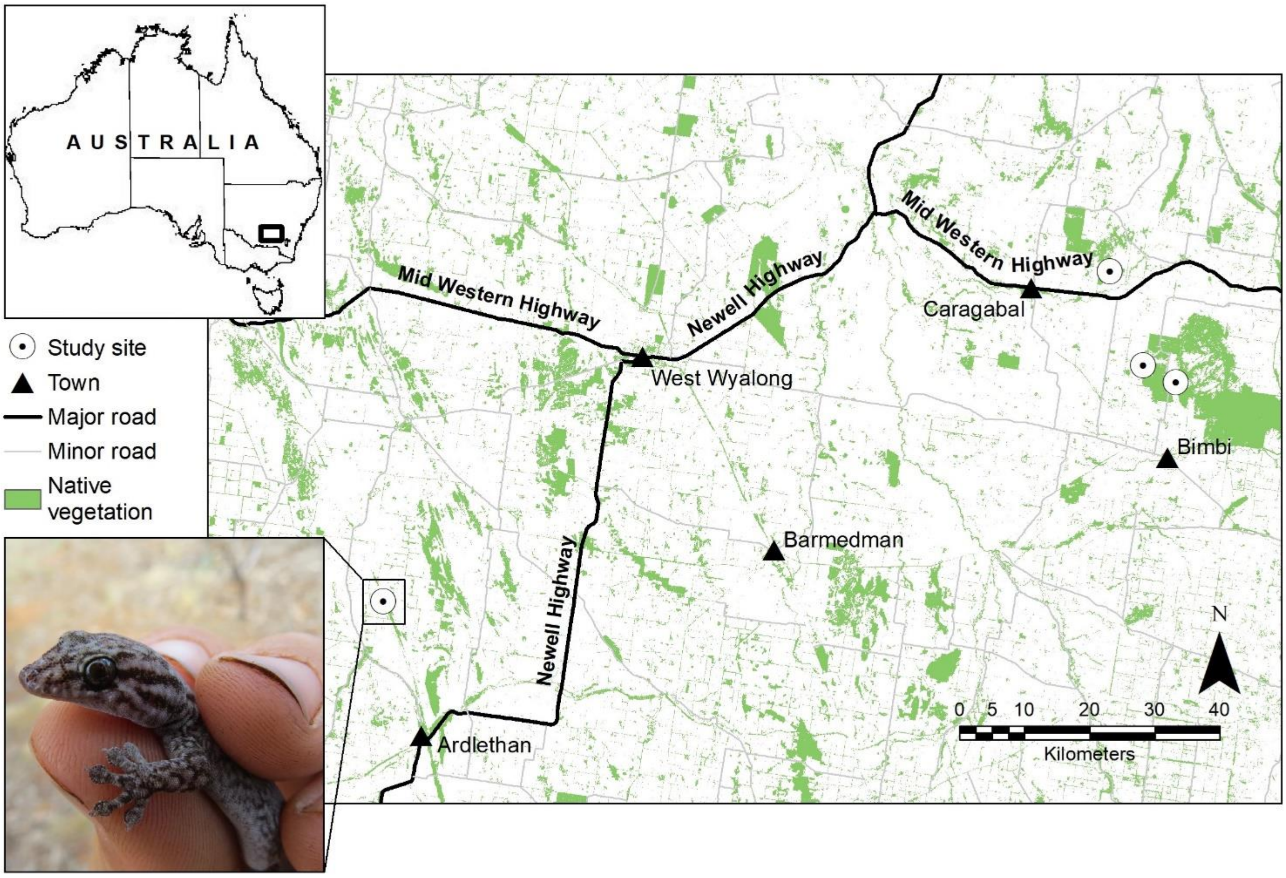
AUSTRALIA
Study site
Town
Major road
Minor road
Native vegetation
Mid Western Highway
Newell Highway
Mid Western Highway
Caragabal
West Wyalong
Bimbi
Barmedman
Newell Highway
Ardlethan
N
0 5 10 20 30 40
Kilometers

Figure 1

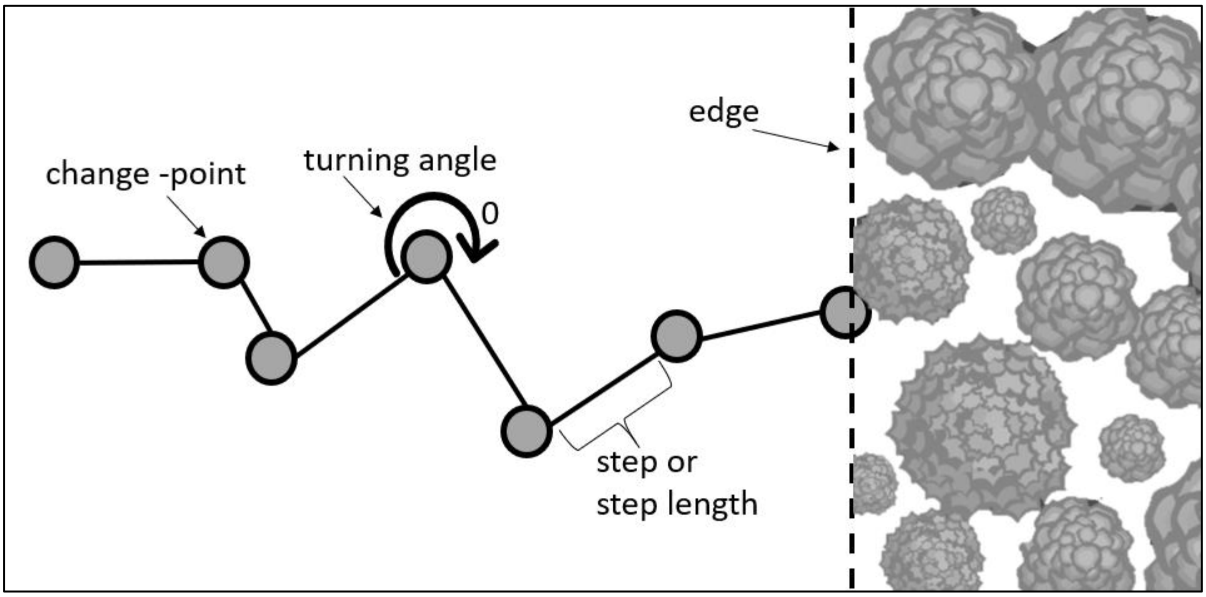

Figure 2

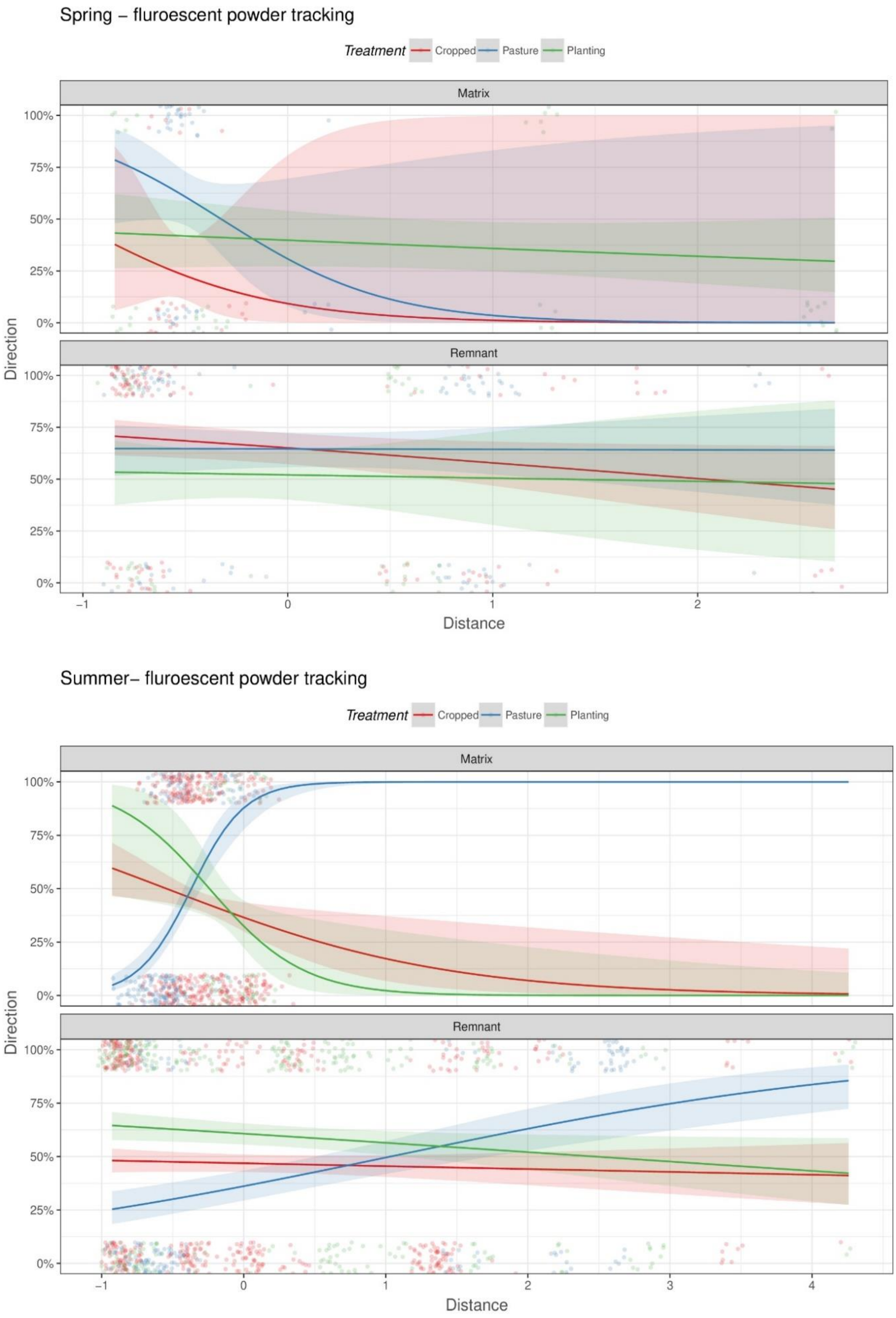
Spring – fluroescent powder tracking
Treatment
Cropped
Pasture
Planting
Matrix
Remnant
Direction
100%
75%
50%
25%
0%
Distance
−1
0
1
2
Summer– fluroescent powder tracking
Treatment
Cropped
Pasture
Planting
Matrix
Remnant
Direction
100%
75%
50%
25%
0%
Distance
−1
0
1
2
3
4

Figure 3

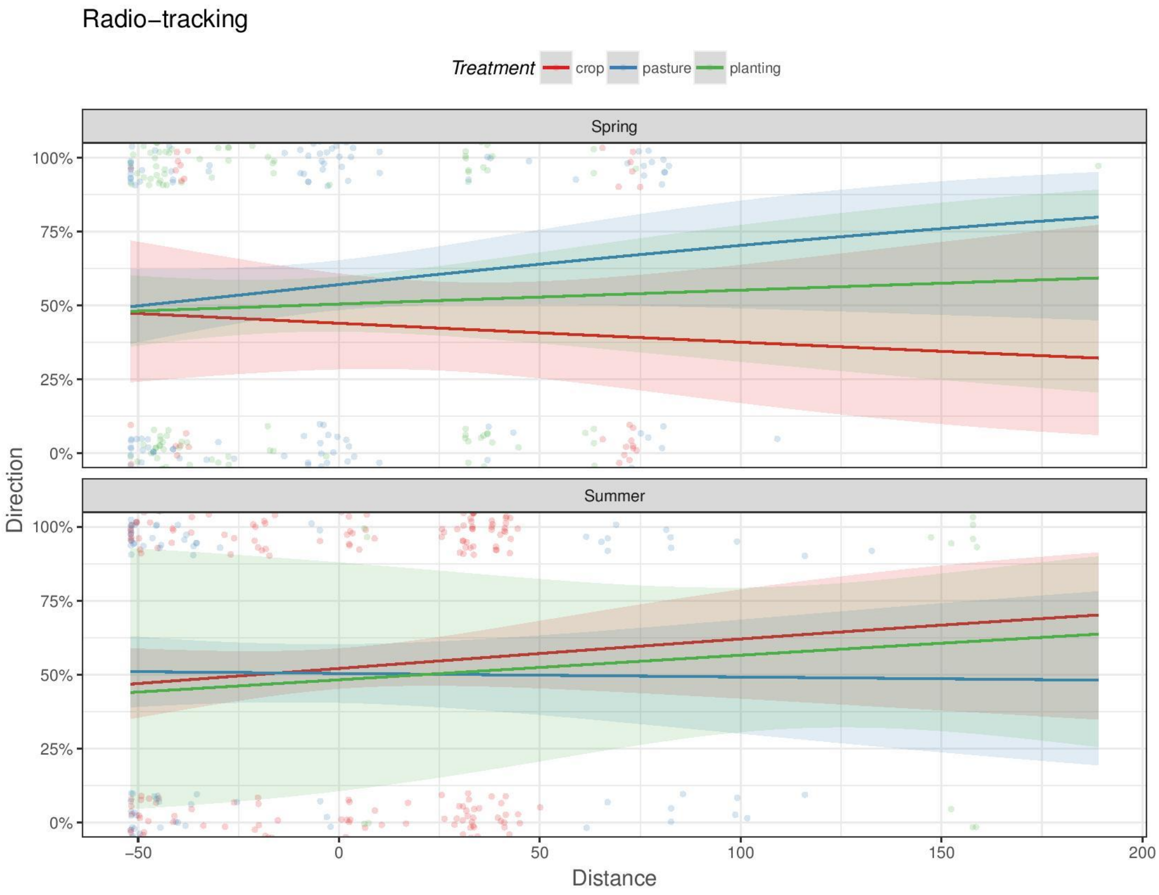
Radio−tracking
Treatment
crop
pasture
planting
Spring
Summer
Direction
100%
75%
50%
25%
0%
Distance
−50
0
50
100
150
200

Figure 4

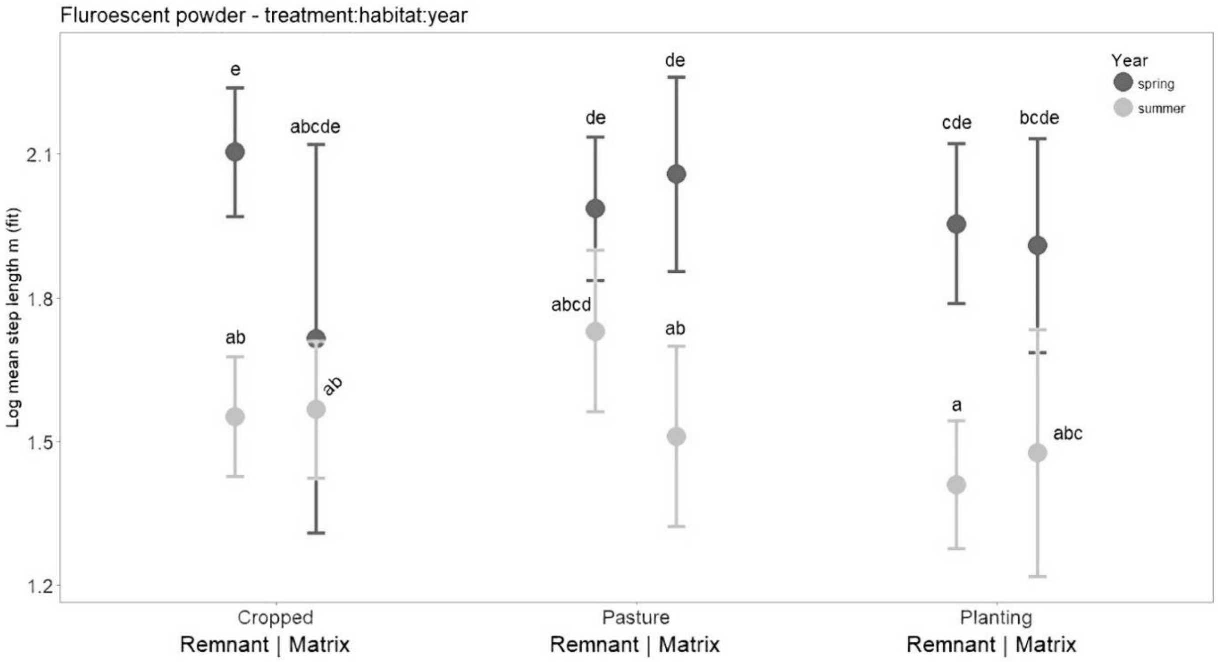
Fluroescent powder - treatment:habitat:year
Log mean step length m (fit)
2.1
1.8
1.5
1.2
Year
spring
summer
e
abcde
de
de
cde
bcde
abcd
ab
ab
ab
a
abc
ab
Cropped
Pasture
Planting
Remnant | Matrix
Remnant | Matrix
Remnant | Matrix

Figure 5

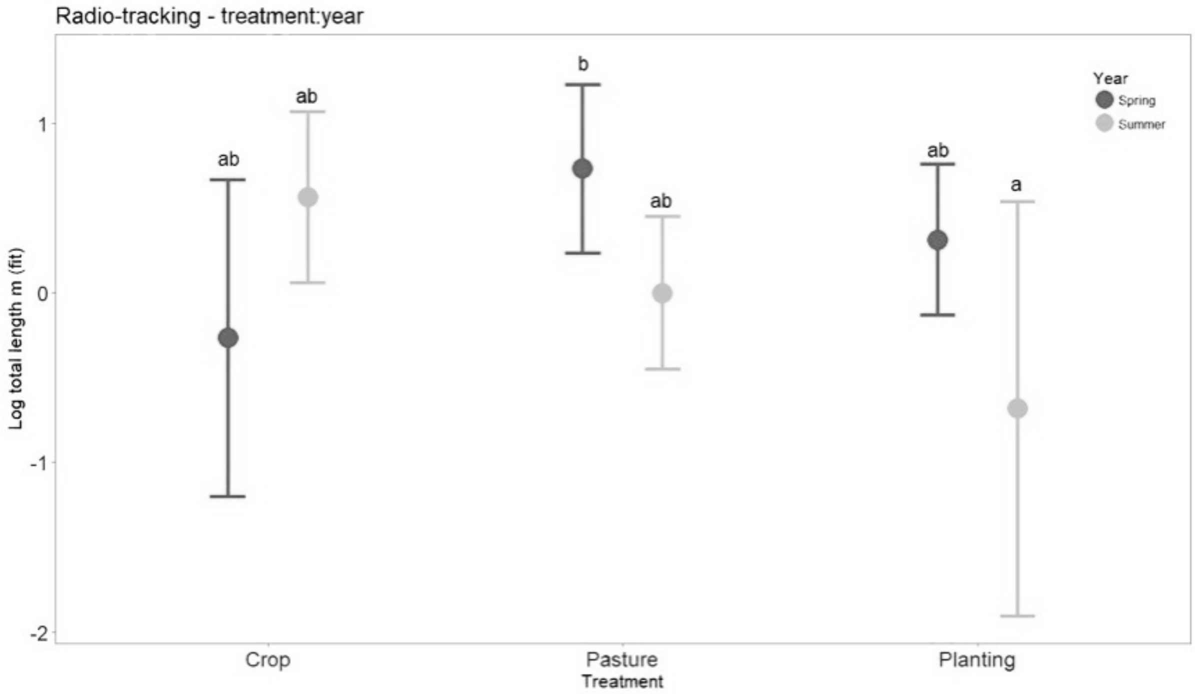
Radio-tracking - treatment:year
Log total length m (fit)
1
0
-1
-2
ab
ab
b
ab
ab
a
Year
Spring
Summer
Crop
Pasture
Planting
Treatment

Figure 6

CHAPTER SIX:

SYNTHESIS AND MANAGEMENT IMPLICATIONS

A key priority in completing this thesis was to produce recommendations that can be used to guide management strategies for the conservation of herpetofauna in agricultural landscapes.

Through studying multiple species across different habitats and land uses, my research has shown that there can be large variation in species responses and individual behaviour within species (Chapters 2 and 3) to the matrix. The matrix may act strictly as a barrier for some species (Chapters 2 and 3) or a selective filter for other species (Chapters 4 and 5). As such, management strategies must be targeted for particular species, or taxa. For example, linear plantings may be important habitat for common (habitat generalist) reptile species, but not for uncommon reptile species, which were more species rich and abundant in remnant patches. Management actions need to focus on protecting and enhancing remnant patches if the aim is to increase reptile diversity (Chapter 2). In another example, land use affects frogs and reptiles differently. Reptiles are affected at the scale of habitat and treatment, while amphibians are likely affected by larger scale changes across treatments and habitats (Chapters 2 and 3).

A summary of the key research findings is shown in *Figure 26*. Subsequently, five key insights and management recommendations emerge from this thesis to improve the conservation of herpetofauna in fragmented cropping landscapes are discussed below.

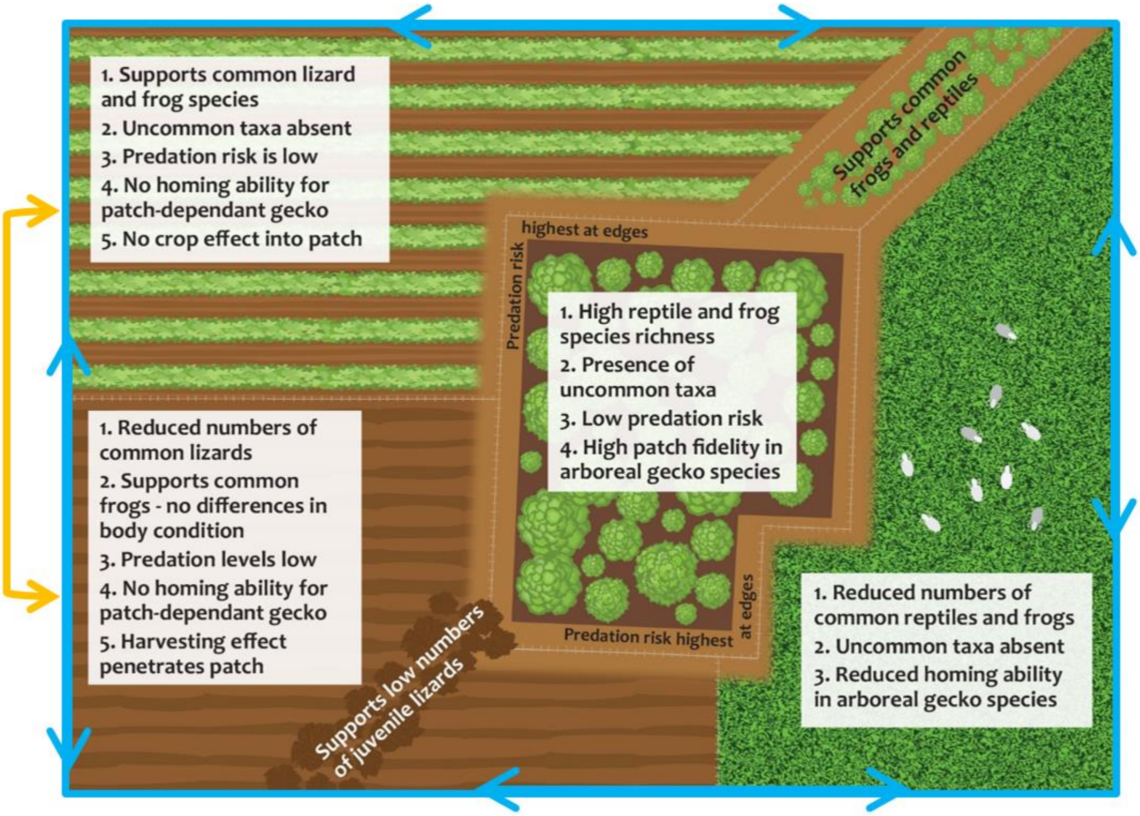

Figure 26 Four different matrix types compared to remnant patches and edges (spatial variation; indicated in blue arrows) across time (pre and post harvesting; temporal variation indicated in orange arrows). *Diagram © Danielle Hansen*

1. *Remnant vegetation is key to maintaining herpetofauna within mixed-cropping landscapes, but requires active management*

The occurrence of many of the reptile species recorded, including uncommon species, were positively associated with remnant native vegetation in contrast to edges and farmland (Chapters 2 and 5), suggesting remnants provided valuable habitat for them. Many of the uncommon, and patch-dependent species recorded are associated with particular microhabitat characteristics that are only available in older aged stands of native vegetation like remnant patches (e.g. fallen timber, mature trees with exfoliating bark; Chapters 2 and 5), a finding consistent with recent investigations by Michael et al. (2018) and Jellinek et al. (2014b). Movement patterns by direct tracking data (Chapter 5) also suggest remnant vegetation is likely influencing the composition and persistence of reptiles within the adjacent farmland. I did not find a strong association between frogs and remnant patches. However, given evidence from previous studies, forest cover is likely to provide important terrestrial habitat for frogs in agricultural-dominated landscapes (Knutson et al. 1999, Porej et al. 2004, Collins and Fahrig 2017).

This study highlights the need to protect remnant native vegetation as valuable habitat for reptiles, and likely for other woodland-dependent species, and the protection of habitat attributes like paddock trees, coarse woody debris and complex ground cover. However, protecting remnant patches is inadequate. I recommend reducing disturbance by restricting livestock access and subsequent grazing pressure as well as and removing course woody debris (e.g. firewood collected). Actively managing exotic predators within the patch and matrix also may be an important conservation strategy to protect native species within patches (Chapter Four).

Currently, landholders are only marginally incentivized by planting schemes to establishing plantings (e.g. the Biodiversity Fund), and trials under the environmental stewardship agreement provide some financial support for the management of woodland remnants (Lindenmayer et al. 2012, Kay et al. 2016a). However, my findings suggest both remnant patches and habitat restoration (discussed below) need to be considered together in future incentive programs to maximize habitat for and diversity of herpetofauna for conserving reptiles in agricultural landscapes.

2. *Increase restoration efforts within crop paddocks and retain existing plantings*

Millions of dollars are expended annually on linear plantings with the aim of habitat restoration and corridor establishment to maintain biodiversity in agricultural landscapes (Hobbs and Harris 2001, Mackey et al. 2010, Pulsford et al. 2015, Lindenmayer et al. 2016). While positive responses to linear plantings have been recorded for birds (Lindenmayer et al. 2010), invertebrates (Ng et al. 2017) and mammals (Šálek et al. 2009, Sullivan et al. 2012), the ecological value of plantings for herpetofauna, particularly in cropping landscapes, remains largely understudied (Munro et al. 2007, Pulsford et al. 2017, Lindenmayer et al. 2018). Of the few studies available, reptile and frog responses to plantings are mixed, showing neutral responses (Thompson et al. 2017), and not differing substantially between plantings and modified areas, responding negatively or varying over time (Atauri and de Lucio 2001, Perry et al. 2009, Davis et al. 2010, Jellinek et al. 2014a, Collins and Fahrig 2017, Lindenmayer et al. 2018).

My findings in Chapters two and three suggest plantings have the potential to promote higher abundances and richness of reptiles (Chapter 2), and (potentially) higher abundances of some species of frog (Chapter 3) within cropping paddocks. I also found some evidence that linear plantings may buffer edge effects on adjacent remnant patches for some reptile species, compared to other matrix types, particularly where patches adjoin crop paddocks (Chapter 2). It has been suggested that linear planting structures within farmland provide refuge, humidity (for frogs) and more cover than the dryer, more open conditions of the crop field (Collins and Fahrig 2017, Thompson et al. 2017, Michael et al. 2018). Some frog species may also use these structures as a component of their seasonal migrations given that complex cover reduces desiccation risk, compared to more exposed land uses (Nowakowski et al. 2013). My findings suggest, for cropping landscapes, to increase restoration efforts along paddock margins and to retain existing plantings. However, the impact of width, length, age, vegetation composition and habitat structure of plantings needs to be further investigated. Further, the importance of proximity of plantings relative to remnant patches for promoting connectivity and habitat use needs to be examined. I am unaware of any studies investigating the relationship between the size, configuration and connectedness of plantings and herpetofauna abundance and richness (but see Phillips et al. 2018).

3. *Linear tree plantings may not provide habitat or functional connectivity for uncommon reptile species in farmland*

I found uncommon reptile species richness and abundance, in particular, was negatively influenced by farmland, irrespective of the presence of plantings within paddocks (Chapter 2). Radio-telemetry and tracking experiments also suggested avoidance of farmland in preference for remnant patches (Chapter 5). Specialist reptile species, particularly arboreal, fossorial (soil-dwelling) and, cryptozoic guilds were missing from farmland assemblages and the species composition within plantings would suggest restoration benefits only a subset of reptile and frog species (Chapters 2 and 3). Previous studies suggest the addition of key habitat attributes such as course woody debris and rock improve the occurrence of particular reptile species within restoration areas (Manning et al. 2013, McDougall et al. 2016, Goldingay and Newell 2017, Michael et al. 2018). We assume the absence of these important features in plantings within this study area may have contributed to lack of response to plantings by uncommon species. I suggest restoration programs should consider increasing microhabitats such as incorporating rock and course woody habitat to improve microhabitat, increase uncommon reptile abundance and create better dispersal opportunities (Thompson et al. 2017, Michael et al. 2018). I encourage land managers to identify target species and their associated microhabitat to inform enhancement of plantings using additional microhabitats. Adding groundcover also may mitigate impacts of crash grazing by domestic livestock. Future studies should focus on experimentally improving microhabitat attributes, including overwintering and basking sites, to improve dispersal opportunities and habitat attributes for target species.

4. *If you build it, they won't necessarily come – lessons for strategic habitat manipulation using woody mulch*

Mulching is one of the recommended management practices for replanting projects as it suppresses weed growth, retains soil moisture, reduces soil temperature and may promote nutrient cycling and increase invertebrate diversity (Chalker-Scott 2007, Fornwalt et al. 2017, Lythe et al. 2017, Ng et al. 2017). However, the benefits of introducing fine woody mulch to cleared landscapes for ground-dwelling fauna such as frogs and reptiles, are largely untested. I predicted mulching would benefit soil and litter-dependent reptiles and frogs by temporarily providing shelter and food resources (Chapters 2 and 3). However, my results indicated that actively restoring a key habitat feature by applying woody mulch to a bare crop paddock did not substantially improve the habitat quality of crop paddocks, or mitigate the short-term impacts of crop harvesting, for frogs or reptiles. Findings from Chapter 4, suggest predation risk was high within woody mulch after harvest. I suggest without other structures and mid to canopy level vegetation for shelter, reptiles and frogs may be easy prey for birds and mammals within the area. Predation risk may also provide a possible explanation to the lack of response to the woody mulch application. An important next step to investigate whether different woody material (e.g. logs) better accommodate a greater range of herpetofauna diversity in agricultural landscapes, when combined with other structural elements such as plantings (Pulsford et al. 2017).

Notably a small number juvenile reptiles (and the occasional adult frog) were recorded in woody mulch after harvesting, but were otherwise absent from bare crop paddocks (Figure 27). I speculate the mulch may have provided suitable egg laying material and neonatal habitat, but this proposition requires further testing.

Figure 27 Left: Juvenile Ctenotus spaldingi recorded within the woody mulch treatment. Right: Litoria caerulea recorded in the woody mulch treatment.

5. *Farmland, surrounding the remnant patches, provides habitat for a subset of common reptile and frog species and needs to be managed*

My findings in Chapters 2 and 3 demonstrate that some common herpetofauna species can use disturbed areas close to remnant native vegetation (Chapters 2 and 3). These results indicate it is important to maintain a mix of land-uses with both spatial and temporal heterogeneity to support overall herpetofauna biodiversity in agricultural landscapes. This includes farmlands which, if managed appropriately, can support high herpetofauna species richness. Similar to Collins and Fahrig (2017) and Rotem et al. (2013), I hypothesise that not all species rely on habitats with complex habitat structure and diversity, and may benefit from the additional prey and shelter resources provided in paddocks. The importance of remnant native vegetation and linear plantings for species found in farmland (e.g. temporary shelter, core habitat, breeding habitat or seasonal buffer) needs to be further explored. Based on these results. I suggest management schemes need to maintain and enhance remnant native vegetation, increase biodiverse linear plantings, and incorporate the use of crop areas to maintain and increase herpetofauna abundance and diversity.

Priority areas for new research

By providing new knowledge on which species use particular matrix types, when they use them and insights into the mechanisms that might limit their use, including predation risk and movement behavior, my study highlights important future research priorities.

One of the preconditions for the long-term persistence of a population within a remnant patch is the ability to disperse between patches, through the agricultural matrix (Driscoll et al. 2013a). This thesis shows that highly modified matrix types limit the use of the matrix by some species (Chapters 2, 4 and 5), while restoration may increase use (Chapters 2 and 3). A necessary next step is to examine if particular matrix types influence an animal’s chance of dispersal successfully between patches. In the current studies this was not explored and would require direct and long-term tracking. Therefore, I suggest that research should focus on the effect of the agricultural landscape on dispersal, through examining how different land uses affect movement between patches.

New research is also needed to understand the consequences of increased predation risk at the edges of patches for within-patch reptile populations (Chapter 4). Does predation risk equate to actual predation events or avoidance of the edge and matrix by prey. If animals venture into edge habitat suffer elevated predation, does the edge act as a demographic sink, or reduce use of linear plantings? Following this, comparison between sites with and without pest control, as well as pest control at edges and along restoration areas, will help to quantify the relative benefits of predator control on herpetofauna populations. Understanding the relative effects of controlling invasive predators, relative to population growth of herpetofauna, would inform land managers of the best predator control strategy. For example, control of predators at the edge of plantings may be sufficient to promote cross-habitat movement of reptiles.

Conclusions

Agricultural intensification and expansion has caused major declines in herpetofauna population's worldwide (Gibbons et al. 2000, Gardner et al. 2007, Böhm et al. 2013). Reducing the risk of species declines and extinctions is dependent on a better understanding of the relative value of different land uses for facilitating movement and population-level responses across diverse agricultural landscapes. It is critical that management interventions are undertaken in an experimental, framework and the findings monitored and communicated to land managers, to help guide and inform conservation actions. Using the conceptual matrix framework (Driscoll et al. 2013b), the results of this thesis suggest herpetofauna communities inhabiting fragmented agricultural landscapes are strongly affected by matrix quality of predation risk. My results also provide evidence that uncommon (habitat specialist) reptiles are negatively affected by harvesting of crops, and improvements to matrix quality are potentially ineffective for these species. Protection and maintenance of remnant native vegetation is critical for the ongoing persistence for reptiles in agricultural systems, and likely other woodland-dependent species.

As global pressure for intensive agricultural production increases (Herrero and Thornton 2013), managing biodiversity on agricultural land is becoming increasingly difficult (Baudron and Giller 2014, Perring et al. 2015). Improving biodiversity outcomes in human-modified landscapes requires and understanding of management practices that support biodiversity whilst permitting ongoing production (Driscoll et al. 2013b, Thompson et al. 2017). The papers in this thesis are a valuable contribution towards this goal, by providing insights into the value of different agricultural land uses, and restoration actions for protecting species diversity.

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