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

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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, of which 87% were native species. Mammalian predators were 60.2% more likely to attack scented models then unscented models. Bird predators were not influenced by scent.

4. We found predator attacks on models were highest at edges (49%, irrespective of adjacent farmland type, with a reduced risk within farmland (29%) and remnant patches

(33%) (*P*<0.01). Both mammal and bird predators contributed to high numbers of predation attempts at edges.

5. Removal of crops did not increase predation attempts in crop fields or other farmland types, although predation attempts were significantly lower along the crop transect after harvesting, compared to the woody debris transect. 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. Our results demonstrate that edge habitats are potentially riskier for lizards than the farmland. Vulnerability to predation may be increased by a lack of shelter within edge habitats such as by increasing visibility of reptiles to predators. Therefore, to benefit reptiles, land managers could provide shelter (rocks, logs and grasses), particularly between remnants and linear plantings which could improve landscape connectivity.

Keywords: edge habitat, edge effects, farming, reptile, matrix, mortality, landscape connectivity, predation risk

INTRODUCTION

Habitat loss and fragmentation resulting from intensive agricultural production is a major threat to global biodiversity (Ellis and Ramankutty 2008, Venter, Sanderson et al. 2016). 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, Banks et al. 2013) 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 (Kay, Driscoll et al. 2016, Pulsford, Driscoll et al. 2017). However, some matrix environments could represent a barrier to movement (Prevedello and Vieira 2010, Pulsford, Driscoll et al. 2017), particularly if there is high mortality risk during dispersal (Anderson and Burgin 2008, Daly, Dickman et al. 2008). Despite increasing research on the impact of matrix heterogeneity on some fauna species (Watling, Nowakowski et al. 2011, Driscoll, Banks et al. 2013), empirical data on the mechanisms explaining reduced use of some matrix types is lacking in agroecosystems (Driscoll, Banks et al. 2013).

The risk of elevated mortality, such as individuals being killed by harvesting machinery (Rotem 2012), increased risk of desiccation (Cosentino, Schooley et al. 2011), or predation (Schtickzelle and Baguette 2003, Schneider, Krauss et al. 2013), at different times and within different matrix environments may be an important driver of matrix use by fauna in agricultural areas (Ewers and Didham 2006, Pita, Beja et al. 2007, Driscoll, Banks et al. 2013). Predation is one of the most important factors influencing mortality (Castilla and Labra 1998) and population persistence (Suhonen, Norrdahl et al. 1994, Purger, Csuka et al. 2008). Predation risk may reduce an individual's willingness to emigrate (Stevens, Leboulengé et al. 2006), their likelihood of reaching a new patch (Pita, Mira 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, Mira 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, Woitke et al. 2005, Cosentino, Schooley et al. 2011). Predator responses to habitat edges also may vary depending on the species, landscape type and scale (Rand, Tylianakis et al. 2006, Driscoll, Banks et al. 2013).

The effects of habitat structure on predation risk has been reasonably well explored for birds (Whittingham and Evans 2004, Purger, Csuka et al. 2008), and mammals (Norrdahl and Korpimäki 1998, Pita, Mira et al. 2009). However, knowledge of the influence of predation risk on reptiles within agricultural areas is limited (Daly, Dickman et al. 2008, Driscoll, Banks et al. 2013, Sato, Wood 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, Cunningham et al. 2013, Michael, Kay et al. 2015). Reptiles also have specific thermal requirements that make them dependent on basking opportunities and, in turn, exposing them to predation risk (Anderson and Burgin 2008, Sato, Wood 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, Banks et al. 2013).

Since the understanding of predation risk on reptiles in agroecosystems is limited, we used scented and unscented plasticine models of a patch-dependant 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*) disperses readily through natural habitat, but farmland may represent a barrier to movement (Sarre, Smith et al. 1995). Using a landscape-scale field experiment we addressed two specific questions:

(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? 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, Jr et al. 2004, Storch, Woitke et al. 2005, Driscoll, Banks et al. 2013). We postulated that structurally simplified farmland types (crops and paddocks) would have higher rates of predation (Storch, Woitke et al. 2005, Purger, Csuka et al. 2008), 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, Whittingham et al. 2005, Michael, Kay 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, Tylianakis 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, Whittingham et al. 2005, Stoate, Báldi et al. 2009).

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 (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, Woitke 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.

(2) Does crop harvest increase predation risk? Harvesting may influence predation rates in all farmland types as predators may move opportunistically to new foraging habitat (spill-over effects) (Storch, Woitke et al. 2005), or compensatory shifts due to the prey source being killed during the mechanical harvesting of crops (Thorbek and Bilde 2004, Rotem, Ziv 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, Ylönen 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, Tylianakis et al. 2006), with the converse effect after harvesting due to the rapid removal of resources (Rotem, Ziv 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 plantings and woody debis; Thorbek and Bilde 2004, Storch, Woitke 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.

1   MATERIALS AND METHODS

1.1   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, Wilson et al. 2013). This species may alter its habitat use in response to availability of food and shelter resources, antagonistic behaviour, mating opportunities (Henle, Davies et al. 2004) and uses the matrix ecotone (observed from a previous study; N A. Hansen unpublished data).

1.2   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.

1.3   Gecko models

Plasticine models are useful for estimating rates of predation (Daly, Dickman et al. 2008, Sato, Wood 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* (see Appendix S1 in Supporting Information Fig. 1 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, Dickman et al. 2008, Purger, Csuka et al. 2008, Sato, Wood et al. 2014, Bateman, Fleming 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.

1.4 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, Woitke et al. 2005, Anderson and Burgin 2008, Daly, Dickman et al. 2008, Arthur, Henry 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; see Appendix S1 Fig. 1 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.

1.5 Statistical analysis

We examined the effect of changes within the matrix environment on predation risk by fitting generalized linear mixed models (GLMM; Bolker, Brooks 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, Maechler 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).

2   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 1). 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, Dickman et al. 2008, Sato, Wood 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).

2.1   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 had 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 Appendix S1).

2.2   Effect of crop harvest on predation risk

We found no three-way 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 (*$P = 0.02$*) (Figure 4). Predation by birds was highest at the edge prior to harvesting compared to the remnant patches and matrix (*$P = 0.04$*) (Tables 2 and Appendix 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 (see Appendix Table 1; Fig. 5B).

2.3   Other responses

3   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 evaluated how farm management practices influence predation risk and developed new insights into the avoidance of particular farmland types by reptiles. Our findings reveal remnant patches, edge and farmland, and harvesting period were important factors influencing predation risk, with highest frequency of predation attempts at habitat edges, particularly prior to harvesting. We also found the harvesting of crops did not result in significantly increased predation attempts 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 observed decline in reptile abundance from edges into some farmland habitats (Hansen 2018). Based on this information, we can improve the capacity for managing predation risk and enhance reptile conservation in agro-ecosystems.

3.1 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, Hill et al. 1998, Šálek, Kreisinger 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, Catterall et al. 2002, Storch, Woitke et al. 2005, Anderson and Burgin 2008), generalist predators crossing edge habitat when penetrating patches from adjacent modified habitats (Andrén 1995, Thompson, Warkentin et al. 2008) and forest-specialist predators spilling over opportunistically from patch into edge habitats (Storch, Woitke 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, Catterall 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, Vander Haegen, Schroeder 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, Best 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, Kreisinger et al. 2009, Šálek, Kreisinger et al. 2010). Our findings demonstrate predation risk is present in both the matrix and in remnant patches. 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, Schroeder et al. 2002, Rand, Tylianakis et al. 2006) and is a process identified as a key driver of species decline within remnants (Saunders, Hobbs et al. 1991, Matthews, Dickman 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.

3.2 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, Csuka et al. 2008, Cosentino, Schooley et al. 2011) and adjacent habitats (Schneider, Krauss 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, Nogales 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 (Miller, Grand et al. 2006, Šálek, Kreisinger et al. 2010).

3.3 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, Dickman et al. 2008, Thompson, Warkentin 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, Morriss et al. 2005, Bytheway, Price 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.

3.4   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, Banks et al. 2013) and inform management decisions to facilitate the persistence of reptiles in fragmented agricultural landscapes (Barton, Lentini et al. 2015, Kay, Driscoll et al. 2016). Our study suggests predation risk – a key ecological driver of reptile movement (Daly, Dickman et al. 2008, Sato, Wood 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, Banks et al. 2013, Sato, Wood 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, Beja 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, Wood 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, Cunningham et al. 2011, Manning, Cunningham et al. 2013). Other studies have found that the lower stratum vegetation cover can provide shelter for reptiles from predators (Fischer, Lindenmayer et al. 2003, Michael, Kay 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, Maron 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 (Driscoll, Banks et al. 2013, Sato, Wood 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, Ziv 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, Ziv 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.

3.5 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).

4 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. All authors'confirm their approval for final publication of the manuscript.

6 DATA ACCESSIBILITY

Data available via Dryad Digital Repository https://doi.org/10.5061/dryad.2f5v427 (Hansen, Sato et al. 2018)

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Table 1. 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, Wood 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 2. 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	$X2$	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

Fig. captions

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.
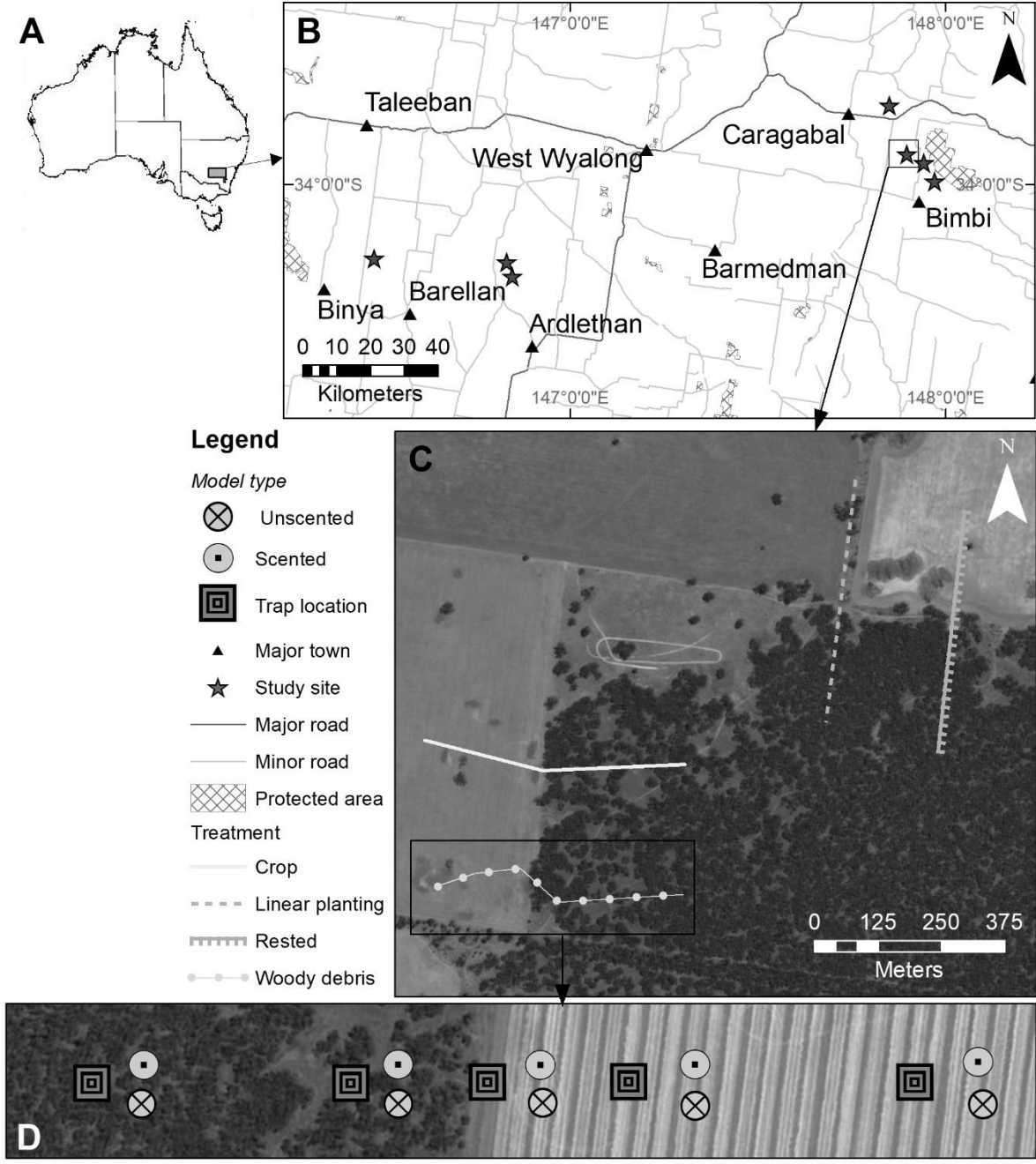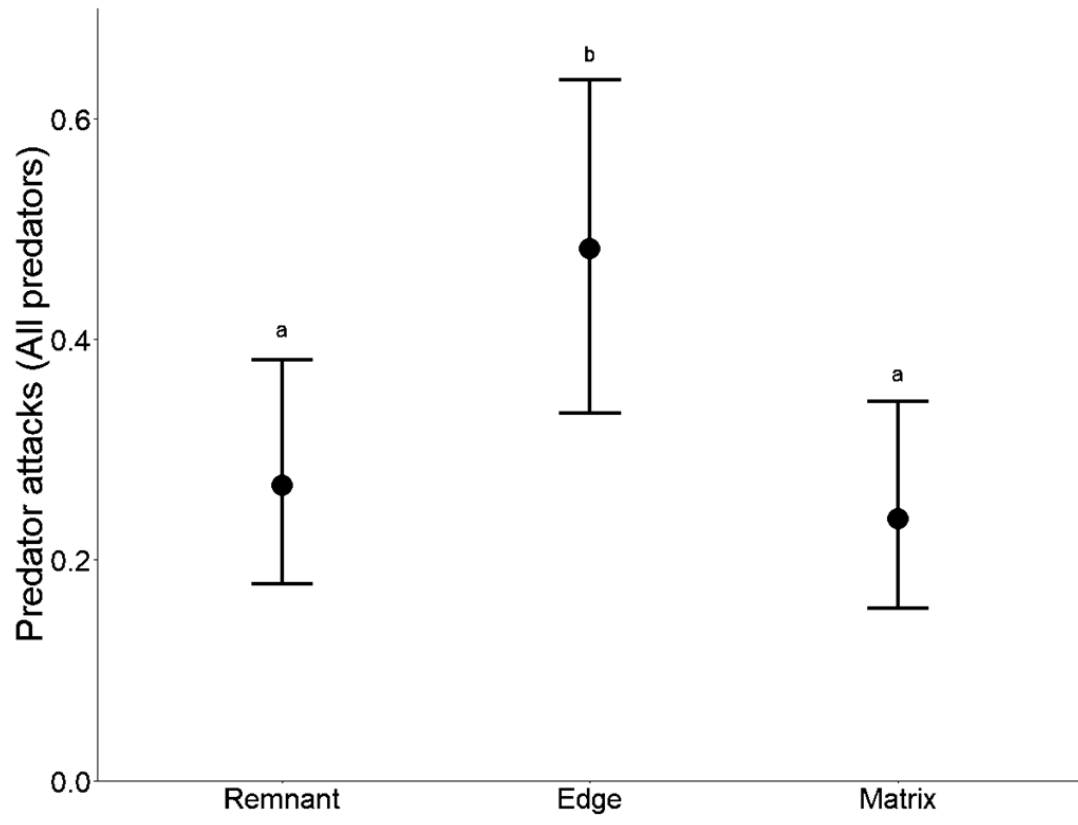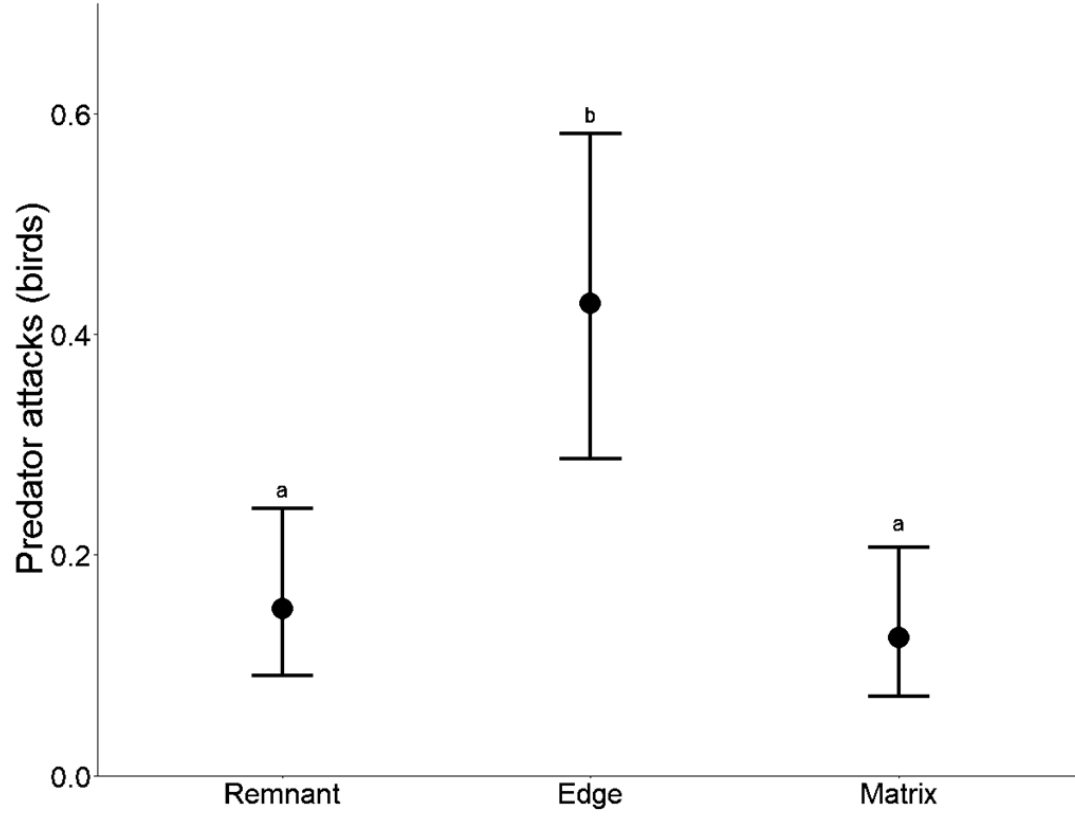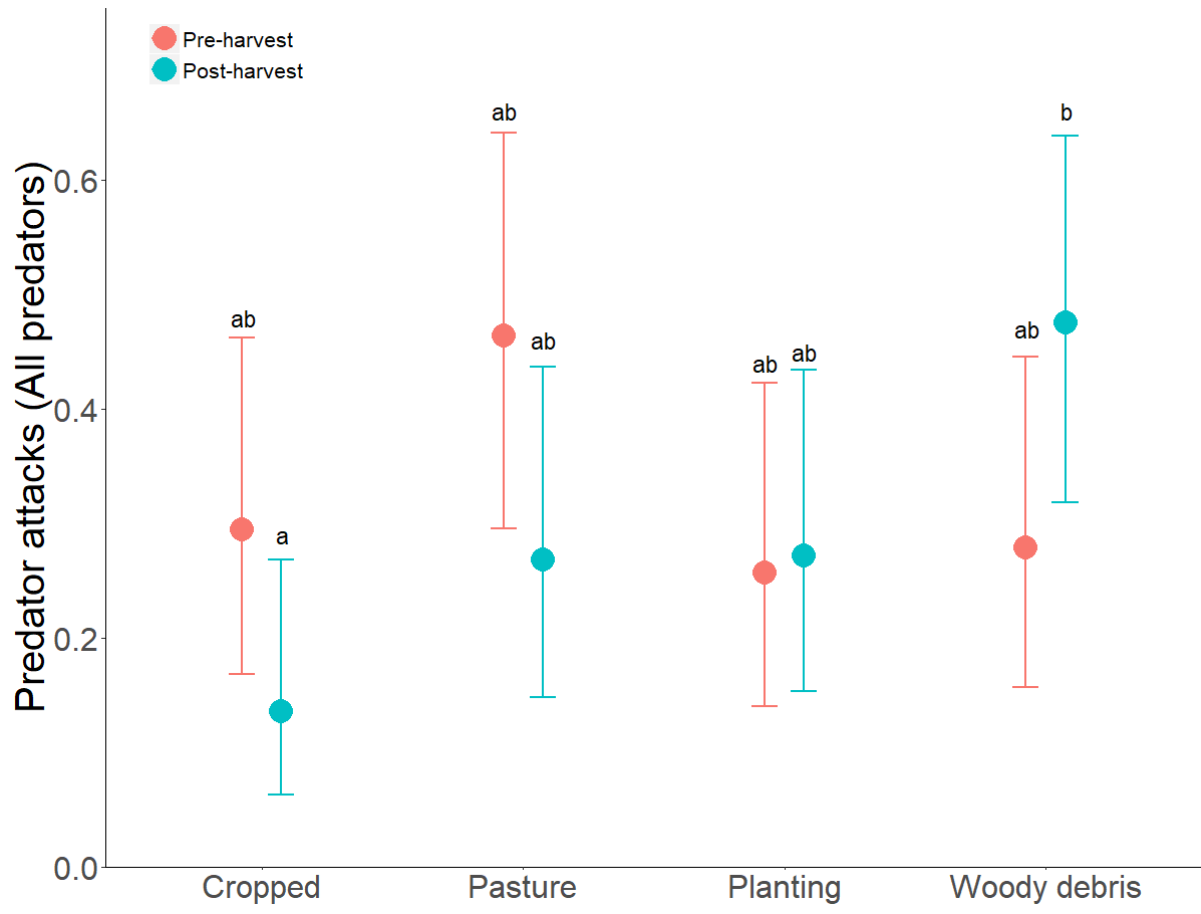
Fig.1

Fig. 2

A

B

Fig.3

Fig. 4

A

Predator attacks (birds)

- Pre-harvest
- Post-harvest

Remnant — ab, ab
Edge — c, bc
Matrix — ab, a

B

Predator attacks (mammals)

- Pre-harvest
- Post-harvest

Remnant — ab, ab
Edge — b, ab
Matrix — a, ab

Fig. 5