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Barking up the right tree: comparative use of arboreal and terrestrial artificial refuges to survey reptiles in temperate eucalypt woodlands

Damian R. Michael*[A, B, C], Daniel Florance*[A], Mason Crane[A], Wade Blanchard[A] and David B. Lindenmayer[A, B]

[A]Fenner School of Environment and Society, The Australian National University, Canberra, ACT, 2601, Australia.

[B]National Environmental Science Program, Threatened Species Recovery Hub, The Australian National University, Canberra, ACT, 2601, Australia.

[C] Corresponding author. Email: damian.michael@anu.edu.au

*These authors contributed equally to this work

Abstract

Context. Artificial refuges (cover boards) are a popular method to survey and monitor herpetofauna worldwide. However, one limitation of using artificial refuges in terrestrial environments is the low detection rates of arboreal species. Furthermore, destructive search techniques can damage critical microhabitat such as exfoliating rock or flaking bark of mature trees.

Aim. We tested a non-destructive, passive method of sampling arboreal reptiles in fragmented agricultural landscapes in south-eastern Australia.

Methods. We installed 84 artificial bark refuges consisting of strips of non-toxic, closed-cell foam attached to eucalypt trees in thirteen patches of remnant vegetation. We used Bayesian statistics to compare differences in detection rates between artificial bark refuges, terrestrial artificial refuges and active searches of natural habitat over a four year period.

Key results. Active searches combined with terrestrial artificial refuges detected the most number of reptile species, including several cryptic fossorial species. Artificial bark refuges detected on average 132 times more individuals of the arboreal southern marbled gecko *Christinus marmoratus* than terrestrial refuges. Gecko abundance patterns were related to tree characteristics such as tree size, bark thickness and stand basal area, as well as survey year.

Conclusions. Traditional survey methods such as terrestrial cover boards in combination with active searches of natural habitat may significantly underestimate counts for arboreal gecko species.

Implications. Artificial bark refuges provide a cost-effective, non-destructive and durable method for surveying and monitoring arboreal reptiles in woodland environments over short to medium time frames. Foil-backed, closed-cell foam has broad application for use in spatial capture-recapture studies and long-term monitoring of arboreal reptiles. This method also may be effective for procuring records of threatened arboreal geckos or as a solution for providing temporary habitat in ecological restoration projects.

Additional keywords: arboreal reptiles, artificial cover boards, environmental impact assessments, habitat restoration, survey method

Introduction

Effective wildlife management requires a detailed understanding of species distributions and habitat preferences (Adams 2016; Fryxell *et al.* 2014). Paramount in achieving this goal is choosing survey techniques that provide reliable estimates of abundance and diversity (Garden *et al.* 2007; Ribeiro-Júnior *et al.* 2008). Survey methods also must have the ability to detect and monitor changes in population trends over time (Lindenmayer *et al.* 2012a) and produce standardised and repeatable empirical data that can be compared across sampling events (Cunningham 2016; Engeman 2005). Survey techniques that fail to adequately detect rare and cryptic species, or particular taxonomic groups and lifeforms, may lead to incomplete inventories, inappropriate management actions and sub-optimal conservation outcomes (Thompson 2013).

The use of artificial refuges (cover boards) to detect reptiles and amphibians is now a well-established method for surveying and monitoring particular taxonomic groups, especially terrestrial snakes, lizards and amphibians (Hampton 2007; Michael *et al.* 2012; Sutherland *et al.* 2016; Willson and Gibbons 2010). A wide range of manufactured materials have been used to survey herpetofauna, including fibrocement slabs to monitor tortoises (Ballouard *et al.* 2013), timber boards and cedar shingles to survey salamanders in Europe, and Asia (Hesed 2012; Monti *et al.* 2000; Willson and Gibbons 2010), Onduline (bitumen) sheets to survey geckos in New Zealand (Thierry *et al.* 2009), and corrugated tin to survey snakes in the United States of America (Grant *et al.* 1992; Halliday and Blouin-Demers 2015; Hampton 2007; Joppa *et al.* 2009). In Australia, timber fence posts have been used to survey grassland reptiles (Michael *et al.* 2004), concrete and terracotta roofing tiles have been used to survey legless lizards (Howland *et al.* 2016; Thompson 2006), and recycled railway sleepers have been used to survey small, nocturnal elapid snakes (Michael *et al.* 2012).

The use of artificial refuges is not without limitations. Artificial refuges placed in terrestrial environments will inherently be biased towards sampling ground-dwelling fauna, and factors such as time of day and weather variables can significantly influence detection rates (Joppa *et al.* 2009; Thierry *et al.* 2009). However, several studies have detected arboreal lizards using terrestrial refuges (Michael *et al.* 2012). In south-eastern Australia, arboreal lizard species also use habitats other than trees, particularly rocky outcrops, fallen timber and buildings (Michael *et al.* 2015). Species such as the ragged snake-eyed skink *Cryptoblepharus pannosus* and the southern marbled gecko *Christinus marmoratus* have been detected on the ground beneath timber posts deployed as a survey method in woodland ecosystems (Michael *et al.* 2004), or beneath sheets of corrugated tin which imitate natural bark habitat (Michael *et al.* 2012). However, using terrestrial refuges to detect arboreal species is likely to result in low detection rates and incomplete inventories. The use of arboreal refuges is therefore likely to improve arboreal species detection rates. Although this method has primarily been applied in studies of invertebrates (Bowie *et al.* 2006; Hodge *et al.* 2007), two studies have targeted reptiles. In New Zealand, the use of arboreal covers led to the detection of more cryptic arboreal forest geckoes than nocturnal spotlighting, terrestrial artificial refuges or trapping (Bell 2009). In the tropical savanna woodlands of northern Australia, arboreal covers were used to compare differences in capture success between visual encounter surveys (Nordberg and Schwarzkopf 2015). However, lizard detections beneath arboreal covers have not been compared to traditional survey methods such as active searches or other forms of artificial refuges. Furthermore, the use of arboreal covers may reduce the need to remove or damage critical habitat such as exfoliating or flaking bark of mature trees. This is an important consideration when undertaking long-term ecological monitoring in areas that support threatened arboreal reptile species or threatened vegetation communities, given that once bark habitat is removed or damaged, it is not readily replaced and may take decades to accumulate. Damage to bark may also introduce a survey artefact with diminishing searchable habitat available with time since monitoring, which may be an important consideration when evaluating restoration outcomes.

To examine the effectiveness of using arboreal covers to survey and monitor temperate zone reptiles, we compared detections of arboreal reptiles between artificial bark refuges, active searches and terrestrial artificial refuges (timber railway sleepers, terracotta roofing tiles and corrugated steel) over a four year period. We addressed three questions: 1) How effective are different survey methods for detecting arboreal species? 2) Are there temporal differences in species detection rates over time? 3) Do tree characteristics (e.g. tree species, trees size class, bark thickness and stand basal area) influence arboreal lizard detection rates?

Materials and methods

Study area

We conducted this study within the Cowra-Young-Boorowa district of the South-west Slopes bioregion of New South Wales (central coordinate: 34°06'30.9"S 148°36'59.6"E). The predominant form of native vegetation in the bioregion is temperate eucalypt woodland (Hobbs and Yates 2000;

Lindenmayer *et al.* 2016). Sites were located on pre-existing long-term monitoring sites on private land within the critically endangered Box Gum Grassy Woodland ecosystem. Sites were located in patches of remnant vegetation where livestock grazing is the dominant land use. The native overstorey species were dominated by white box (*Eucalyptus albens*), yellow box (*E. melliodora*) and Blakely's red gum (*E. blakelyi*) (Keith and Wales 2004).

Terrestrial and arboreal artificial refuges

In 2010, we established 268 reptile monitoring plots (1 ha = 50 m x 200 m search grids) across the critically endangered White Box-Yellow Box-Blakely's Red Gum Woodland and Derived Native Grassland ecological vegetation community in south-eastern Australia (Lindenmayer *et al.* 2012b). Within each permanently marked monitoring plot, we installed two arrays of terrestrial artificial refuges (Figure 1). These consisted of four timber railway sleepers (1.2 m in length), four terracotta roof tiles, and one double stack of 1 m^2 corrugated steel sheet (Michael *et al.* 2012). Each array was placed 100 m apart along the centre of the monitoring plot. During 20th - 24th May 2013, we selected thirteen sites from a subset of pre-existing monitoring sites located within the Lachlan-Murrumbidgee catchment where arboreal lizard species (e.g. southern marbled gecko *Christinus marmoratus*) had been previously detected through either active searches or artificial terrestrial refuges (Kay *et al.* 2013). We then installed arboreal artificial bark refuges (N = 84 bark refuges) in a 1 ha area adjacent to our existing monitoring sites. The bark refuges consisted of a non-toxic, foil-backed strip of closed-cell foam (NSL 4005 5 mm, 1000 mm wide x 50 m roll, manufactured by PJ Bowers Pty Ltd, Queensland). We cut the material into 500 mm wide strips and covered the entire circumference of selected tree trunks, restraining the covers with rope attached to shock cords and metal 'S' clips (Figure 1). Each bark refuge was installed at a height of 1.3 metres above the ground (for logistical reasons). This attachment method allowed for quick removal from the tree to facilitate searching underneath. The foil faced outwards to provide weather resistance and thermal insulation. At each site, six trees were selected (mean distance between selected trees = 24.8 m), representing the two dominant overstory species (*E. blakelyi* and *E. melliodora*) and three size classes measured at breast height (small: 10 – 30 cm, mean = 26.18 cm; medium: 31 – 60 cm, mean = 46.56 cm; > 60 cm, mean = 77.81 cm). The bark refuges were positioned on trees 100 m from our terrestrial monitoring plots to reduce confounding effects between artificial refuge methods. Arboreal and terrestrial refuges remained *in situ* throughout the entire study. The total cost of all artificial bark materials (foam, rope, shock cord and clips) ranged from $5.8 to $13.75 AUD/tree, depending on tree circumference (approximately $6 AUD/m). We conducted the first survey in spring, four months after the artificial bark refuges were installed, and in conjunction with active searches and inspections of terrestrial artificial refuges.

Survey protocols

We collected count data (abundance) on lizards from thirteen sites using three different survey techniques, time-constrained (20 min) active searches of natural habitat (including lifting bark of trees, logs and rocks, and conducting visual surveys of tree trunks and logs), terrestrial artificial refuges and arboreal artificial refuges. The time required to inspect the two arrays of terrestrial refuges and the bark refuges was 10 minutes for each method. We conducted one survey each year between September and November 2013, 2014, 2015 and 2016, and compared detection rates among survey methods using these years for comparison. We did not individually mark lizards in this study. All surveys were conducted by the same group of ecologists on clear days between 0900 - 1400 hours.

Statistical analysis

Differences in lizard occurrence and abundance among the three survey methods were compared using logistic and Poisson (or negative binomial when over dispersion was present) regression respectively. We chose the negative binomial model over the Poisson model using leave-one-out cross-validation information criteria (LOOIC) (Gelman *et al.* 2014; Vehtari *et al.* 2015; Watanabe 2010) which we described in more detail below. Over-dispersion was present when the negative binomial model had a lower LOOIC than the corresponding Poisson model. Data were collapsed to the site level for this stage of the analysis and site was used as a random effect in the regression models to account for dependence among the survey methods and for multiple visits over years. The effect of survey method was assessed by comparing models with and without different survey methods. Differences in lizard occurrence beneath bark refuges over time were compared using presence absence data at the tree level for each year. Site was fitted as a random effect and year was modelled as a categorical variable. The effect of year on occurrence rates was assessed by comparing models with and without survey year. To evaluate tree characteristics effecting abundance we fitted tree species, size class, tree diameter (measured at breast height, log transformed), stand basal area (m^2/ha, log transformed) and bark thickness (log transformed). We did not include size class and the other size variables in the same model, since size class was associated with other tree characteristics (e.g. tree diameter, stand basal area and bark thickness). Survey year was retained in all models as this was considered important for detections. Bayesian methods were employed in all analyses using the brms (Bayesian regression models using Stan) package (Buerkner 2016) in R (R Core Team (2015). Brms provides a convenient interface to Stan (Carpenter *et al.* 2017) for many commonly occurring generalized linear mixed models and also provides several extensions. Cauchy priors (location = 0, scale = 5/2) were assigned to all regression parameters and continuous variables were standardized prior to analysis (Gelman *et al.* 2008). Four Hamiltonian Markov Chains were run for 2000 iterations each and convergence was assessed by visual examination of the trace plots. In the interest of model parsimony, we chose the simplest model within two LOOIC units of the best fitting model (Gelman *et al.* 2014; Vehtari *et al.* 2015; Watanabe 2010).

Results

Summary statistics

The closed-cell foam material remained viable throughout the four year deployment period suggesting this material is weather-resistant in field conditions. Damage caused by invertebrates and avifauna was evident on some foam pieces, but this did not seem to affect reptile use. Overall, we recorded thirteen reptile species from five families. Four reptile species were detected beneath the bark refuges, eight species were detected beneath terrestrial refuges, and eleven reptile species were detected using actives searches (Table S1, available as supplementary material to this paper). Boulenger's skink *Morethia boulengeri* accounted for 54% of all reptile observations and was detected most frequently beneath corrugated steel (123 observations) followed by active searches (65 observations). The southern marbled gecko *Christinus marmoratus* accounted for 33% of all observations and was most frequently recorded beneath artificial bark refuges (142 observations) compared to actives searches (7 observations) and corrugated steel (1 observation). Given the low number of detections of most lizard species beneath artificial bark refuges, we restricted our analysis to *C. marmoratus*.

What is the optimal survey method for detecting C. marmoratus?

The model that allowed for differences in detection of *C. marmoratus* among the three survey methods was highly preferred (Δ LOOIC = 66.87) over the model that assumed a constant detection rate among survey methods. Negative binomial models fitted our abundance of *C. marmoratus* better than the Poisson models (lower LOOIC in all cases), and the model that allowed for differences in abundance among the three survey methods was preferred to the constant abundance model (Δ LOOIC = 88.14). Abundance estimates from artificial bark refuges were 20.5 times (95% credible interval 9.3, 52.4) and 132 times (29.3, 1695.5) higher than active search and terrestrial artificial refuges, respectively (Figure 2, Table S2, available as supplementary material to this paper). A similar difference between survey methods was observed for detection rates (Table S3, available as supplementary material to this paper).

Temporal differences in detection rates

The model that allowed for differences in detection rates of *C. marmoratus* among years was preferred to the constant detection rate model (LOOIC = 15.27). The lowest rate was observed in 2013 (8.1% detection probability) and we found no evidence of differences in detection rates (range

26.2% - 31.4%) among subsequent survey years (2014-2016). (Table S4, available as supplementary material to this paper).

Tree characteristics and bark refuge abundance

We considered 18 models of varying degrees of complexity (see Table S5 for a complete listing available as supplementary material to this paper) to model the abundance per tree of *C. marmoratus*. The most parsimonious model showed the following effects: abundance per tree was positively associated with tree diameter (slope 1.06, 95% credible interval [0.77, 1.36]), bark thickness (0.28, [0.09, 0.48]) and basal area (0.23, [0.01, 0.47]) and survey year (Figure 3). Abundance per tree was lower in 2013 compared to 2014-2016, with no evidence of differences among 2014-2016 (Table S6, available as supplementary material to this paper).

Discussion

In many studies of herpetofauna, a combination of survey methods is required to procure comprehensive inventories (Garden *et al.* 2007; Michael *et al.* 2012). Effective survey methods also must have the ability to detect and monitor changes in population trends over time (Lindenmayer *et al.* 2012a) and produce standardised and repeatable empirical data that can be compared across sampling events (Cunningham 2016; Engeman 2005). In this study, we compared detection rates of reptiles over a four year period using three different survey methods. We specifically examined the effectiveness of using a novel survey method to detect arboreal reptiles in fragmented agricultural landscapes.

We found active searches of natural habitat resulted in the greatest number of detections of reptile species. Two species (*Anilios nigrescens* and *Lerista bougainvillii*) were detected only beneath terrestrial refuges, three species (*Aprasia parapulchella*, *Cryptoblepharus pannosus* and *Egernia* *cunninghami*) were detected only during active searches and only one individual *E. striolata* was detected beneath artificial bark refuges. These findings provide evidence to suggest that using both active searches and artificial refuges such as corrugated steel to survey reptiles in temperate eucalypt woodlands can procure complimentary species (Michael *et al.* 2012), especially cryptic fossorial species which are often difficult to detect in highly disturbed agricultural environments. Surprisingly, we detected very few *C. pannosus* beneath bark refuges even though this species was detected more frequently during actives searches (basking on trees) during the surveys. In a similar study, Nordberg and Schwarzkopf (2015) found that *Cryptoblepharus* sp. was one of the most commonly detected species beneath artificial bark refuges. Given the tendency for this species to prefer heavily timbered habitats with abundant amounts of fallen timber and dead trees (Cunningham *et al.* 2007; Michael *et al.* 2014), the widespread practice of cleaning up fallen and dead timber in agricultural landscapes may have reduced its abundance in the historically heavily grazed study area that was the focus of the investigation reported here.

Optimal survey method for detecting C. marmoratus

We found significantly more individuals of *C. marmoratus* beneath artificial bark refuges than any other survey method (Figure 1). The species was 132 times more abundant beneath bark refuges than beneath terrestrial refuges, and 20 times more abundant beneath bark refuges than on sites where active searches were used. This suggests that traditional methods such as terrestrial cover boards and active searches may underestimate the abundance of this species, although this may depend on region, habitat condition and the presence of rock habitat (Lettink 2007; Michael *et al.* 2012). Considering we installed only six bark refuges over 1 ha and, on average, more trees were inspected (by carefully lifting exfoliating bark) during active searches, the differences in detection rates between survey methods is even more compelling. Population estimates for *C. marmoratus* in rocky environments have been reported to be approximately 150 animals/ha (Kearney and Predavec 2000). However, in non-rocky environments, it is difficult to locate geckos sequestered beneath the bark of trees without causing substantial damage to their habitat. If we were to comprehensively search for sheltering geckos by completely removing bark from all suitable trees, it is likely that active searches would produce higher detection rates, but this activity would at the same time reduce the quality of habitat for this and other arboreal species. Incorporating artificial bark refuges in future fauna surveys would not only negate the need to damage critical bark habitat but could significantly increase the probability of detecting arboreal species. This has important implications for the refinement of survey methods used to target threatened arboreal species in environmental impact assessments.

Temporal differences in detection rates

We found *C. marmoratus* occupied the artificial bark refuges relatively soon after they had been installed (8.1% detection probability at four months since installation). In the following year, detection rates beneath bark refuges had increased by a factor of four (31.4% detection probability), thereafter remaining stable. Over time, arboreal refuges may provide stable detection probabilities and reliable population estimates. Unlike terrestrial refuges (both natural and artificial), which are subject to considerable variability in temperature (Huey *et al.* 1989; Kearney 2002) and corresponding fluctuations in the occupancy patterns of cryptozoic species (Webb and Shine 1998; Thierry *et al.* 2009), bark habitat may provide opportunities for geckos to thermoregulate during different seasons and hence, detectability issues associated with temperature are predicted to be reduced. We suggest bark refuges may provide thermally suitable microhabitats because they are wrapped around the entire circumference of the tree, allowing individuals to select a broad range of dial and seasonal thermal conditions. *Christinus mamoratus* is known to regulate its body temperature through positional and postural mechanisms, as well as through retreat site selection (Kearney and Predavec 2000). Artificial bark refuges may provide a range of thermally suitable microhabitats that may promote long-term occupation and site fidelity. Further research is required to examine the relationship between gecko occupancy patterns and the thermal conditions of artificial refuges compared to natural retreat sites.

Tree characteristics and abundance patterns

Previous studies in the temperate eucalypt woodlands of south-eastern Australia have reported *C. marmoratus* to be an arboreal generalist (Michael *et al.* 2015), associated with old growth vegetation (Cunningham *et al.* 2007), large trees and high amounts of native vegetation in the landscape (Michael *et al.* 2017). In this study, we found the majority of *C. marmoratus* observations beneath bark refuges were from trees with an average diameter of 78 cm. We also found between 20 - 40% of *C. marmoratus* observations were on trees with an average diameter of 47 cm. The model which best explained *C. marmoratus* abundance patterns included tree diameter, bark thickness and stand basal area as important variables (Figure 2). These findings suggest that large diameter trees with thick bark located in timbered areas, regardless of tree species may be the best trees to target for artificial bark installation for future herpetofauna inventory and monitoring projects.

Our findings also suggest that artificial bark refuges may have broad application in ecological restoration programs, especially in relation to increasing arboreal habitat in secondary vegetation communities (regrowth woodland) where stem density is high and tree size is small (Ikin *et al.* 2015). Bark refuges placed in areas that lack large trees with suitable bark habitat could facilitate greater dispersal and gene flow between lizard populations that occur in fragmented agricultural landscapes. Habitat loss and fragmentation can disrupt fine-scale movements and dispersal capabilities of some arboreal species (Hoehn *et al.* 2007), prompting some researchers to suggest creating 'stepping stone' habitats as a method for improving connectivity for arboreal geckos (Kay *et al.* 2016).

Implications for research and management

Artificial bark refuges led to the detection of substantially more individuals of the arboreal *C. marmoratus* than terrestrial artificial refuges or active searches suggesting that traditional survey methods may significantly underestimate the abundance of this species. The foil-backed, closed-cell foam product used in this study was weather resistant over the four years of field deployment, suggesting that it is a suitable material for use in short to medium-term studies. Artificial bark refuges also provide a cost-effective and non-invasive, practical method for surveying arboreal nocturnal reptiles and will thereby reduce the need to damage critical bark habitat when conducting fauna surveys or environmental impact assessments. The need to preserve bark habitat is extremely important as, for some tree species, this micro-resource can take decades to accumulate and may not be readily renewed when destroyed or damaged. Longer-term assessment of the durability of this product in the field will continue. For long-term studies, alternative materials may be required and it is recommended that alternative products are tested in the field.

Bark refuges have enormous potential for use in spatial capture-recapture studies (Sutherland *et al.* 2016) or for obtaining empirical spatial data on rare and cryptic arboreal species (Bell 2009). For inventory and monitoring projects, a combination of census techniques will provide the greatest diversity and detection of herpetofauna and it is recommended that artificial bark installation be considered to complement other survey methods. An observed delay in herpetofauna colonisation following artificial bark installation should be considered when planning deployment of artificial bark and monitoring schedules. The use of artificial bark refuges also has application as a temporary solution to creating arboreal habitat in ecological restoration programs that aim to improve habitat connectivity in fragmented agricultural landscapes. We recommend that further research focus on the use of bark refuges as a habitat restoration tool and as a method for procuring records for threatened arboreal reptiles in different woodland and forest ecosystems.

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References

Adams, C. E. (2016) 'Urban Wildlife Management.' (CRC press, Taylor & Francis Group: Boca Raton.)

Ballouard, J.-M., Caron, S., Lafon, T., Servant, L., Devaux, B., and Bonnet, X. (2013). Fibrocement slabs as useful tools to monitor juvenile reptiles: a study in a tortoise species. *Amphibia-Reptilia* **34**, 1-10.

Bell, T. P. (2009). A novel technique for monitoring highly cryptic lizard species in forests. *Herpetological Conservation and Biology* **4**, 415-425.

Bowie, M. H., Hodge, S., Banks, J. C., and Vink, C. J. (2006). An appraisal of simple tree-mounted shelters for non-lethal monitoring of weta (Orthoptera: Anostostomatidae and Rhaphidophoridae) in New Zealand nature reserves. *Journal of Insect Conservation* **10**, 261-268.

Buerkner, P.-C. (2016). brms: An R package for Bayesian multilevel models using Stan. Available at: https://cran.r-project.org/web/packages/brms/vignettes/brms.pdf.

Bob Carpenter, Andrew Gelman, Matthew D. Hoffman, Daniel Lee, Ben Goodrich, Michael Betancourt, Marcus Brubaker, Jiqiang Guo, Peter Li, and Allen Riddell. 2017. Stan: A probabilistic programming language. Journal of Statistical Software 76(1). DOI 10.18637/jss.v076.i01

Cunningham, R. B. (2016). Design and analysis of quasi-experiments in landscape ecology: responses of fauna to landscape vegetation transformation in South-Eastern NSW. PhD Thesis (The Australian National University, Canberra, ACT.)

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

Engeman, R. M. (2005). Indexing principles and a widely applicable paradigm for indexing animal populations. *Wildlife Research* **32**, 203-210.

Fryxell, J. M., Sinclair, A. R., and Caughley, G. (2014) 'Wildlife Ecology, Conservation and Management.' (John Wiley & Sons: UK)

Garden, J. G., McAlpine, C. A., Possingham, H. P., and Jones, D. N. (2007). Using multiple survey methods to detect terrestrial reptiles and mammals: what are the most successful and cost-efficient combinations? *Wildlife Research* **34**, 218-227.

Gelman, A., Hwang, J., and Vehtari, A. (2014). Understanding predictive information criteria for Bayesian models. *Statistics and Computing* **24**, 997-1016.

Gelman, A., Jakulin, A., Pittau, M. G., and Su, Y.-S. (2008). A weakly informative default prior distribution for logistic and other regression models. *The Annals of Applied Statistics* **2**, 1360-1383.

Grant, B. W., Tucker, A. D., Lovich, J. E., Mills, A. M., Dixon, P. M., and Gibbons, J. W. (1992). The use of coverboards in estimating patterns of reptile and amphibian biodiversity. In 'Wildlife 2001: Populations'. (Ed. D. R McCullough & Barrett, R. H.) pp. 379-403. (Springer: Netherlands)

Halliday, W. D. and Blouin-Demers, G. (2015). Efficacy of coverboards for sampling small northern snakes. *Herpetology Notes* **8**, 309-314.

Hampton, P. (2007). A comparison of the success of artificial cover types for capturing amphibians and reptiles. *Amphibia-Reptilia* **28**, 433-437.

Hesed, K. M. (2012). Uncovering salamander ecology: a review of coverboard design. *Journal of Herpetology* **46**, 442-450.

Hobbs, R. J. and Yates, C. J. (2000) 'Temperate Eucalypt Woodlands in Australia: Biology, Conservation, Management and Restoration.' (Surrey Beatty & Sons Pty: Sydney)

Hodge, S., Vink, C. J., Banks, J. C., and Bowie, M. H. (2007). The use of tree-mounted artificial shelters to investigate arboreal spider communities in New Zealand nature reserves. *Journal of Arachnology* **35**, 129-136.

Hoehn, M., Sarre, S., and Henle, K. (2007). The tales of two geckos: does dispersal prevent extinction in recently fragmented populations? *Molecular Ecology* **16**, 3299-3312.

Howland, B. W., Stojanovic, D., Gordon, I. J., Fletcher, D., Snape, M., Stirnemann, I. A., and Lindenmayer, D. B. (2016). Habitat preference of the striped legless lizard: Implications of grazing by native herbivores and livestock for conservation of grassland biota. *Austral Ecology* **41**, 461-470.

Huey, R. B., Peterson, C. R., Arnold, S. J., and Porter, W. P. (1989). Hot rocks and not-so-hot rocks: retreat-site selection by garter snakes and its thermal consequences. *Ecology* **70**, 931-944.

Ikin, K., Mortelliti, A., Stein, J., Michael, D., Crane, M., Okada, S., Wood, J., and Lindenmayer, D. (2015). Woodland habitat structures are affected by both agricultural land management and abiotic conditions. *Landscape Ecology* **30**, 1387-1403.

Joppa, L. N., Williams, C. K., Temple, S. A., and Casper, G. S. (2009). Environmental factors affecting sampling success of artificial cover objects. *Herpetological Conservation and Biology* **5**, 143-148.

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

Kay, G. M., Michael, D. R., Crane, M., Okada, S., MacGregor, C., Florance, D., Trengove, D., McBurney, L., Blair, D. and Lindenmayer, D. B. (2013) A list of reptiles and amphibians from Box Gum Grassy Woodlands in south-eastern Australia. *Check List* **9**, 476-481.

Kearney, M. (2002). Hot rocks and much-too-hot rocks: seasonal patterns of retreat-site selection by a nocturnal ectotherm. *Journal of Thermal Biology* **27**, 205-218.

Kearney, M. and Predavec, M. (2000). Do nocturnal ectotherms thermoregulate? A study of the temperate gecko *Christinus marmoratus*. *Ecology* **81**, 2984-2996.

Keith, D. A. and Wales, N. S. (2004) 'Ocean Shores to Desert Dunes: The Native Vegetation of New South Wales and the ACT.' (Department of Environment and Conservation: NSW.)

Lettink, M. (2007). Comparison of two techniques for capturing geckos in rocky habitat. *Herpetological Review* **38**, 415.

Lindenmayer, D. B., Gibbons, P., Bourke, M., Burgman, M., Dickman, C. R., Ferrier, S., Fitzsimons, J., Freudenberger, D., Garnett, S. T., and Groves, C. (2012a). Improving biodiversity monitoring. *Austral Ecology* **37**, 285-294.

Lindenmayer, D. B., Michael, D. R. Crane, M., Barton, P., Ikin, K., Okada, S. (2016) 'Wildlife Conservation in Farm Landscapes'. (CSIRO Publishing: Collingwood, Melbourne.)

Lindenmayer, D. B., Zammit, C., Attwood, S. J., Burns, E., Shepherd, C. L., Kay, G., and Wood, J. (2012b). A novel and cost-effective monitoring approach for outcomes in an Australian biodiversity conservation incentive program. *PloS one* **7**, e50872.

Michael, D. R., Cunningham, R. B., Donnelly, C. F., and Lindenmayer, D. B. (2012). Comparative use of active searches and artificial refuges to survey reptiles in temperate eucalypt woodlands. *Wildlife Research* **39**, 149-162.

Michael, D. R., Ikin, K., Crane, M., Okada, S., and Lindenmayer, D. B. (2017). Scale-dependent occupancy patterns in reptiles across topographically different landscapes. *Ecography* **40**, 415-424.

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

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

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

Monti, L., Hunter, M., and Witham, J. (2000). An evaluation of the artificial cover object (ACO) method for monitoring populations of the redback salamander *Plethodon cinereus*. *Journal of Herpetology* **34**, 624-629.

Nordberg, E. J. and Schwarzkopf, L. (2015). Arboreal cover boards: using artificial bark to sample cryptic arboreal lizards. *Herpetologica* **71**, 268-273.

R Core Team (2015) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ribeiro-Júnior, M. A., Gardner, T. A., and Ávila-Pires, T. C. (2008). Evaluating the effectiveness of herpetofaunal sampling techniques across a gradient of habitat change in a tropical forest landscape. *Journal of Herpetology* **42**, 733-749.

Sutherland, C., Muñoz, D. J., Miller, D. A., and Grant, E. H. C. (2016). Spatial capture–recapture: a promising method for analyzing data collected using artificial cover objects. *Herpetologica* **72**, 6-12.

Thierry, A., Lettink, M., Besson, A. A., and Cree, A. (2009). Thermal properties of artificial refuges and their implications for retreat-site selection in lizards. *Applied Herpetology* **6**, 307-326.

Thompson, M. J. (2006) The use of artificial refuges to census populations of the ‘threatened’striped legless lizard, *Delma impar* in Western Victoria. (Department of Zoology: La Trobe University.)

Thompson, W. (2013) 'Sampling rare or elusive species: concepts, designs, and techniques for estimating population parameters.' (Island Press: Washington, DC.)

Vehtari, A., Gelman, A., and Gabry, J. (2015). Efficient implementation of leave-one-out cross-validation and WAIC for evaluating fitted Bayesian models. *arXiv preprint arXiv:1507.04544*. https://github.com/jgabry/loo.

Watanabe, S. (2010). Asymptotic equivalence of Bayes cross validation and widely applicable information criterion in singular learning theory. *Journal of Machine Learning Research* **11**, 3571-3594.

Webb, and Shine, R. (1998) Using thermal ecology to predict retreat-site selection by an endangered snake species. *Biological Conservation* **86**, 233-242.

Willson, J. D. and Gibbons, J. W. (2010). Drift fences, coverboards, and other traps. In 'Amphibian Ecology and Conservation: A Handbook of Techniques'. (Ed. C. K. Dodd.) pp. 229-245. (Oxford University Press: New York.)

Figure 1. Terrestrial artificial refuges (left), double stack of corrugated steel, roofing tiles and timber railway sleepers. Foil-backed, closed-cell foam (right) used as an arboreal artificial bark refuge.

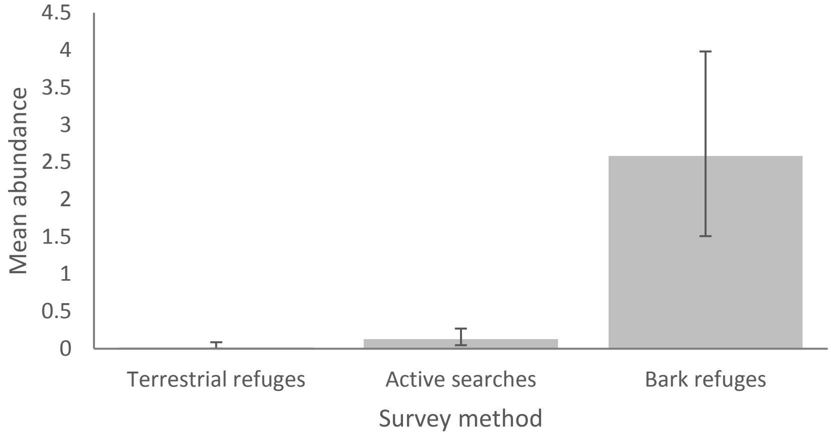

Figure 2. Mean abundance (95% credible interval) of the southern marbled gecko *Christinus marmoratus* using three different survey methods between 2013 and 2016.

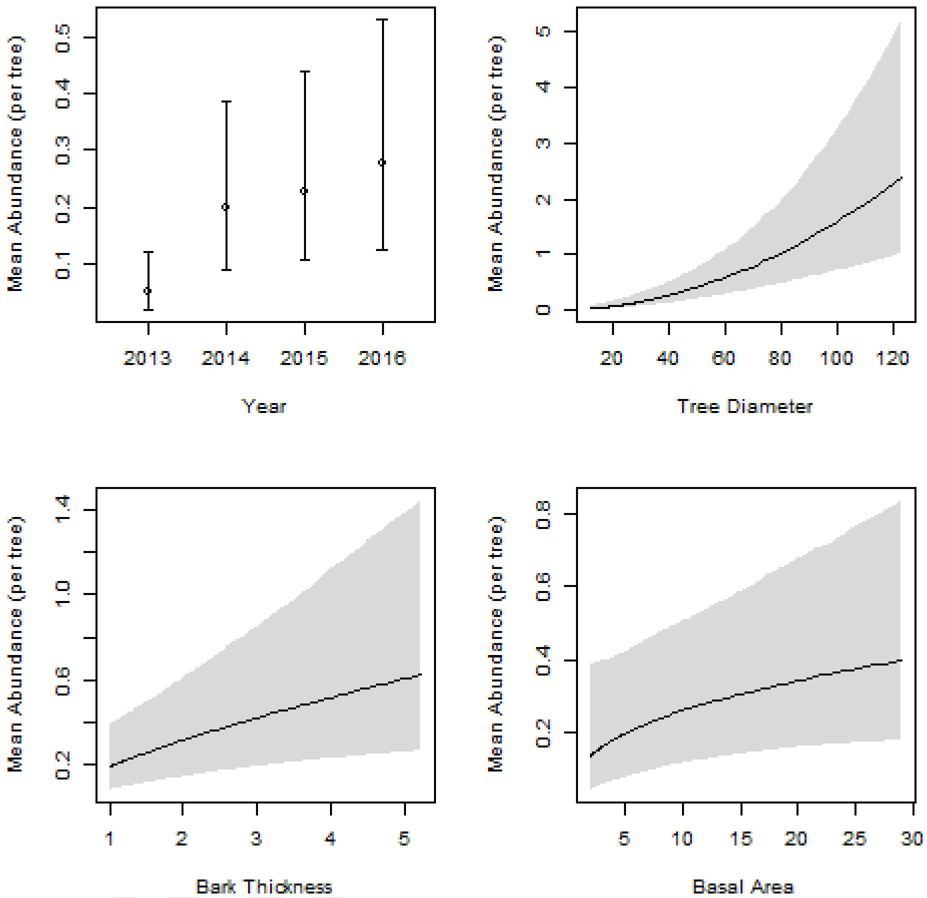

Figure 3. Relationships between the abundance of the southern marbled gecko *Christinus marmoratus* and survey year, tree diameter (cm), bark thickness (cm) and stand basal area (m^2/ha) with 95% credible intervals.

Supplementary material

Barking up the right tree: comparative use of arboreal and terrestrial artificial refuges to survey reptiles in temperate eucalypt woodlands

Damian R. Michael[A, B, C], Daniel Florance[A], Mason Crane[A], Wade Blanchard[A] and David B. Lindenmayer[A, B]

[A]Fenner School of Environment and Society, The Australian National University, Canberra, ACT, 2601, Australia.

[B]National Environmental Science Programme, Threatened Species Recovery Hub, The Australian National University, Canberra, ACT, 2601, Australia.

[C]Corresponding author. Email: damian.michael@anu.edu.au

Table S1. List of reptile species recorded and the total number of detections between 2013 and 2016 (four surveys) using three different survey methods: arboreal artificial refuges, actives searches and terrestrial artificial refuges (corrugated steel, timber railway sleepers and terracotta roofing tiles). Note: individual animals were not marked, so numbers for some species may represent multiple detections over survey years.

Common Name	**Species**	**Lifeform**	**Arboreal bark refuges**	**Active searches**	**Corrugated Steel**	**Railway sleepers**	**Roofing tiles**
Gekkonidae							
Southern Marbled Gecko	*Christinus marmoratus*	Arboreal	142	7	1	0	0
Thick-tailed Gecko	*Underwoodisaurus milii*	Terrestrial	0	1	0	0	0
Pygopodidae							
Pink-tailed Worm-lizard	*Aprasia parapulchella*	Fossorial	0	1	0	0	0
Olive Legless Lizard	*Delma inornata*	Terrestrial	0	1	0	0	0
Scincidae							
Southern Rainbow Skink	*Carlia tetradactyla*	Terrestrial	0	5	3	2	1
Ragged Snake-eyed Skink	*Cryptoblepharus pannosus*	Arboreal	4	11	0	0	0
Eastern Striped Skink	*Ctenotus spaldingi*	Terrestrial	0	6	8	4	5
Cunningham's Skink	*Egernia cunninghami*	Terrestrial	0	1	1	1	1
Tree Skink	*E. striolata*	Arboreal	1	0	0	0	0
Three-toed Earless Skink	*Hemiergis talbingoensis*	Fossorial	0	0	1	0	0
South-eastern Slider	*Lerista bougainvillii*	Fossorial	0	0	1	0	0
Dwarf Skink	*Menetia greyii*	Terrestrial	0	2	0	0	0
Boulenger's Skink	*Morethia boulengeri*	Terrestrial	1	65	123	15	43
Typhlopidae							
Blackish Blind Snake	*Anilios nigrescens*	Fossorial	0	0	1	0	0
Elapidae							
Dwyer's Snake	*Parasuta dwyeri*	Terrestrial	0	1	0	0	0
Total number of species			4	11	8	4	4

Table S2. Abundance per site estimates of *Christinus marmoratus* by survey method and relative differences of survey methods. The upper part of the table gives the posterior estimates of the probability of detection and the associated 95% credible limits. The lower portion of the table, gives relative ratios and their associated 95% credible limit for comparison of rates between any two years. Note, that if the 95% credible limit does not include 1, we conclude there is evidence of a difference between the two detection rates being compared.

Group	Estimated abundance per site	Lower 95% credible interval	Upper 95% credible interval
Active searches	0.126	0.047	0.277
Terrestrial refuges	0.019	0.002	0.087
Bark refuges	2.585	1.508	3.982
Relative Differences			
Terrestrial refuges vs active searches	0.156	0.011	0.837
Bark refuges vs active searches	20.594	9.267	52.375
Bark vs terrestrial refuges	132.005	29.323	1695.457

Table S3. Detection rates of *Christinus marmoratus* by survey method and odds ratios comparing survey methods. The upper part of the table gives the posterior estimates of the probability of detection and the associated 95% credible limits. The lower portion of the table, gives the odds ratios and their associated 95% credible limit for comparison of odds ratios between any two years. Note, that if the 95% credible limit does not include 1, we conclude there is evidence of a difference between the two detection rates being compared.

Group	Probability of detection per site	Lower 95% CI	Upper 95% CI
Active searches	12.9%	4.5%	26.7%
Terrestrial refuges	1.8%	0.1%	8.0%
Bark refuges	75.5%	58.1%	88.9%
Comparisons (Odds Ratio Scale)			
Terrestrial refuges vs active searches	0.13	0.01	0.72
Bark refuge vs active searches	21.86	7.11	78.67
Bark vs terrestrial refuge	174.00	30.74	2988.32

Table S4. Detection rates per tree of *Christinus marmoratus* by year and odds ratios comparing yearly detection rates. The upper part of the table gives the posterior estimates of the probability of detection and the associated 95% credible limits. The lower portion of the table, gives the odds ratios and their associated 95% credible limit for comparison of odds ratios between any two years. Note, that if the 95% credible limit does not include 1, we conclude there is evidence of a difference between the two detection rates being compared.

Survey Year	Probability of detection per tree	Lower 95% CI	Upper 95% CI
2013	8.1%	2.9%	17.4%
2014	31.4%	17.1%	48.8%
2015	28.5%	14.7%	45.6%
2016	26.2%	12.8%	43.0%
Comparisons (Odds Ratio Scale)			
2014 v 2013	5.16	2.32	13.24
2015 v 2013	4.49	1.98	11.67
2016 v 2013	4.03	1.67	10.53
2015 v 2014	0.86	0.43	1.71
2016 v 2014	0.77	0.36	1.58
2016 v 2015	0.90	0.41	1.92

Table S5. Summary of models used to explain *Christinus marmoratus* abundance beneath bark refuges and tree characteristics. We used the following short hand to specify the models in the table: SY = survey year, TS = tree species, SC = size class, BA = log basal area, BT = log bark thickness, D = log tree diameter and LOOIC = leave one out information criteria.

Model No	Model	No Terms	LOOIC
1	SY	1	541.40
2	SY + TS	2	541.93
3	SY + SC	2	459.44
4	SY + TS + SC	3	459.82
5	SY + TS + BA	3	536.35
6	SY + TS + BT	3	500.09
7	SY + TS + BA + BT	4	499.83
8	SY + TS + D	3	441.14
9	SY + TS + D + BA	4	438.11
10	SY + TS + D + BT	4	437.01
11	SY + BA	2	535.08
12	SY + BT	2	504.18
13	SY + BA + BT	3	502.26
14	SY + D	2	441.05
15	SY + D + BA	3	438.14
16	SY + D + BT	3	435.33
17	SY + D + BA + BT	4	**433.14**
18	SY + TS + D + BT + BA	5	433.77

Table S6. Best fitting model for the abundance per tree estimates of *Christinus marmoratus* for the bark refuge. Note, that the continuous variables have been standardized (on the log scale). We also present the estimated abundance per tree by year assuming tree with the continuous covariates set at their mean value.

Parameter	Estimate	Lower 95% CI	Upper 95% CI
Intercept (2013)	-2.95	-3.88	-2.11
2014	1.32	0.70	2.04
2015	1.46	0.82	2.16
2016	1.65	1.03	2.34
Log tree diameter	1.06	0.77	1.36
Log bark thickness	0.28	0.09	0.48
Log stand basal area	0.23	0.01	0.47
Random effect SE	1.08	0.62	1.84
Year estimates	Abundance per tree	Lower 95% CI	Upper 95% CI
2013	0.05	0.02	0.12
2014	0.20	0.09	0.39
2015	0.23	0.11	0.44
2016	0.28	0.13	0.53
Relative differences			
2014 v 2013	3.72	2.00	7.71
2015 v 2013	4.25	2.27	8.67
2016 v 2013	5.14	2.80	10.34
2015 v 2014	1.14	0.74	1.74
2016 v 2014	1.39	0.90	2.12
2016 v 2015	1.21	0.80	1.86