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Monitoring methods influence native predator detectability and inferred occupancy responses to introduced carnivore management

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ABSTRACT

Context. Management actions that suppress introduced predator densities can benefit the population recovery of native species. Nevertheless, ensuring that predator management produces measurable population-level benefits can be influenced by multiple factors affecting species detection. Monitoring designs using multiple survey methods may perform better than increasing sampling effort with single-method protocols. **Aims.** This study aimed to estimate individual and cumulative detection probabilities and site occupancy estimates from the use of five different monitoring methods to survey a native mesopredator, the lace monitor (*Varanus varius*). Second, we assessed the effect of lethal red fox (*Vulpes vulpes*) baiting on lace monitor detection probabilities and site occupancy estimates collected from each monitoring method. **Methods.** Multi-method sampling for *Varanus varius* occurred at 76 sites across lethal fox baited and non-baited habitats in East Gippsland, Victoria. Bayesian site occupancy models were used to estimate the effects of detection method and fox-baiting treatments on *Varanus varius* detection probability and site occupancy. **Key results.** Method-specific detection probabilities ($P = 0.00–0.12$) and site occupancy estimates ($\Psi = 0–0.53$) varied considerably among methods, but combinations of multi-method monitoring improved lace monitor detection probability ($P = 0.11–0.18$) and site occupancy ($\Psi = 0.87 \pm [0.66–0.93]–0.91 \pm [0.76–0.97]$ mean ± [95% credible intervals]) above any single method. However, there was extreme heterogeneity in the size and direction of the introduced predator baiting effect on method-specific lace monitor detection. Three methods (box traps and two different visual search surveys) all indicated lace monitor detection probabilities increased in fox-baited sites. However, sand pads reported a decrease in lace monitor detection at fox-baited sites, whereas pipe traps obtained no detections. **Conclusions.** Combining detection data from all methods led to the inference of a positive fox-baiting effect, albeit with a smaller magnitude and better certainty than that estimated using a reduced method monitoring design, which had fewer detection data after excluding biased detection from sand pads. **Implications.** Using a multi-method monitoring approach improved lace monitor detection and reduced sampling effort. However, depending on sampling methodology, the management effects on lace monitors can change.

Keywords: biodiversity monitoring, detection method evaluation, detection probability, lace monitor, lethal fox baiting, management inference, site occupancy, *Varanus varius*.

Introduction

Introduced mammalian predators have caused globally significant ecological impacts, including the decline and extinction of native species (Doherty *et al.* 2016). For instance, the 19th century introduction of the European red fox (*Vulpes vulpes*) into Australia has had well documented and continental-scale biodiversity impacts (Glen and Dickman 2008; Saunders *et al.* 2010; Woinarski *et al.* 2019). Since the 1980s, landscape-scale poison baiting programmes have been a key management action used to suppress the density of introduced fox populations across Australia (Kinnear *et al.* 2002;

Hayward and Somers 2012; Braysher 2017; Legge *et al.* 2018). Fox baiting has produced measurable biodiversity benefits for both threatened and non-threatened native species, and helped restore ecological processes (Kinnear *et al.* 1998; Dexter and Murray 2009; Claridge *et al.* 2010; de Tores and Marlow 2012). However, it is also sometimes evident that fox baiting may have weak, absent, or unintended (e.g. introduced mesopredator or herbivore release) biodiversity consequences (Walsh *et al.* 2012; Marlow *et al.* 2015; Lindenmayer *et al.* 2018; Jessop *et al.* 2021). Evaluating the processes underpinning ineffective or unforeseen native biodiversity responses from fox-baiting outcomes is essential for innovating and guiding future management plans, and helps ensure that scarce conservation funds can best achieve positive conservation benefits (Walsh *et al.* 2012; Lindenmayer *et al.* 2018). Not discounting that environmental, ecological, or baiting protocol-related processes could affect the magnitude and direction of native biodiversity responses to fox-baiting programmes. It is also important to recognise that the monitoring method(s) and associated experimental designs used to measure native species responses can have significant implications for data quality, survey success, and arising population response estimates used to evaluate wildlife management effectiveness (Thompson and Thompson 2007; Nichols *et al.* 2008; Lindenmayer *et al.* 2020). For example, indirect or direct population estimates for a target species obtained from different monitoring methods may be poorly correlated and indicate method-specific detection biases (Long *et al.* 2007, 2012; Hayward *et al.* 2015). Similarly, monitoring methods that use baits, lures or traps can affect animal behaviour that may positively or negatively influence detection, and consequently bias population-level estimates (Thompson 2013; Comer *et al.* 2018; Stewart *et al.* 2019). Ultimately, any monitoring method that achieves poor, or biased, detection probability could obscure environmental managers from accurately assessing their actions on wildlife populations (Yoccoz *et al.* 2001; Kéry and Schmidt 2008).

Population monitoring designs that use multiple concurrent methods have been advocated to reduce uncertainty produced by low detection probability from single method monitoring designs (Bailey *et al.* 2004; Nichols *et al.* 2007; Otto and Roloff 2011). Multi-method monitoring protocols can be particularly advantageous if they increase sampling opportunities to reduce imperfect detection (MacKenzie *et al.* 2017; Einoder *et al.* 2018). Similarly, through improved detection, such designs might reduce sampling effort compared with single method sampling designs. Additionally, one monitoring method may have relatively high detectability, but may be biased if it only detects part of the population. Then integration with other methods can allow concurrent methods to better obtain unbiased estimates (Descalzo *et al.* 2021). Using multiple methods is not without problems, including that different methods can achieve dissimilar detection of target species, or if one method is far better, it can produce inefficient monitoring (Nichols *et al.* 2008; Mattfeldt *et al.* 2009). Similarly, if multiple methods within a sampling site lack spatial independence, they may produce overlapping and correlated detections that produce inefficient monitoring (Clare *et al.* 2017). Also, method-specific biases can increase or decrease detection probability relative to the population's actual occurrence (Bailey *et al.* 2004). In such cases, method-specific biases may propagate uncertainty in estimates of environmental management effects on population responses (Nichols and Williams 2006; MacKenzie *et al.* 2017).

This study's objective was to use a multi-method monitoring design to address two aims: (1) compare how survey methods vary in their individual and combined ability to influence detection and site occupancy of a varanid lizard, the lace monitor (Varanus varius); and (2) evaluate how red fox removal (*via* poison baiting) influenced lace monitor detectability and site occupancy. The lace monitor is a sizeable semiarboreal monitor lizard that can weigh up to 14 kg and attain a maximum body length of approximately 2 m (Guarino 2002; Jessop *et al.* 2010; Anson *et al.* 2014; Fig. 1*a*). It is distributed throughout the non-arid regions of eastern Australia (Smissen *et al.* 2013). As a generalist predator, lace monitors consume a broad array of prey, including insects, small to medium-sized mammals, and carrion (Guarino 2002; Jessop *et al.* 2012). These monitor lizards are expected to provide an important trophic influence in Australia's terrestrial ecosystems (Doody *et al.* 2015; Feit *et al.* 2020). However, the way different monitoring methods influence lace monitor detection and site occupancy (and thus their potential to benefit from lethal fox-baiting programmes) remains poorly understood.

The first goal was to assess how the use of multi-method monitoring design would allow us to measure the extent to which different survey methods varied in their ability to detect lace monitors and influence method-specific site occupancy estimates. It was presumed that methods could vary substantially in their detection of lace monitors, but overall, a multi-method monitoring design would better reduce the total survey effort needed to conduct population monitoring and achieve good estimates of site occupancy. A reduced survey effort was considered especially important given our study area experiences a highly seasonal climate that restricts reptile activity (and hence detection) to a relatively short summer period (Jessop *et al.* 2013). Similarly, demonstrating method-specific differences in detection is essential to inform how to best allocate survey effort in future monitoring of lace monitor populations.

The second goal was to determine if different monitoring methods consistently produced results that inform whether fox removal is an effective tool for promoting native wildlife. Here we compared the effect of a large-scale introduced fox lethal baiting programme on method-specific lace monitor detection probabilities and site occupancy. Prior studies have

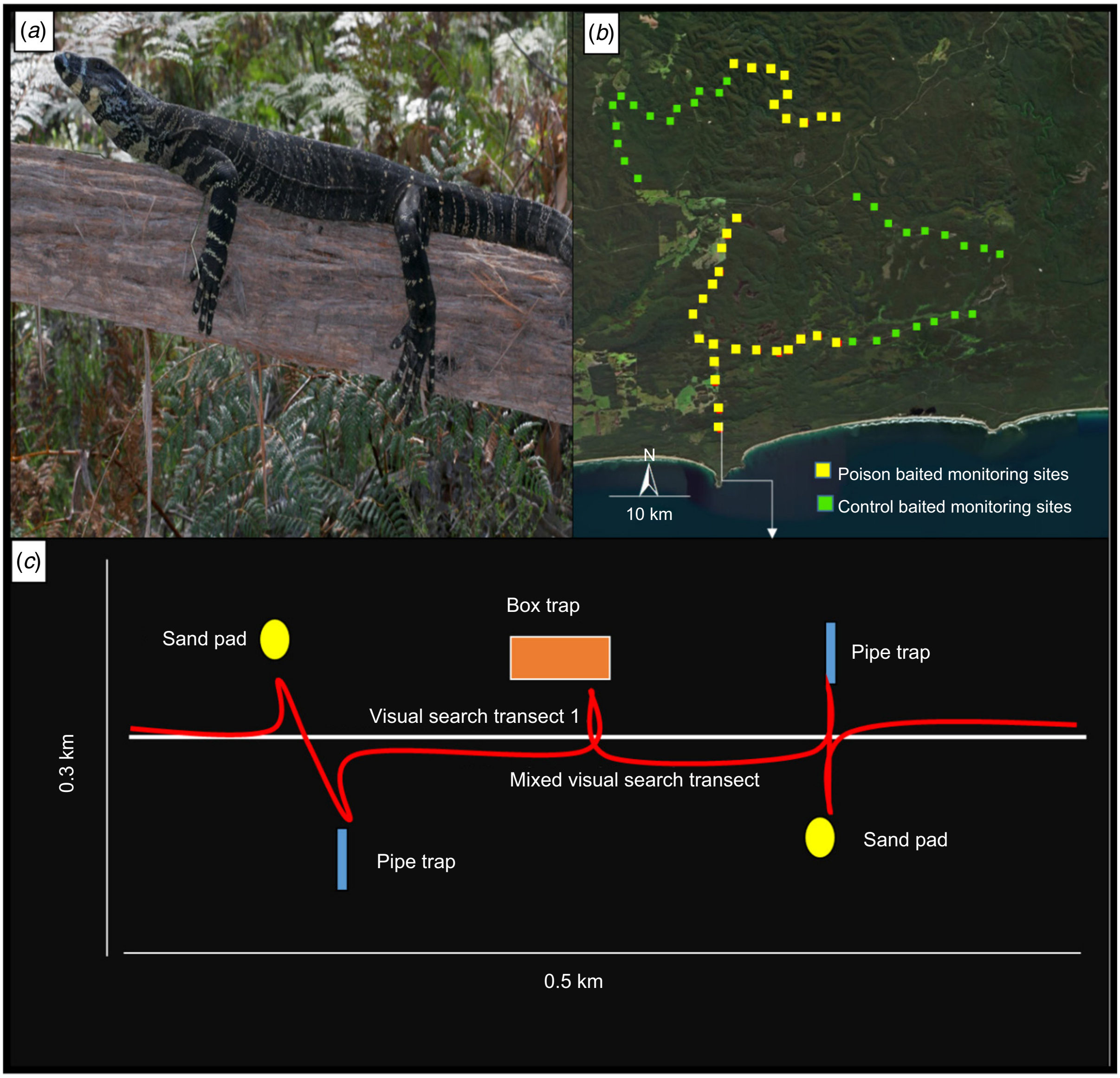

Fig. 1. This study estimated the detection probability and site occupancy of (*a*) lace monitors across 76 sites in East Gippsland in Eastern Victoria, Australia. (*b*)Yellow squares represent monitoring sites in red fox baited areas (i.e. deployment of 1080 poison) with low fox population densities. Green squares represent sites in control areas without lethal fox baiting and have high fox population densities. (*c*) We deployed a multi-method monitoring design within each site that used a ground-based box trap, two arboreal pipe traps, two sand pads, and two different visual survey transects to detect lace monitors.

demonstrated that monitor lizard populations can sometimes benefit from fox baiting, possibly because it releases these native predators from predation or competition (Anson *et al.* 2013; Anson *et al.* 2014; Hu *et al.* 2019; Jessop *et al.* 2021). However, it remains unclear if different monitoring methods also allow reporting consistency in how fox baiting influences monitor lizard detection and site occupancy. If all methods are relatively effective and unbiased, they should produce consistent detection responses to fox baiting (Read and Scoleri 2015). Conversely, the effect of fox baiting could lead to method-specific lace monitor sampling biases. For example, different fox densities between baited and non-baited landscapes could influence how lace monitors (i.e. a native mesopredator) competitively interact with this apex predator (Ritchie and Johnson 2009; Anson *et al.* 2013). One consequence could be that lace monitors alter behaviour, such as risk-sensitive foraging or daily activity patterns, in unbaited habitats with higher fox densities (Moll *et al.* 2017). Differences in lace monitor foraging activity could allow sampling biases in monitoring methods that use food-based baits to detect individuals (Anson *et al.* 2013; Moll *et al.* 2017). If so, method-related detection biases could affect site occupancy estimates and thus weaken evidence to deduce if fox baiting benefits this lace monitor population.

Methods

Study area

The study area comprised 42 000 ha of coastal forest located within the Cape Conran Coastal Park (37°490S, 148°440E) and Murrungowar State Forest (37°568S, 148°753E) in East Gippsland, Victoria, Australia. Mean maximum and minimum temperatures ranged from 27.0°C (January) to 4.7°C (July), and annual rainfall for the region averages ~846 mm (http://www.bom.gov.au/climate/averages/tables/cw_084030.shtml, accessed 12 February 2021). Within the area, study sites were primarily located in two widespread vegetation types: (1) coastal woodland dominated by *Banksia integrifolia*, and *Banksia serrata*; and (2) lowland forest dominated by *Eucalyptus globoidea* and *Eucalyptus sieberi* (see Anson *et al.* 2013). A minority of sites consisted of heathland or vegetation ecotones. Generally, the habitat transitioned from Banksia woodland near the coast into eucalypt forest further inland.

Introduced predator management

The study area was overlaid onto the Southern Ark programme's experimental fox population management treatments. This programme is a large-scale and ongoing fox suppression programme managed by the Department of Environment, Land, Water and Planning, Victoria, Australia (Murray *et al.* 2006; Dexter and Murray 2009). It was initially established to examine fox suppression effects on native threatened mammals. The programme area comprised two management treatments, each with two replicate blocks (~6000 ha each). Two blocks were assigned as areas of lethal fox baiting to cause fox population density suppression, and two replicates were assigned as control block areas (i.e. deployment of poison-free baits). To avoid any potential 'halo effect' where lethal fox baiting can decrease fox or increase native animal densities in non-baited habitat immediately adjacent to the baited area (Glen *et al.* 2013), a minimum boundary area of 2 km was used to promote spatial independence between and within each management treatment. Before the commencement of this study, poison and control baits had been deployed consistently within their respective blocks since May 1999 (Murray *et al.* 2006; Dexter and Murray 2009).

Fox suppression was achieved using Foxoff Econobaits (Animal Control Technologies, Melbourne), a commercially available manufactured bait, pre-poisoned with 3 mg of sodium fluoroacetate ('1080' poison). This sodium fluoroacetate dose is lethal to canids but not toxic to varanid lizards (Mcilroy *et al.* 1985; Twigg and King 1991).

Study design and monitoring methods

In the summer of 2008/2009, we established 76 multi-method monitoring sites over the study area (Fig. 1*b*). We allocated 38 monitoring sites each to the lethal fox-baited treatment and the non-lethal baited control treatment. Each sampling site (15 ha, 500 m long × 300 m wide) was accessed using unsealed management or logging tracks. All sites were at least 2 km apart to promote spatial independence in lace monitor detections among sites (Jessop *et al.* 2013). Monitoring at each site was conducted for six consecutive days and only during periods with consistently warm days (>25°C) and clear sky (<25% cloud cover), to limit false absences due to unfavourable climatic conditions reducing lizard activity (Jessop *et al.* 2013). At each site, five concurrent monitoring methods (Fig. 1*c*) were used to detect lace monitors:

1. Visual drive survey: Two observers in a vehicle travelling at 10 km/h searched for lace monitors along 500 m of management track, which comprised the midline of each site (Fig. 2*a*). The search area consisted of searching forward from the vehicle's mid-line out to 90° on either side of the observer's position. The search area was constrained to a maximum distance of 30 m on either side of the vehicle. This was considered the maximum distance one could reliably see a monitor lizard in forested habitats. Visual drive surveys were the first method used to detect lace monitors in each daily survey. Furthermore, we always surveyed from the first to the last site before we returned to assess for additional lace monitor detections from the remaining four monitoring methods within each site. This method resulted in a standard area (i.e. 500 m × 60 m) being sampled on each census;
2. Mixed visual search: This type of search comprised driving through each site at 40 km/h and then stopping the vehicle at regular intervals to walk into the forest to check each site's box trap, sand pads and pipe traps. Monitor lizards observed either from the vehicle or on foot within a site during these searches (15 min/site) were recorded. To reduce the potential for repeated detections of any lace monitors encountered at a site during the aforementioned visual drive survey, we waited for 30 min before conducting the mixed visual search method;
3. Box traps: One aluminium box trap (2 × 0.3 × 0.3 m) for lace monitors was positioned randomly within each site to allow direct capture of individual lizards (Fig. 2*b*). Traps were baited with raw beef infused with tuna emulsion oil. Meat baits were replaced if removed or on the morning of the 4th day of the survey if not consumed. Replacement of unused baits on the morning of the 4th day was done to limit variation in bait attractiveness (i.e. mass and odour) and reduce

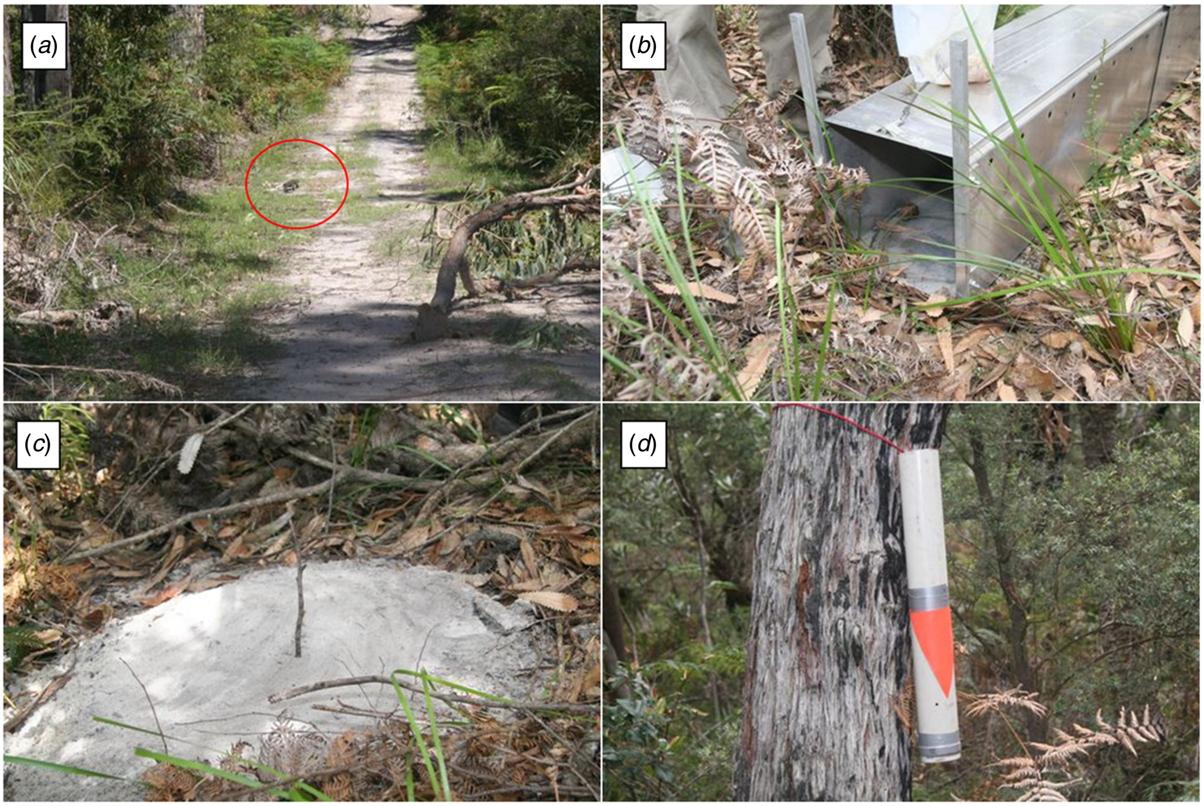

Fig. 2. Different monitoring methods were used to detect lace monitors at each site in the study area. (*a*) Illustrates a 500-m vehicle base visual search method conducted along management tracks that bisected each site. Here a lace monitor (red circle) can be seen moving along the track. (*b*) To capture lace monitors directly, we used purpose-built box traps placed on the ground at each site. (*c*) Two baited sand pads were also constructed at each site and were used to indirectly detect lace monitors from their distinctive claw marks and tail drag marks left imprinted in the sand. (*d*) Two arboreal pipe traps were baited and secured to trees within each site in an attempt to capture arboreal juvenile lace monitors.

heterogeneity in daily bait detection by lace monitors across the survey period. This step was informed from a similar study that demonstrated that monitoring methods that do not replace meat baits after 3 days had reduced varanid lizard detections (Ariefiandy *et al.* 2013). All individual lizards were microchipped to provide a means to record the potential for repeat captures (i.e. non-independent detections);

4. Sand pads: Two sand pads (75 cm in diameter and 10 cm high) were constructed from beach sand (Fig. 2*c*). A small piece of cow heart covered in tuna oil was buried to a 10 cm depth in each pad's centre. Meat baits in sand pads were replaced if removed or on the morning of the 4th day of the survey if not consumed. Because lace monitors are the only large lizard in the study area, their presence on sand pads was determined from their diagnostic claw and tail drag marks (Jessop *et al.* 2013);
5. Pipe traps: Two PVC pipes (1.5 m length × 15 cm diameter) closed-off at one end were placed vertically on two large trees and secured with rubber strapping (Fig. 2*d*). Traps were baited with raw beef. Meat baits were replaced if removed or on the morning of the 4th day of the survey if not consumed. The size of pipe traps and their placement were identical to those used to successfully capture arboreal juveniles of another large varanid lizard, the Komodo dragon (*Varanus komodoensis*) (Purwandana *et al.* 2021).

The locations of box and pipe traps and sand pads were assigned using a random number table to give x (0–500 m) and y (−150–150 m) coordinates within each site. All monitoring methods were positioned a minimum of 50 m away from the nearest edge of the management track. Each monitoring method was separated by a minimum distance of 100 m from any other method to reduce the likelihood of overlapping detections among methods. The spacing interval among each method was based on a pilot study conducted in 2006/2007, which indicated limited overlap in lace monitor detections between box traps deployed at 100-m intervals. In the current study, we further conducted a two-tailed Pearson correlation test with 1000 bootstraps to statistically assess the extent of correlations among method-specific detection patterns within sites.

Estimating detection and site occupancy estimates

Hierarchical occupancy models (MacKenzie *et al.* 2006; Nichols *et al.* 2007) were used to estimate method-specific lace monitor detectability and site occupancy, and the effect of introduced predator baiting on these estimates. An integrated monitoring design assumes that each sampling method is sufficiently separated to produce independent detections (Clare *et al.* 2017; Descalzo *et al.* 2021). A consequence of non-independence between methods is expected to inflate the overall detection probability of a species and produce a negative bias in state parameters (Clare *et al.* 2017). Although our sampling methods were spatially discrete, we did not explicitly test this assumption by using occupancy models that can accommodate observation covariance among each survey method (Clare *et al.* 2017). However, we did qualitatively assess the capacity of our sampling design to result in non-independence of detections *via* assessing the recapture rate of lace monitors within and between sites, and by assessing the degree of correlation between detection methods across sampling sites.

To address our aims, we modelled the occurrence of lace monitors at site i as a draw from the Bernoulli distribution with parameter ψ, which is the probability that the lace monitors occupies site i:

$$z_i \sim \text{Bernoulli}(\psi).$$

An occurrence is represented by $z_i, = 1$, and an absence is represented by $z_i, = 0$.

It was assumed that a site was either occupied or not across all sampling occasions and that the probability that a site was occupied was the same for all sites.

We modelled the probability of detecting lace monitors given that they were present using method j for n surveys at site i as a draw from the Bernoulli distribution with parameters d,j, which is the probability of detecting lace monitors using method j on a single sampling occasion given they were present. Thus, we calculated:

$$y_{i,j,n} \sim \text{Bernoulli}(d, j, n),$$

where a detection is represented by $y_{i,j,n} = 1$, and non-detection is represented by:

$$y_{i,j,n} = 0.$$

Combining these two processes produced the observation model that modelled the observations as the product of occupancy and detection:

$$y_{i,j,n}|z_i = \text{Bernoulli}(z_i p).$$

An observation is represented by $y_{i,j,n}\,|\mathrm{z}_i = 1$, and a failure to observe lace monitors is represented by $y_{i,j,n}|\mathrm{z}_i = 0$.

The model was run using Winbugs 1.4.2 (Lunn *et al.* 2000) called from programme Presence 2.12.36 (Hines 2006). A uniform prior distribution for occupancy and detection probabilities was used to represent a lack of prior information and ensure that the parameter estimates were driven by the data. Parameter estimates were based on 1000 samples subsampled from 5000 samples after a 5000 burn in, which was more than sufficient for WinBUGS to stabilise convergence.

Following Descalzo *et al.* (2021), we first ran occupancy models that combined all five sampling methods as a reference to then compare the mean posterior distribution estimates [±95% credible intervals (CI)] for detection probabilities and site occupancy against models that were evaluated for each individual method and combinations of the four, three and two best lace monitor sampling methods. To compare individual and combined sampling method performance, we used an accuracy index that combines measures of bias and precision through estimating the mean square error (MSE) to assess the performance of each individual, or the combinations, of sampling methods:

$$\text{MSE} = \sigma^2 + \text{Bias}^2$$

Thus, we estimated for each lace monitor sampling method and combinations therein the probability of detection (mean and s.d.), occupancy (mean, s.d. and coefficient of variation), and the MSE.

Next, we ran occupancy models that tested the effect of fox baiting on the individual method-specific probability of lace monitor detection reported. Similarly, we tested the effect of fox baiting on combinations of methods used to estimate lace monitor site occupancy. The strength of evidence for meaningful differences between posterior mean detection probabilities from the different monitoring methods was evident when their 95% CIs did not overlap. Similarly, evidence for a strong posterior effect of introduced predator management on lace monitor detection and site occupancy was obtained when their 95% CIs did not overlap (McCarthy 2007).

Ethical standards

The protocols used were approved by the Animal Ethics Committee of the University of Melbourne (Permit Number: 0911328). The research was carried out on public land under a *Victorian Department of Sustainability Wildlife and National Parks Act* (1975) research Permit 10005037.

Results

Method specific detection probability and site occupancy

We surveyed 76 composite monitoring sites for six consecutive days, resulting in 109 lace monitor detections at 52 sites. Box traps, sand pads, mixed visual searches, visual drive surveys, and pipe traps reported 43, 43, 13, 10 and 0 lace monitor detections respectively. At least from box trap-related detections (i.e. direct capture), there was little evidence (two of 43 individuals) that the same individual was detected on multiple occasions (i.e. false positives) within the sampling period. There was no evidence of significant correlations among detections reported from box traps, sand pads, mixed visual search or the visual drive survey within sites (Pearson two-tailed test: all *P*-values > 0.05; pairwise Pearson $R^2 = -0.060–0.190$) (Supplementary Table S1, available online as Supporting Information).

The method-specific estimates of lace monitor detection probability (*P*) ranged from 0.000 to 0.121 (Table 1). Box traps ($P = 0.120 \pm [0.086–0.162]$ [mean ± 95% credible intervals (CI)]) and sand pads ($P = 0.121 \pm [0.086–0.160]$) performed similarly and substantially better than the visual search ($P = 0.030 \pm [0.015–0.049]$) and mixed visual search surveys ($P = 0.038 \pm [0.021–0.060]$). Because pipe traps failed to detect lace monitors, no estimates of detection were possible. Overall, pending the combination of multiple sampling methods, the detection probability of lace monitors could be increased above estimates obtained from any single best method.

The method-specific lace monitor site occupancy (ψ) estimates ranged from 0.00 to 0.53 (Table 1). Box traps ($\psi = 0.53 \pm [0.03–0.73]$ [mean ± 95% credible intervals (CI)]) and sand pads ($\psi = 0.49 \pm [0.03–0.660]$) produced higher occupancy estimates that the mixed visual search ($\psi = 0.28 \pm [0.07–0.68]$) and visual search surveys ($\psi = 0.24 \pm [0.06–0.60]$). Because pipe traps failed to detect lace monitors, no occupancy estimates could be obtained. It was evident that different combinations of multi-method monitoring designs substantially increased the lace monitor site occupancy estimate compared with any single method used (Table 1). Indeed, all individual methods reported a strong negative bias and higher MSE scores than sampling designs that incorporated two or more sampling methods (Table 1). Furthermore, it was evident that reduced combinations of different sampling methods could lead to a similar performance in site occupancy estimates compared with the full method sampling design (Table 1).

Lethal fox-baiting effects on method-specific lace monitor detection probability and site occupancy

The magnitude of the fox-baiting effect on detection probabilities varied depending on the monitoring method used to make the assessment (Fig. 3*a*). Baiting resulted in a positive effect on lace monitor detectability reported from box traps (*P* baiting effect = $0.045 \pm [-0.024–0.120]$), visual search (*P* baiting effect = $0.035 \pm [0.001–0.072]$) and mixed visual search (*P* baiting effect = $0.038 \pm [-0.002–0.079]$) methods (Fig. 3*b*). However, the lace monitor detection probability on sand pads exhibited a strong negative baiting effect (*P* baiting effect = $-0.150 \pm [-0.235$ to $-0.074]$), indicating that lace monitor detections increased on sand pads in unbaited control sites compared with sites sampled in fox-baited sites. There was no effect of fox baiting on pipe trap detection probability (*P* baiting effect = $0.000 \pm [0.010$ to $-0.010]$).

The use of combined detection methods indicated that lace monitor site occupancy was higher at fox-baited sites ($\psi = 0.867 \pm [0.543–0.994]$; naive occupancy = 30 of 38 sites occupied) than at unbaited sites ($\psi = 0.645 \pm [0.323–0.904]$, naive occupancy = 22 of 38 sites occupied) (Fig. 4*a*). To further consider the influence of the negative fox-baiting effect on lace monitor detection probability estimated from sand pads, we removed these data and reanalysed our estimates using the remaining four methods. Removal of sand pad data reduced estimates of lace monitor site occupancy by ~8% across the study area (four methods – sand pad detection

Table 1. Detection probability (*P*) and occupancy (ψ) posterior estimates (mean; s.d., standard deviation and CV, coefficient of variation) using occupancy models for different survey methods of lace monitors and best method combinations.

Method	*P*	s.d.	ψ	s.d.	CV	Bias	MSE
All methods (BT + SP + VDS + MVS + PT)	0.11	0.02	0.87	0.09	10.05	–	0.01
Best four methods (BT + SP + VDS + MVS)	0.10	0.03	0.90	0.09	10.47	0.02	0.01
Best three methods (BT + SP + MVS)	0.17	0.04	0.91	0.09	10.08	0.04	0.01
Best two methods (BT + SP)	0.18	0.06	0.75	0.11	15.39	−0.13	0.03
Box trap	0.12	0.03	0.53	0.20	38.36	−0.34	0.16
Sand pad	0.12	0.03	0.49	0.19	38.61	−0.38	0.18
Mixed visual search	0.04	0.01	0.28	0.18	64.29	−0.59	0.39
Visual drive survey	0.03	0.01	0.24	0.17	69.79	−0.63	0.43
Pipe trap	0.00	0.00	0.00	0.00	–	−0.87	0.76

We used as reference the combined use of all survey methods [Box trap (BT) + Sand pad (SP) + Mixed visual search (MVS) + Visual drive survey (VDS) + Pipe trap (PT)] to calculate the bias for each lace monitor sampling method or best method combinations. Methods are ranked according to the mean square error (MSE) as a criterion of the accuracy of an estimator.

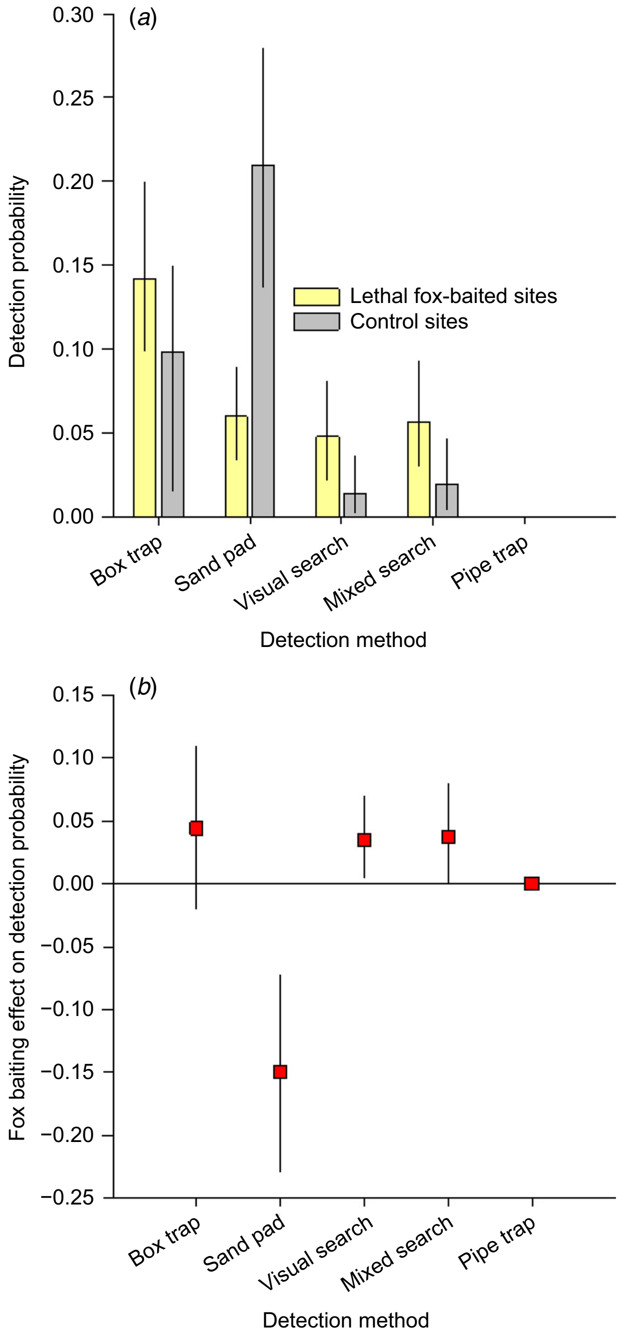

Fig. 3. (*a*) Method-specific lace monitor detection probabilities estimated for lethal fox baited or control (i.e. non-lethal fox-baited) sites. (*b*) The effect sizes of fox bating on method-specific detection probability. All estimates report the posterior mean and 95% credible intervals.

data $\psi = 0.794 \pm [0.665–0.923]$, naive occupancy = 52 of 76 sites occupied vs five methods $\psi = 0.711 \pm [0.486–0.870]$, naive occupancy = 43 of 76 sites). This effect was most evident in unbaited sites where site occupancy was reduced by 15% compared with that estimated using all five

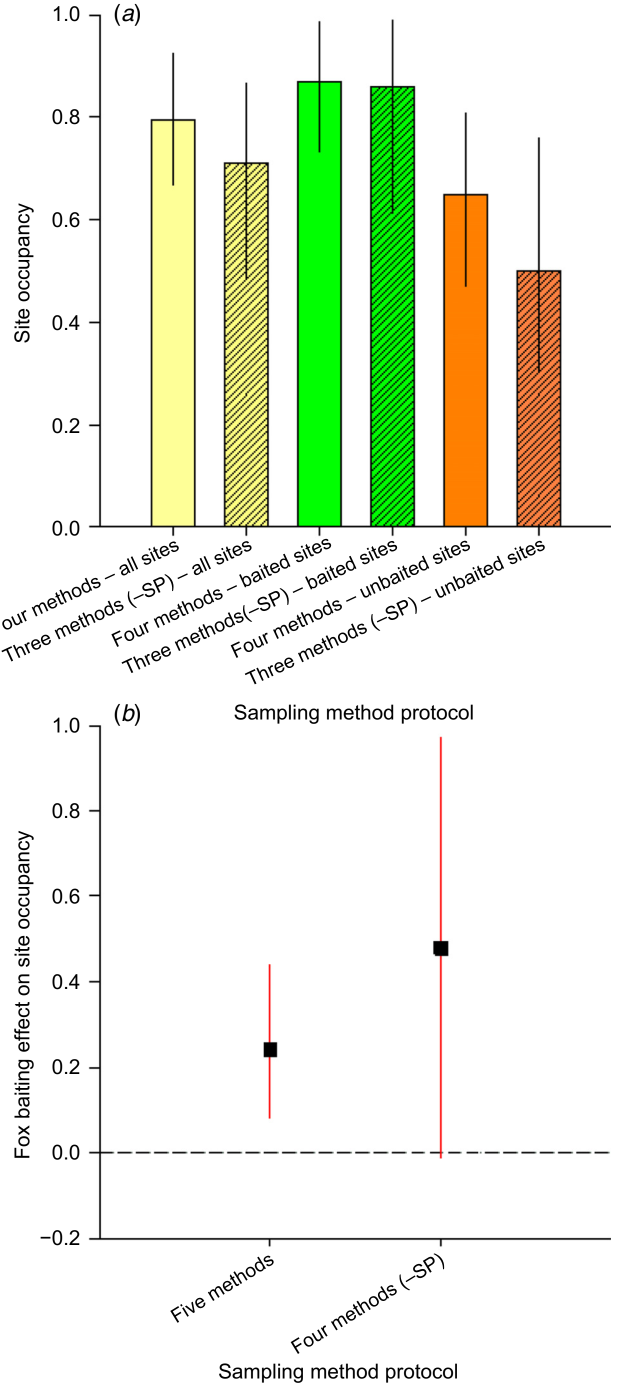

Fig. 4. (a) Multi-method site occupancy estimates of lace monitors for the entire study area and at fox-baited and unbaited (i.e. control) sites. Bars with hatching indicate the site occupancy estimates in which detection data from sand pads (i.e. SP) has been excluded. (b) The effect sizes of fox baiting on lace monitor site occupancy under the full method monitoring design and where detection data from sand pads have been excluded (i.e. drop SP). All estimates report the posterior mean and 95% credible intervals.

methods combined (Fig. 4*b*). This in turn caused the mean fox-baiting effect on lace monitor site occupancy to increase by ~50% ($B = 0.479 \pm [-0.012\text{–}0.973]$ vs $0.241 \pm [0.080\text{–}0.442]$). However, this revised estimate had much larger credible intervals (i.e. spanned zero), meaning evidence of a fox-baiting effect on lace monitor site occupancy was weakened relative to the original estimate (Fig. 4*b*).

Discussion

Introduced mammalian predators, such as the red fox, remain a significant threat to Australia's biodiversity (Radford *et al.* 2018; Hradsky *et al.* 2019). As important native Australian predators, varanid lizards are expected to benefit in landscapes where management actions have caused adequate exclusion or suppression of fox populations (Anson *et al.* 2014; Read and Scoleri 2015; Hu *et al.* 2019). This study assessed how five different monitoring methods and lethal fox baiting influenced lace monitor detection and site occupancy estimates.

Our results indicated that different monitoring methods varied considerably in their capacity to detect lace monitors and influence site occupancy estimates. Box traps and sand pads were 3–4-fold more effective in obtaining lace monitor detections than either of the visual search methods, and pipe traps were entirely ineffective. These detection differences similarly translated into a two-fold increase in site occupancy estimates for box traps and sand pads over both visual search methods. Higher detection and site occupancy estimates obtained at baited box traps and sand pads likely occurred because both methods use meat baits to attract lace monitors (Ariefiandy *et al.* 2013; du Preez *et al.* 2014; Comer *et al.* 2018). Visual survey methods had lower detection and site occupancy, possibly due to a reliance on random encounters, less sampling effort (i.e. time duration) and the difficulty of sighting lace monitors in forest (Griffiths and McKay 2007; Ariefiandy *et al.* 2014; Boback *et al.* 2020). Unlike other varanid lizard studies, pipe traps failed to capture any juvenile lace monitors, which are presumably a significant fraction of the population (Imansyah *et al.* 2008; Jessop *et al.* 2020).

A key advantage of multi-method monitoring protocols was to improve combined estimates of lace monitor detection and site occupancy over any single method (i.e. high bias, low detection) (MacKenzie *et al.* 2017; Einoder *et al.* 2018; Descalzo *et al.* 2021). It is assumed that our multi-, relative to single, method monitoring protocols increased lace monitor detections and site occupancy estimates by multiple processes. First, having additional detectors within a sampling site would increase the sampling effort (i.e. total detection area and sampling duration) relative to using any single method. Increased site-specific sampling effort would thus increase the probability that lace monitors are detected during the survey. Second, each sampling device is expected to be associated with detection biases that favour or preclude different individuals (e.g. life stages, behavioural phenotypes) of the lace monitor population to be detected. Thus, when different methods are combined, they are expected to increase the overall proportion of individuals available for detection (Clare *et al.* 2017; Descalzo *et al.* 2021). For example, as discussed below, sand pads could detect neophobic or wary individuals that might otherwise avoid entering box traps. Thus, the combined use of sand pads and box traps within sites is expected to sample a more significant proportion of the lace monitor population than each method alone.

Additionally, there was no substantial evidence of correlated lace monitor detections within or among methods, suggesting the improved efficacy of different methods to record largely independent site lace monitor detections. Thus, multi-method monitoring considerably reduced sampling effort compared with the single best method (e.g. box traps) for detecting this native predator (Nichols *et al.* 2008; Martin *et al.* 2009). Similarly, just using the single best sampling method would have required a greatly expanded survey effort that would have been both costly and potentially unfeasible, given that a highly seasonal climate reduces annual lace monitor activity in the study area (Michael *et al.* 2012; Jessop *et al.* 2013; McGrath *et al.* 2015). Furthermore, it was possible to ascertain the most effective sampling design by comparing how different combinations of methods influenced the accuracy and precision of lace monitor detection and site occupancy estimates. It was evident that using the three best methods (box traps, sand pads and mixed visual search) could produce similar results with similar accuracy (i.e. low bias) and precision (i.e. low CV) to that obtained from all five methods. Consequently, future studies that used this reduced design would benefit from less survey effort and cost without loss of monitoring performance.

This study's second aim was to assess how different monitoring methods could influence inference due to the effect of fox baiting on lace monitor detection and site occupancy. A multi-method monitoring design demonstrated that fox baiting was associated with method-specific heterogeneity in lace monitor detection probabilities (Boback *et al.* 2020). Of the four successful detection methods, three (i.e. box traps and two visual survey methods) indicated small positive effects of fox baiting on lace monitor detection. Positive increases in detection with fox baiting are consistent with lace monitors experiencing mesopredator release, resulting in higher population densities in fox-suppressed landscapes (Anson *et al.* 2014; Read and Scoleri 2015; Jessop *et al.* 2016; Hu *et al.* 2019).

In contrast, the lace monitor detection probability estimated from sand pads was higher at unbaited sites, indicating a strong negative fox-baiting effect. This reversed detection probability effect on sand pads is possibly the consequence of the interplay between food rewards (i.e. meat bait within sand pads) and introduced predator-mediated influences on lace monitor foraging behaviour (Anson *et al.* 2013; Jessop *et al.* 2015). In particular, risk-sensitive foraging theory predicts that prey depletion by competitors is likely to affect food-based reward–risk ratios influencing the foraging decisions of inferior competitors (Caraco *et al.* 1980; Barnard and Brown 1985). So if lace monitors exhibit stronger competition-induced reward-motivated foraging behaviour for novel meat baits, it could explain this positive bias in sand pad-based detections in non-fox-baited sites compared with fox-baited sites (Phillips and Winchell 2011; Willson *et al.* 2011). Behavioural studies of monitor lizards in areas with and without baiting for foxes could help clarify this scenario.

How could method-specific sampling biases affect the capacity to determine if fox baiting benefited the lace monitor population within the study area? For example, because sand pads produced a positive detection bias, this inflated lace monitor site occupancy in non-fox baited sites. This result reduced the overall fox-baiting effect on lace monitor site occupancy estimated across the study area. Re-analysis excluding the sand pad data produced a more significant mean fox-baiting effect on lace monitor site occupancy. However, removal of the sand pad detection data produced an estimate with larger credible intervals, reducing the evidence of a fox-baiting effect on the lace monitor population. Thus, these results highlight how the use of multiple monitoring methods, while producing better overall detection, may nevertheless influence the assessment of target species population management (Nichols *et al.* 2008).

Since this study was undertaken, we note that camera traps have been demonstrated to be a highly effective monitoring tool for some larger reptile species, including monitor lizards, with high and unbiased detection probabilities reported (Ariefiandy *et al.* 2013, 2014; Einoder *et al.* 2018; Moore *et al.* 2020). Therefore, replacing sand pads with baited camera traps in our multi-method approach could retain high, but less biased, detection that would increase the magnitude and certainty that fox baiting had a positive effect on lace monitor populations (Ariefiandy *et al.* 2013; Jessop *et al.* 2013; Purwandana *et al.* 2014). Noting that camera traps can be placed in the environment for relatively long periods, without checking, extending the time during which detections can be obtained.

Management implications

There are two broader outcomes for management from this study. First, integrating different monitoring methods can improve detection and site occupancy estimates for target wildlife species because it inherently increases the number of detections and reduces the influence of species-specific detection biases or method failures (Stokeld *et al.* 2015; Boback *et al.* 2020). This result is significant because it can often be challenging to infer target species responses to management actions if they have poor detection. Second, even when individual methods detect target species well, they might not accurately report management effects on wildlife due to detection biases that affect site occupancy estimates. Thus wildlife ecologists must be aware of the strengths and limitations of different detection methods, and associated sampling biases, to best demonstrate the benefits of wildlife management for biodiversity (Lindenmayer and Likens 2010; Hayward *et al.* 2015).

Supplementary material

Supplementary material is available online.

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Data availability. The data supporting this study will be shared upon reasonable request to the corresponding author.

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