Rapid colonisation, breeding and successful recruitment of eastern barn owls (*Tyto alba delicatula*) using a customised wooden nest box in remnant mallee cropping areas of southern Yorke Peninsula, South Australia

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Short Summary

Avian predators play a key role in rodent pest ecology, but are limited by the availability of nesting resources. This study aimed to design a suitable pole-mounted nesting box for eastern barn owls on remote, house mouse-affected crops in southern Australia, and found that the prototype was successful for barn owl reproduction and observation. This design promotes barn owl welfare, breeding and prey intake whilst maximising minimally-invasive monitoring techniques for future research.

Abstract

Context: The introduced house mouse (*Mus domesticus*) causes significant economic damage to Australia's agricultural enterprises. As part of the Great Southern Ark re-wilding project on the southern Yorke Peninsula (SYP), we focused on the eastern barn owl (*Tyto alba delicatula*) as a potential bio-controller of mice, by providing nesting spaces where natural hollows are limited.

Aims: To assess pre-manipulation owl densities and design an appropriate pole-mounted wooden nest box, to enhance barn owl breeding and house mouse hunting capacity on farmland adjacent to remnant native vegetation.

Methods: A prototype nest box was collaboratively designed with a nest box manufacturer using data from previous barn owl studies and anecdotal reports. Following the initial barn owl census spotlight survey, 11 pole-mounted wooden boxes with platforms were installed at distances > 1.4 km apart on properties near Warooka, SYP, and monitored over a six-month period using external trail cameras.

Key results: Pre-manipulation owl densities averaged 2.14 owls per 1000 hectares. Of the 11 nest boxes installed, 55 percent were colonised within a month after establishment, and 82 percent were colonised within seven months. Occupied nest boxes were actively used by paired owls for mating, breeding and rearing of chicks which resulted in up to 35 fledgling owlets.

Implications: Our nest box design successfully supported eastern barn owl colonisation and reproduction on the SYP. The inclusion of the platform not only provided easy, minimally-invasive monitoring of barn owl activity and prey intake by researchers, but also increased usable space for barn owl behaviours, such as copulation and wing-flapping.

Introduction

Internationally, rodent crop damage has been estimated to cost tens to hundreds-of-millions $USD annually, and is often a primary limiting factor impacting crop yield (Stenseth *et al.* 2003; Baldwin *et al.* 2014; Capizzi *et al*. 2014). Mitigating the effects of rodent pests globally has proven to be difficult, unsustainable and costly. Long-term use of rodenticides – the leading method of rodent control – has resulted in significant economic losses, especially for developing regions (Skonhoft *et al.* 2006), non-target species mortality (Cox & Smith 1990), and physiological (Thijssen 1995) or behavioural (Brunton *et al*. 1993) poison resistance, which has been observed in mice following ingestion of sub-lethal doses of zinc phosphide (Brown *et al.* 2002). Habitat modification can slow but not prevent rodent outbreaks (Brown *et al.* 2010), and research into immunocontraceptive or disease methods may not be feasible unless all non-target impacts can be eliminated (Redwood *et al*. 2008).

A more promising area of research is the implementation of ecologically-based integrated management systems (IMS), which encompasses elements of these methods with an increasing understanding of complex rodent ecology, behaviour and movement (Makundi *et al*. 1999; Singleton *et al*. 1999). An important and often overlooked aspect of rodent ecology is avian predators (Kross *et al.* 2016; Krijger *et al*. 2017). Raptors exist naturally where rodent populations occur and their positive relationship with agricultural systems has been noted since as early as the 1870's (Kronenberg 2013). The only published manipulative study in Australia used perches to attract two native diurnal raptors, nankeen kestrels and black-shouldered kites, to soy bean crops in NSW (Kay *et al.* 2004). Contrastingly, outside Australia, the barn owl (*Tyto alba*) has been the focus of 86% of all raptor studies (Labuschagne *et al.* 2016). Australia's native equivalent, the eastern barn owl (*Tyto alba delicatula*, Gould, 1837) (Parker 1977) would make an ideal candidate for a comparative manipulative study in Australia, as it can flourish in agricultural landscapes where rodent prey is abundant (Baxter 1995) and nesting sites are available (McLaughlin 1994). Over 90% of the eastern barn owl's diet consists of introduced house mice (Mortin & Martin 1979; Baker-Gabb 1984; McLaughlin 1994) but it is capable of eating other species opportunistically if mouse numbers are low (Tores *et al.* 2005; Avery *et al.* 2005; Kitowski 2013) and fly up to 10 km from a roost to hunt (Hyem 1936). It is able to produce up to 3-4 clutches annually when food is abundant, and reaches sexual maturity 95 days after hatching (McLaughlin 1994). Owlets grow rapidly, with higher energy requirements than adults (McLaughlin 1994; Durant & Handrich 1998). In natural settings, barn owls nest an average 1.4 km apart (McLaughlin 1994; Wendt and Johnson 2017) but can live and nest in much higher densities if food is abundant (McLaughlin 1994; M. Browning unpublished data, 2017). Thus, if a sound method of evaluating prey intake and rodent pest impacts could be determined, manipulation of barn owl numbers could be optimised for inclusion into ecologically-based integrated management systems.

In Australia's wheat belt, eastern barn owls are limited primarily by the availability of suitable nesting cavities. These regions are dominated by mallee scrub, characterised by sparse, mostly cleared, narrow-trunked *Eucalyptus*-dominated habitats, and inhabited by competing cavity nesters such as galahs (*Eolophus roseicapilla*), brush-tailed possums

(*Trichosurus vulpecula*) (McLaughlin 1994) and feral honey bees (*Apis mellifera*), which can negatively impact nesting success by barn owls (Charter *et al*. 2010a). By providing nesting cavities and perching spaces to the native barn owl on mouse-affected properties, its hunting impact could be greatly increased. However, some previous nest box studies have had serious negative implications for barn owl welfare and reproduction, likely due to human factors (Martin 2009) and nest-box design faults (Klein *et al*. 2007). Additionally, only a select few studies have discussed the design and positioning of nest boxes, with regards to temperature control, safety to owlets, ventilation and ease of access for researchers and landholders alike (Lambrechts *et al.* 2012).

As a part of the Great Southern Ark Rewilding project on the southern end of Yorke Peninsula, South Australia, we performed the area's first pilot study on barn owls, one of the Rewilding project's key target native predators. Our aims were to: (i) design a nest box for eastern barn owls, which would be readily colonised by the target species, support reproductive success and ease of monitoring and (ii) to trial a novel method of evaluating the effectiveness of nest boxes at reducing mice numbers, by means of a minimally-invasive trail camera, installed near the nest box to observe the owls, their behaviours and prey intake. This paper discusses the design of a wooden barn owl best box and reports on its success in being colonised and used for breeding by eastern barn owls.

Materials and methods

Study area and site selection

The study took place between November 2017 and August 2018 at a total of eleven sites (Figure 1) surrounding the towns of Warooka and Point Turton on southern Yorke Peninsula, South Australia (34.99° S, 137.40° E). These sites covered an area of approximately 12 km x 12 km. The area has a semi-arid, Mediterranean climate, with hot, dry summers and cool, wet winters. The region is flat and exposed, in some places gently undulating, where the small townships intersperse large, mostly cleared farming enterprises. Crops contain common grains or legumes, often rotated with livestock or fodder crops. Remnant scrub, characterised by native grasses, chenopod scrubland, low-growing mallee (*Eucalyptus* spp.) and *Allocasuarina* sp., exists on road verges and windbreaks. The study area is bordered to the east by a large saltpan. Site locations details are described in Figure 1 and Table 1.

[Figure 1]

Figure 1. The locations of nest box sites (S1 to S11) within the study area of the Southern Yorke Peninsula, South Australia. Each site represents one nest box and a mouse survey site, located nearby. The sites were positioned on 9 properties offered for study by 7 volunteer landholders, and selected based on their juxtaposition to trees > 5 m tall, proximity to representative mouse survey sites (≤ 1000 m), presence of a stone pile for future studies, vehicle accessibility, crop type – focusing on wheat or barley crops, distance from main roads (≥ 1 km), and seasonal climatic patterns. Sites were approximately > 1.4km apart. Three sites (1, 5 and 8) were chosen within a scrub/revegetation site, as these were the only suitable sites available on each donated property with adequate tree coverage and vehicle access. The rest were selected at the edge of fields amongst *Eucalyptus* or *Allocasuarina* windbreaks.

Table 1. Site details, including coordinates, distances and directions to the closest field and mouse survey sites, and field usage during the study period.

Brackets indicate the pasture species grazed by livestock, often remaining crops from previous years.

[Table 1]

Assessing pre-manipulation barn owl abundance

Known breeding barn owl populations living within the Warooka township and surrounding farm buildings were reported by landholders. However, in November 2017, prior to installing the nest boxes, we performed a preliminary owl census survey to obtain an estimate of pre-manipulation owl densities. The survey was carried out at night by spotlighting from the back of a utility vehicle. Owls were counted within a 180° arc across the front of the vehicle. Vehicle speed was set at 15 km/hr from a set point, covering a distance of 2 km for every 100 ha observed (Bloomfield 1999). For standardisation, these transects were performed across two consecutive nights (~28 km / night) to produce an index of owl numbers. Transects were driven within the same hour after sunset and on nights when the weather was clear (Saunders *et al.* 1995). A total of three different spot lighting transects were assessed along three roads running east-west in this region, representing three different biomes (a, b, c) within the study area. Owl abundance was calculated in owls per hectare.

Nest box design and orientation

The barn owl nest box used in this study was developed by assessing barn owl nest box designs from published overseas studies under the supervision of a South Australian native fauna nest box manufacturing company, fauNature™. The studies referenced for dimensions, efficacy and suitable pole height are listed in Table 2. The dimensions of natural hollows as reported by McLaughlin (1990) were also considered. Choice of construction material (plywood) was based on findings by Wendt & Johnson (2017) that barn owls were seven times more likely to colonise wooden nest boxes than plastic.

Table 2. A summary of published literature containing details of nest box design, locations, heights from the ground and colonisation rates

[Table 2]

The selected box design utilised 15mm plywood with dimensions of an internal height of 50 cm, width of 45 cm, and depth of 65 cm (Figure 2 and 3A). The entrance hole was circular, with a diameter of 12.5 cm, and located centrally 37 cm from the box base. In overseas studies, there is evidence that smaller entrance holes can prevent the predation of smaller owl species nesting in these cavities by larger owl species (Hakkarainen & Korpamaki 1996), although the barn owl is the larger of only two owl species on the SYP. Smaller entrance holes can also help prevent premature fledging, lower human-induced stress (Roulin *et al*. 2010), and potentially lower the incidence of owlet ectoparasite incidence by reducing contact with intruding species (Lambrechts *et al.* 2012). A 22 cm x 20 cm platform, designed by fauNature™, was secured 12.5 cm below the entrance and extended out another 20 cm with two sections of c. 20 mm wooden rod (Figure 3C). The platform was designed to address some of the concerns of Klein *et al.* (2009). The solid platform, along with the high entrance hole, were added to prevent owlets from prematurely falling out of the entrance hole or onto the ground where they would be susceptible to predation, while the two adjacent perches were incorporated to allow fledglings to practice flight as they would at a natural nest by hopping between tree branches. The perch also aimed to increase the total usable space available to the owls for behaviours potentially limited by the internal cavity space, such as copulation, and encourage owls to use the visible space outside the nest box for external monitoring. This would be particularly important for recording prey intake.

The rear wall was designed to open on hinges to allow access into the box. 10 mm ventilation holes were positioned along the tops of the long sides of the box, protected by a 20 mm overhang of the top, which extended to about 7 cm over the nest box entrance.

[Figure 2]

Figure 2. Barn owl nest box dimensions, as indicated by the red arrows. Depth (A) is 65 cm internally / 68 cm externally; Height (B) is 50 cm internally / 53 cm externally; Width (C) is 45 cm internally / 48 cm externally; and entrance hole diameter (D) is 12.5 cm. The roof overhang provides additional protection to the entrance hole. The platform (pictured prior to the affixing of the additional wooden rod perches) is attached 37 cm from the box base and reinforced underneath with a plywood brace.

All boxes were designed to be mounted on a pole in rodent-affected paddocks where buildings or large trees are absent. The square poles used for mounting the boxes were 4 m long, 7.5 x 7.5 cm wide, and made from 0.25 cm thick galvanised steel. Steel was chosen over wooden poles to prevent cats or possums from climbing into the box from below. Square-hollowed posts were chosen over circular poles to ensure structural support of the box during windy weather. The galvanised steel mounting bracket was constructed from slightly wider sections of post, capped on the top and reinforced along the top and bottom of one side of the box to ensure stability, and fixed to the post by sliding over it like a sleeve then secured by tightening the end of a large bolt onto the smaller post. Boxes were first attached to the pole, then erected using a minimum of two people to gently lever the pole into 75 cm – 100 cm deep holes, as straight as possible with spirit levels (to prevent egg rolling), and set with concrete. Overall nest box height was thus c. 300 cm.

[Figure 3]

Figure 3 (A to D). A: The internal box dimensions, as described in Figure 2, showing a ladder affixed to the front of the box to allow owls to climb out of the box. B: the back wall of the box can be opened on hinges to allow for access and maintenance of the boxes by landholders or researchers. C: the galvanised steel sleeve bracket, following attachment to the box using nuts and bolts. D: boxes were manually erected using 2-3 people, stabilised according to a spirit level while set into the ground with fast-setting concrete and compacted soil. Holes were either manually dug using shovels + crowbars, or drilled using a portable fence-post digger, to a depth of 75 cm – 100 cm.

Boxes were installed within a 300 cm radius of slightly-taller trees with the ability to cast shade onto the boxes (particularly from the west), with the entrances facing north-east to allow the box to warm in the morning but ensuring that they were not exposed to full sun in summer (Charter *et al.* 2010b). Only one box, Site 7, could not be installed easterly to the tree next to it due to a layer of limestone which prevented hole digging at a more ideal location, and thus was exposed to westerly sun.

Following installation, a 5-8 cm deep layer of clean wood shavings (particulate size 5-20 mm^2 x 1 mm thick) were laid on the floor of each box, with a slight depression in the middle, to prevent eggs from rolling to the edges of the box where incubation would be difficult.

Nest box success was represented by time to colonisation, total colonisation rate, time to first fledgling emergence and estimated number of fledglings. A summary of nest box details is presented in Table 3.

Table 3. A summary of box orientation, relationship with surrounds and hunting grounds, mammal species present at the site and proximity to other wild bird species.

[Table 3]

External nest box monitoring system.

Nest boxes were monitored from February 2017 to August 2018 using Scout Guard SG560k-HD trail cameras. These cameras were attached to nearby trees approximately 1.5 – 3 m from the nest box entrance using zip ties or Tek screws through the protective housing box. Limited by the location of surrounding trees, the cameras were either facing the nest box entrance (Sites 1, 5, 6, 7 and 9), directly side on (Sites 2, 3, 8 and 10) or side-on + upwards towards the entrance (Sites 4 and 11). Cameras were accessed throughout the study by ladder. Cameras were periodically removed and kept overnight for battery charging, settings review and maintenance, before being reinstalled the following morning. The cameras were set to take bursts of 3 photos at 12MP, with PIR trigger sensitivity adjusted to Normal or High based on background movement of foliage. Timer triggering was set to 0; Timer Interval set to OFF and monitoring period set from 1700 hrs to 0800 hrs. A second camera, set to Video, was also installed next to the photo cameras at 6 sites, however this data was deemed duplicative and excluded from the study.

[Figure 4]

Figure 4. A: Scoutguard camera, as highlighted by the red circle, attached to a nearby tree to monitor a nest box (S1) from February 2017 to August 2018. B: Camera (at S1) being accessed by ladder at 1-3 monthly intervals.

Photo tagging and data collation

Photos were collected at 1 – 3 monthly intervals over the six-month monitoring period. These were downloaded directly from the camera SD cards before being sorted and tagged in Exifpro 2.0. Tags were divided into six main categories; Number of Owls, Activity, Prey Number, Prey Type, Other Species and Comments. Once a site was tagged for each monitoring period, the tags were converted to a text file for transposing into Excel. Here, tags could be categorised into different owl activity ‘events’ based on their timing, and cleaned for analysis.

Determination of a behavioural event, such as surveillance, mating or feeding young, was done by examining the three photos within the burst to identify owl movements, and then comparing these movements and time elapsed from the previous burst. All events containing at least one owl were called ‘owl events.’ Any event containing an owl and a prey item, usually one that had just been hunted and returned to the nest in the owl's beak or foot, was called an 'owl + prey' event. Prey items were classified as mouse, rat, rodent, bat or unknown. Bursts taken within five minutes of the last owl + prey burst were considered the same event, with the exception of the following rules:

i. The previous prey item was of a different identity to the current one

ii. The previous prey item was now being passed to another owl or into the nest box;

iii. The previous prey item was now being eaten.

The total monitoring period was divided into five periods (Period 1: 30/01 – 21/02; Period 2: 22/02 – 29/03; Period 3: 30/03 – 26/04, Period 4: 27/04 – 05/06; Period 5: 06/06 - 14/07), separated by camera retrieval/maintenance works and mouse abundance surveys.

All activities involving wildlife associated with this project were approved by the University of Adelaide Animal Ethics Committee (Approval Number: S-2017-072, Application ID: 32091).

Results

Pre-manipulation barn owl abundance

Along the 28 km of transects spotlighted, a total of four barn owls were observed on night one. Two owls were observed on night two. The average number of owls therefore was three per 28 km, which represented three owls per 1400 ha or 2.14 owls per 1000 ha. Owl densities were higher along sections closer to the township of Warooka (Transect 3), at five owls per 1000 ha.

Nest box colonisation rate

Within one month of installation, by late December 2017, five of the 11 nest boxes (S1, S2, S4, S9 and S10) had been colonised by barn owls (as detected by the trail cameras). Site 1 was initially colonised by a single owl before being joined by another in February 2018. The other four boxes were colonised by pairs. Site 11 was colonised by a pair in February 2018, followed by another pair at both Sites 3 and 8 in March 2018. Site 5 was the last box to be colonised by a single owl in July 2018, with several camera events indicating an owl's interest in the box as early as May 2018. Box 7 was also initially inspected by a single owl in January 2018, however the owl did not inhabit the box. The colonisation rate at February 2018 was 55%, rising to 73% in March and 82% by July and at completion of the study in

August 2018. No other species were recorded living in the boxes at any time, although galahs (*Elophus roseicapillus*), little ravens (*Corvus mellori)*, magpies (*Gymnorhina tibicen*), grey butcher birds (*Cracticus torquatus*), European starlings (*Sturnus vulgaris*) and a brown goshawk (*Accipiter fasciatus*) were observed inspecting the boxes throughout the study.

Table 4. Time to colonisation, time of observed courtship, first fledgling emergence and estimated number of fledglings

[Table 4]

Evidence of reproductive success observed at nest boxes

Mating and courtship behaviours were observed on the perch or roof of the first eight colonised boxes within the first two months of colonisation. These behaviours included mutual preening and regular 'gifting' of prey from the male to the female, followed by copulatory posturing of the female and subsequent mating (Figure 5). Following mating, a 6 – 8 week period of solo hunting was observed, with males entering the box with prey to deliver to the brooding female. One female was photographed on the perch at Site 8 with an exposed brood patch (Figure 6).

[Figure 5]

Figure 5. Two mating events recorded on the 18th of March at Site 1. During mating, the male balances on the female's back whilst holding onto her neck feathers with his beak. Mating is often preceded by a prey gift from the male, resulting in a 'cache' of prey exceeding the female's appetite. The gifted mouse prey item can be seen on the perch in these photos.

[Figure 6]

Figure 6. A female barn owl, identified by her larger size and darker colouration, stands outside the nest box entrance at Site 8 with an exposed brood patch. The brood patch is an area of sparsely feathered skin, allowing for greater skin/heat contact between the hen and her eggs during incubation. Fledglings emerged in late May at this site, indicating that this hen was actively incubating eggs or young chicks at the time.

Fledglings were observed emerging around three-to-five months following the initial courtship (between April and July 2018; Figures 8 and 9). The active sites produced an average of four fledglings, with a minimum of one (Site 9) and maximum of six fledglings (Site 11). A conservatively estimated total of 32 fledglings were observed during the study, however this number may have been closer to 35 as it was difficult to distinguish adults from fledglings in later photos.

[Figure 7]

Figure 7. Examples of fledgling events at each site. Site 1 saw the emergence of four fledglings in July 2018. Two fledglings emerged in April 2018 at Site 2 (seen here interacting with a parent) with more potentially present in the box. An estimated four fledglings emerged at Site 3 (possibly five). Five fledglings were present at Site 4 (pictured with a prey exchange between a fledgling and an adult). Between three and four fledglings were present at Site 8 (pictured with an adult returning with prey), while only one fledgling was recorded at Site 9 in May 2018 (again pictured with a returning adult). Site 10 produced between five and six fledglings (pictured with a prey item) in June/July 2018. Site 11 produced the highest number of fledglings, between six and seven, in June 2018. Fledglings were difficult to distinguish from parents as they had reached adult size and plumage before emerging from the nest box, however they were often identified behaving passively/submissively, wing stretching and flapping in preparation for flight, begging for food and squabbling between each other on the perch.

[Figure 8]

Figure 8. Histograms demonstrating the time following the first indications of courtship when fledglings were first detected (A) and the number of fledglings at each box (B). A. illustrates the variance in time between mating periods and the emergence of fledglings. B. illustrates a conservative estimate of number of fledglings for each nest box, giving a mean of four owlets and a median of five

Discussion

Nest box design success and reproduction

The primary aim of this study was to design a pole-mounted nest box suitable for eastern barn owls on the southern Yorke Peninsula (SYP). The lack of suitable nesting cavities for existing barn owl populations in this region was evident in our study and verified in two ways; the increased density of barn owls observed near the township during the pre-manipulation survey, and the rapid uptake of nest boxes following manipulation. An owl was detected at 10 out of the 11 nest boxes at least once throughout the period; nine were colonised by August (within 32 weeks), and eight were actively used by paired owls throughout the study period for reproduction. From these eight nest boxes, the population of SYP barn owls was increased by 32 - 35 within six months.

The nest box designed for this study proved very successful in avoiding off-target species colonisation and optimising barn owl reproduction. Our first consideration was the importance of balancing the internal cavity space, which can positively influence barn owl clutch size (Hattingh pers.comm. 2017), with the retention of a size/weight that facilitated the safe and easy mounting of the nest box onto a pole. fauNature’s choice of materials (plywood – 5ply) was considered a key factor in achieving this.

Secondly, the addition of the front perch, after advice from Dave Irwin at Raptor Domain on Kangaroo Island (SA), proved integral to the study, allowing not only extra space for owls and fledglings to carry out important behaviours such as practicing flight, but also to provide a stage on which to capture these behaviours with an external monitoring system. As a result, we were able to keep track of important behaviours, such as courtship and fledgling emergence. Such evidence of owl reproduction, as shown in Figures 4 – 8, is an important indicator of nest box success, particularly from the perspective of manipulating owl density for increased hunting capacity. The ability to monitor reproductive behaviours may allow for more intimate research on barn owl biology in future studies. Finally, detection of reproductive behaviours, as well as the subsequent number of fledglings detected at each box, provides a base on which estimations in energy requirements of owls can be made throughout the breeding season, and for these to be compared to detected prey intake, which will be discussed in a subsequent paper.

From a welfare stand-point, it is also likely that we avoided many of the concerns expressed by Klein *et al.* (2007) such as premature fledging, nest falls, prevention of adequate flight practice and room for copulation, by providing the platform/perch and high placement of the entrance hole. All fledglings were regularly photographed using the platform and gripping perches to stretch their wings and flap in preparation for flight. Owls were also observed hopping to-and-from the box roof from the perch, which was particularly important for sites with large numbers of fledglings, which were often photographed crowding the perches. The placement of boxes near trees also likely benefitted the survival of owlets, with photographic evidence of owlets using them to practice short-distance flights. It's not known whether the trees allowed owlets to climb to safety, if any fell. Two feral foxes (*Vulpes vulpes*) were detected looking up at a nest box during the study, indicating the importance of implementing predator-proofing design measures, including the smooth metal pole for mounting, where possible.

Additionally, the inclusion of nesting material in the form of wood shavings, wood chips, carpet or another substrate, is important for preventing unwanted egg-roll. Barn owls are secondary cavity nesters and do not line their nests with materials before egg laying, instead relying on pre-existing nesting materials (Lambrechts *et al*. 2012). Typically, the base of the nest boxes are smooth, flat and usually on an angle due to the imperfect nature of installation on a pole. The prevention of egg rolling within the nest box is thus crucial for successful incubation.

It is difficult to ascertain which particular features of the boxes resulted in uptake by only barn owls, although it may have been due to combination of design features, such as the exclusion of climbing cavity nesters (e.g. brush-tail possums) and/or a shortage of competing species. Overseas, barn owls have been known to destroy or predate the eggs, young or adults of smaller, competing cavity-nesting bird species before assuming occupancy of those nests (Charter *et al*. 2010a). Three months following the end of our study, one farmer noted that one of their nest boxes (Site 9) had been abandoned by the owls and re-colonised by European honey bees. This issue was expected before the study and has been controlled by the use of permethrin (Efstathion *et al.* 2016).

Owls failed to colonize two of the nest boxes, Sites 6 and 7. We speculate that the presence of nesting magpies < 3 m from the Site 6 box likely prevented its colonisation. Australian magpies are notoriously territorial and will aggressively defend nesting sites from other species, including humans (Morgan *et al*. 2005). The failure of Site 7 to colonise is harder to explain, as it was located in a revegetated paddock, close to a grain crop with ideal mouse abundance. However, as mentioned in the methods, this box was the only one exposed to western sun. Full sun exposure to nest boxes has been associated with lower colonisation rates and lower reproduction rates (Charter et al. 2010b). Whether magpies or another territorial competitor was present at this site is unknown. Nesting magpies were present at other sites, including Site 4, which was also located beneath an active black-shouldered kite (*Elanus axillaris*) nest, however this nest box was colonised by barn owls.

A component to nest box design that was not investigated during this study was thermoregulation and insulation. Next boxes have historically struggled to replicate the insulative properties of natural cavities (Goldingay & Stevens 2009; Amat-Valero *et al.* 2012; Wendt & Johnson 2017). In southern Australia, where winter temperatures can reach zero and summer temperatures over 45°C, it is likely that the internal temperatures of exposed, pole-mounted boxes would reach dangerous temperatures without some intervention (Meyrom *et al*. 2009). The plywood used for our boxes was 15 mm thick (5 Ply), thus we relied on the shade of trees and orientation of the box entrance to lessen the impact of harsh weather events. The use of an internal temperature logger and experimentation with materials of increased thermal mass, as well as differing levels of sun exposure and comparisons between natural (tree hollow) and artificial nests, would be valuable for future studies of this nature.

The predation of house mice by the barn owls, as monitored by the external remote cameras, will be presented in a subsequent paper.

Conclusion

The findings of this study have indicated that the eastern barn owl is an excellent candidate for use as an avian predator on house mouse-affected properties of southern Australia. Our nest box design was sound and provides a safe and very effective nesting cavity for breeding barn owls where naturally occurring hollows are a limiting resource. The addition of a platform with wooden rod perches and installation of the box near trees were found to be very beneficial for successful breeding and fledging of eastern barn owls. The external platform and perches were also valuable to researchers by providing a target space to monitor owls using an external camera.

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Conflicts of Interest

The authors declare no conflicts of interest.

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(Attached: figures, images and tables)

Figure 1.

Table 1.

Site no.	Coordinates	Distance to closest field	Direction to field	Distance from mouse survey site	Direction to mouse survey site	Field type during study
S1	34°58'14.00"S 137°24'24.00"E	152m	SW	160 m	SW	Barley
S2	35° 0'48.00"S 137°26'7.00"E	4m	W	12 m	W	Barley
S3	35° 0'41.89"S 137°27'25.25"E	10m	SWW	30 m	NW	Sheep (Vetch)
S4	35° 1'15.69"S 137°25'48.83"E	25m	NE	80 m	NE	Sheep (Vetch)
S5	34°58'3.00"S 137°19'52.00"E	140 m	NE	135 m	NE	Barley
S6	34°57'42.59"S 137°21'53.44"E	4 m	W	130 m	NE	Barley/Sheep (lentils)
S7	34°59'19.00"S 137°22'40.00"E	27 m	W	30 m	W	Barley

S8	35° 1'42.90"S 137°22'45.31"E	30 m	N	950 m	SWW	Cattle/Barley
S9	35° 2'14.67"S 137°22'22.53"E	14 m	NE	30 m	N	Cattle, Sheep/Barley
S10	34°57'59.26"S 137°23'19.09"E	60 m	SW	250m	SE	Wheat/Barley
S11	35° 2'55.00"S 137°23'32.00"E	5 m	W	160m	NE	Sheep (Vetch)/Barley

Table 2.

Source	**Location**	**Height x width x depth**	**Entrance hole size**	**Height from ground**	**Colonisation rates**
Marti *et al.* (1979)	USA (northern Utah); crops	43 cm x 56 cm x 56 cm	25 cm x 33 cm	900 cm	50% occupancy in the first year and 80% occupancy in the second year.
Taylor *et al.* (1992)	Scotland (southern region; conifer plantation	(91 L drums) 46.4 cm x 46.5 cm x 55.25 cm	10 cm x 10 cm	400 – 500 cm	11.5 % (1985); 50.9% (1988); correlated with vole abundance.
Parker & Castrale (1996)	USA (Indiana); reclaimed grasslands	40 cm x 40 cm x 91 cm	18 cm x 18 cm	Not specified	53%
Klein *et al.* (2006)	Hungary	70 cm x 50 cm x 80 cm	10 cm x 10 cm	Not specified	(Only used in outdoor aviaries for rescued birds)
Meyrom *et al.* (2009); Charter *et al.* (2012)	Israel (Hula Valley); immature palm date plantation	50 cm x 50 cm x 75 cm	25 cm x 15 cm	250 – 300 cm	Fluctuating between 48.1% - 73.5% over four years.
Raid (2012)	USA	45 cm x 96 cm x 31 cm	15 cm x 18 cm	121 cm, 244 cm and 366 cm	90% colonisation in second year. 366 cm boxes colonised first, then 244 cm, then 121 cm.

Figure 2.

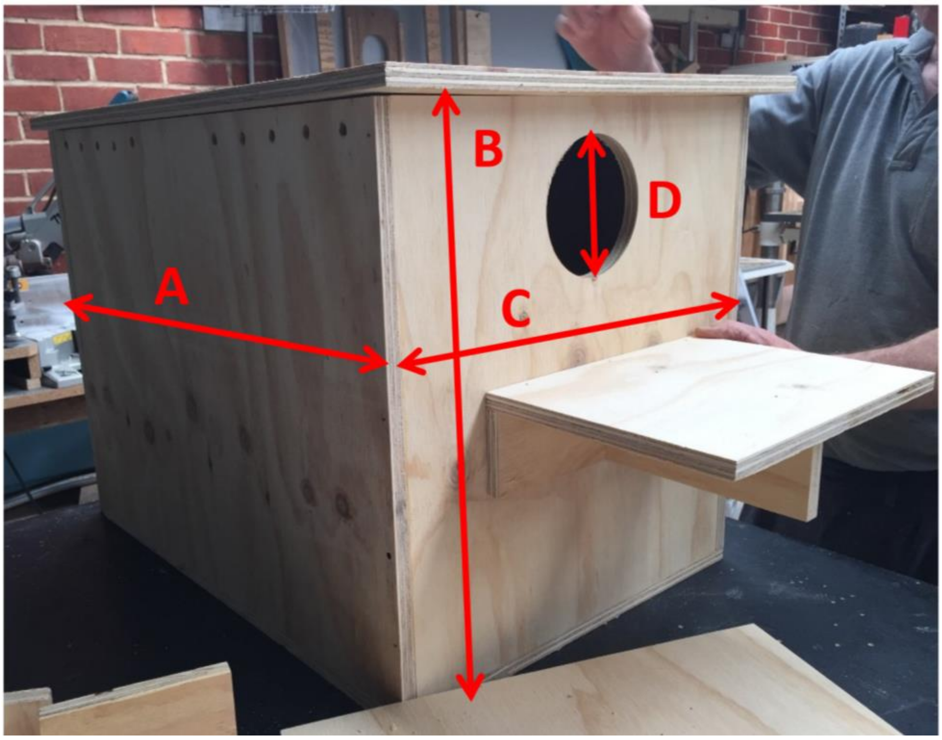


Figure 3.

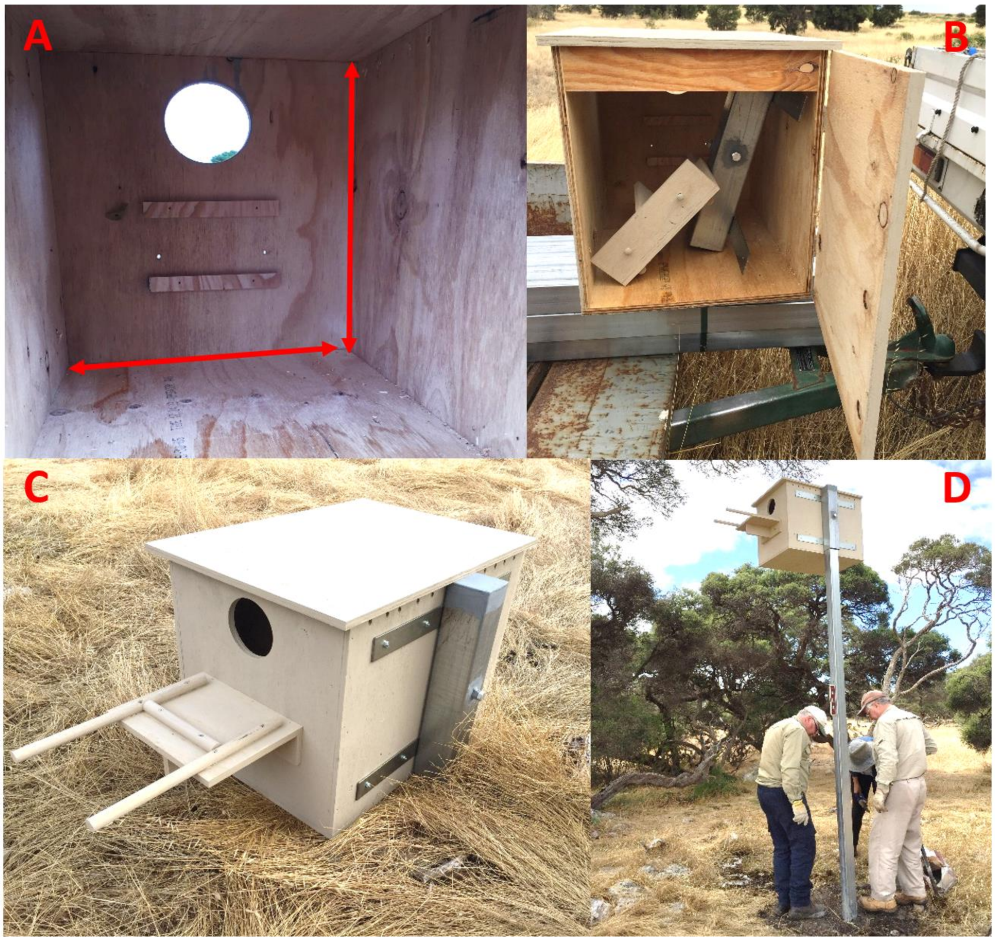


Table 3.

Site no.	**Box orientation**	**Box entrance facing**	**Direct viewing of field from box**	**Other birds nesting nearby**	**Land animals det. by camera**	**Other bird species detected at nest boxes by camera**
S1	NE	Open scrub/rock pile	No	Unknown	Kangaroos, fox	Galah, brown goshawk, crow, grey butcher bird, common starling
S2	NE	Scrub/trees	Yes/no	Unknown	Sheep	None
S3	NE	Scrub/Field	No	Unknown	Sheep	Common starling, galah
S4	NE	Field	Yes	Yes (Black-shouldered kite; magpie)	Sheep	None
S5	NE	Scrub/trees	No	Unknown	Sheep	Magpie
S6	NE	Scrub/Field	Yes/no	Yes (magpie)	Sheep	Magpie
S7	NE	Scrub/Field	Yes	Unknown	Sheep	Magpie
S8	NE	Scrub/trees	No	Unknown	Cattle, fox	Common starling
S9	NE	Field	Yes	Unknown	Cattle, sheep	Owlet-nightjar
S10	NE	Scrub/Trees	Yes/No	Unknown	Cattle	Willy wagtail
S11	NE	Scrub/Trees	Yes	Unknown	Sheep	Willy wagtail

Figure 4.

Table 4.

Site no.	Time to colonisation	Time of observed courtship	Time of first fledgling emergence	Estimated number of fledglings
S1	1 month	March - Apr	July	4
S2	1 month	February	April	2
S3	3 months	April	July	4 - 5
S4	1 month	March	June	5
S5	6 months	-	-	-
S6	N/A	N/A	N/A	N/A
S7	N/A	N/A	N/A	N/A
S8	3 months	March - Apr	Late May	3 - 4
S9	1 month	Feb	May	1
S10	1 month	Feb - March	June	5 - 6
S11	2 months	March - Apr	June	6

Figure 5.

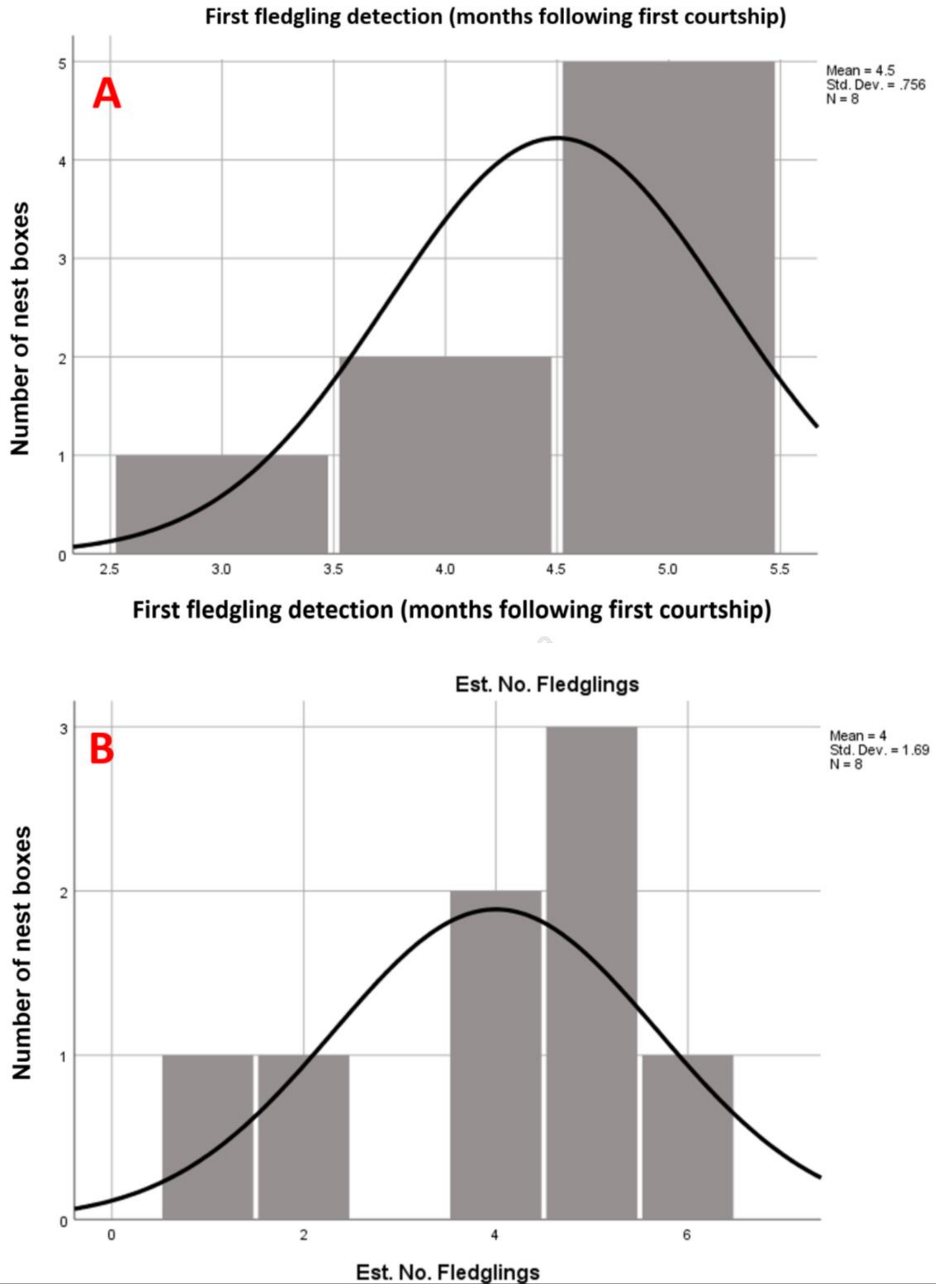
Figure 6.

Figure 7.


Site 1
2018.07.14
Site 2
2018.04.22 03:14
Site 3
2018.07.11
Site 4
2018.05.15 03:45:50


Site 8
2018.06.11 01:49:03
Site 9
Site 10
Site 11
2018.06.14

Figure 8.


First fledgling detection (months following first courtship)
A
Mean = 4.5
Std. Dev. = .756
N = 8
Number of nest boxes
0
1
2
3
4
5
2.5
3.0
3.5
4.0
4.5
5.0
5.5
First fledgling detection (months following first courtship)
Est. No. Fledglings
B
Mean = 4
Std. Dev. = 1.69
N = 8
Number of nest boxes
0
1
2
3
0
2
4
6
Est. No. Fledglings