OPTIMIZING NEST-BOX MONITORING EFFORT TO DETECT AMERICAN KESTREL SITE OCCUPANCY

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ABSTRACT.–When designing nest monitoring protocols for raptors, investigators face a tradeoff between the desire to detect all nesting attempts and limited time and resources. In practice, American Kestrel (*Falco sparverius*) nest box occupancy (i.e., traditionally defined as the number of nest boxes used divided by the number of nest boxes available) is often the principal metric for tracking kestrel population size and trend. However, traditional nest-box monitoring can lead to underestimates of local population size when kestrel pairs establish territories at nest boxes but are undetected because they do not lay eggs or their nests fail early in the nesting cycle. We analyzed empirical data collected during frequent visits (1 to 7 d intervals) to nest boxes throughout the breeding season (March - June, 2008-2014) in a dynamic occupancy modeling framework to assess the timing and intensity of monitoring efforts needed to detect, with the same confidence level provided by frequent visits, the presence of kestrels on nest box territories in Florida. Modeled estimates of occupancy were similar to observed rates but trended slightly higher, especially in years with infrequent monitoring. Detection probability varied markedly across the breeding season; therefore, using a constant detection probability to determine the minimum number of visits needed to detect kestrel presence at a 95% confidence level produced misleading results. Modeling results indicated that >3 nest box inspections per season did not improve estimates of nest box occupancy. The common practice of monitoring American Kestrel nest boxes at approximately monthly intervals appears sufficient to detect the percentage of nest box territories used by kestrels, provided that monitoring visits are timed to straddle the peak period of egg laying, as we have done. We recommend three kestrel nest box visits during the breeding season in peninsular Florida coincident with mid-March, mid-April, and mid-to-late May to maximize detection of kestrel nests. Investigators at other latitudes will need to adjust the timing of our recommendations to local phenology. In addition, if accurately tracking local kestrel population size and trend is a project goal, then studies would benefit from using an occupancy approach rather than simply recording the percentage of nest boxes with nests, especially in years when fewer visits are possible.

KEY WORDS: American Kestrel; Bayesian analysis; conservation; monitoring protocol; nest boxes; occupancy; research design; timing of surveys

INTRODUCTION

Nest monitoring for bird species that have long incubation and nestling periods requires repeated visits over many weeks or months. When designing nest monitoring protocols for raptor species, investigators face a tradeoff between the desire to detect all nesting attempts and territory occupancy and the limited time and resources that are available (Steenhof and Newton 2007). Breeding pairs that fail early in the nesting cycle are less likely to be detected than successful pairs, which can lead to overestimates of nesting success and an underestimate of the number of breeders in the population (Mayfield 1975, Newton 1979).

The American Kestrel (*Falco sparverius*) is a small falcon whose populations have declined throughout most of North America (Farmer and Smith 2009, Smallwood et al. 2009a). Nest boxes have been used to maintain or increase kestrel populations since the 1960s (Heintzelman and Nagy 1968, Hamerstrom et al. 1973). Most of what we know about the species has been derived from studies that use nest boxes, but nest box programs require time, staff, and resources and often involve community scientists who need guidance to obtain useful data. Many investigators seeking to track kestrel nest box occupancy inspect nest boxes at approximately monthly intervals (e.g., Breen and Parrish 1997, Smallwood et al. 2009b, Steenhof and Peterson 2009, Del Corso 2016), which may or may not be sufficient to detect all nesting attempts. Other studies inspect nest boxes less frequently (Loftin 1992, Williams et al. 2021) or report insufficient details to determine the frequency of nest-box monitoring visits (Rusbuldt et al. 2006, Santolo and Tamamoto 2009).

In practice, nest box occupancy (i.e., traditionally defined as the number of nest boxes used divided by the number of nest boxes available) is often the principal metric for tracking kestrel population size and trend (Toland and Elder 1987, Smallwood and Collopy 2009, Smallwood et al. 2009a). However, traditional nest-box monitoring can lead to underestimates of local population size when kestrel pairs establish territories at nest boxes but are undetected because they do not lay eggs (Newton 1979), the nest attempt fails before it is detected, or when they are undetected because they use alternative nest sites in the study area (Brown and Collopy 2013). Therefore, it is essential for investigators to collect accurate and complete site visit data while still maximizing efficiency and available resources. Standardization of nest-box monitoring protocols is helpful in comparing results across studies and timeframes (McClure et al. 2017b).

We analyzed empirical data collected during frequent visits (1-7 d intervals) throughout the breeding season (March–June, 2008-2014) of an America kestrel population in north-central Florida, USA. We used a dynamic occupancy modeling framework to assess the timing and intensity of monitoring efforts needed to detect the presence of kestrels in territories associated with nest boxes.

METHODS

Study Area. We studied the Southeastern American Kestrel (*F. s. paulus*), a non-migratory and genetically distinct subspecies (Ruegg et al. 2021) listed as Threatened in the state of Florida (FWC 2011), which has declined because of loss of nest sites (Hoffman and Collopy 1988) and loss of foraging habitat (Miller et al. 2019). During 2008-2010 and 2012-2014 we monitored a network of ca. 150 kestrel nest boxes in north-central Florida first established during the 1990s (Miller and Smallwood 1997, Smallwood and Collopy 2009). Our study area was located within Levy and Marion counties, centered at approximately 29° 21’ N, 82° 23’ W. Pastures, row crops, old fields, and other agricultural land uses were the predominant habitats around nest boxes, interspersed with longleaf pine (*Pinus palustris*)/turkey oak (*Quercus laevis*) sandhills and oak (*Quercus* spp.) hammocks. Nest boxes were constructed from 2.5-cm cedar or cypress lumber and placed 6-7 m above ground on roadside utility poles or live trees.

Monitoring. All nest boxes were visited, cleaned, and repaired and filled with a 5-cm layer of wood shavings each year in February, and monitored for breeding activity from the first week of March through at least the last week of June. During 2010, 2013, and 2014, boxes were checked for occupancy and contents at 10-24-d intervals. During 2008, 2009, and 2012, we visited nest boxes at 1-7 d intervals, with more frequent visits during the peak of egg-laying to obtain more precise information about laying and hatch dates. Nest box inspections were made by direct observation after climbing aluminum extension ladders or with a Wireless Cavity Inspection System (ibwo.org, Little Rock, AR) mounted on an extendable fiberglass pole. At each nest box visit, all detections of adult kestrels were recorded. We considered a kestrel nest box site to be occupied if we found either evidence of breeding kestrels in the nest box or observed ≥1 adult kestrel within ca. 100 m of the nest box while visiting the nest box.

Because kestrels lay eggs approximately every second day, and clutch size is typically 4-5 eggs, all nesting attempts, or nests, were found during laying or early incubation (Smallwood and Bird 2002). Nest initiation date (when the first egg was laid) was thus observed directly or back-calculated from the number of eggs first observed in the nest box. Mean (± SD) nest initiation date during 2008-2012 was 2 April (± 19.4 d), with the earliest on 16 Feb and the latest on 22 Jun.

Additional nest box disturbances by investigators included banding activities. Nearly all nestlings were banded, and during 2008-2009, most were fitted with patagial tags with unique colors and/or alphanumeric characters (Smallwood and Natale 1998) at 21- to 24-d old. We also captured and marked adult kestrels during 2008-2010. We attempted to trap all adult females inside boxes near the end of incubation with a custom-made net on an extendable pole. We banded and individually marked all newly captured adults with unique patagial tags. All bird handling and marking conformed to the Guidelines to the Use of Wild Birds in Research (Fair et al. 2010). Research protocols (#00329) were reviewed and approved by the Institutional Animal Care and Use Committee at the University of Nevada, Reno, and by the Florida Fish and Wildlife Conservation Commission.

Analysis. We assessed how many of the nest box sites were occupied by kestrels every year using a dynamic occupancy model in R 4.1.2 (Kery and Schaub 2012, R Core Team 2021). A detection history ($y(I,t)$), directly analogous to an encounter history in a mark-recapture analysis, was generated for each nest box site in which "0" indicated that kestrels were not seen in the vicinity of that particular box, and "1" was recorded when kestrels were found at the site, regardless of whether breeding activity (eggs or nestlings) was noted. Similar to robust design mark-recapture models, the encounter history of nest boxes within each season contributed to the estimation of the probability of detecting kestrel presence, because each year was considered a primary sampling period and each site visit within the year a secondary sampling period (Pollock 1982). Because visit frequency varied across and within years, we down-sampled our detection histories to twice monthly sampling periods, with any one detection within that roughly 2-wk period sufficient to count the nest box as occupied. If nest boxes were not visited during a 2-wk period for any reason, the occupancy status for that period was recorded as unknown.

With multiple primary sampling periods, two additional parameters can be estimated to represent the probability of kestrels occupying a previously unoccupied site (γ or "colonization"), and the probability that a site that had hosted kestrels was occupied again the following year (ϕ or "survival"). The dynamic occupancy model is therefore composed of two component processes: the observation model that is conditional on the state process of occupancy, $y(i,t) \mid z(i,t)$, and the state model that is only partially observed $z(i,t)$ with $z = 1$ if the site is occupied or 0 if it is not. The initial occupancy vector is a Bernoulli random process of the initial occupancy probability ψ_1

$$z(i,1) \sim \text{Bernoulli}(\Psi_1) \text{ for } i = 1,2,\ldots,R \tag{1}$$

and in the following primary periods

$$z(i,t)|z(i,t-1) \sim \text{Bernoulli}\{z(i,t-1)\phi_t + [1 - z(i,t-1)\gamma_t\} \tag{2}$$

for t=2,3,…,T; ϕ as the local survival probability and γ as the colonization parameter. The observation model is given by

$$y_j(i,t)|z(i,t) \sim \text{Bernoulli}[z(i,t)p_t] \tag{3}$$

with p_t the probability of detection, given the site j is occupied at time t. Although it is possible to assess covariate influences on p, we did not expect any influence of habitat or other extrinsic variables on our ability to detect kestrel presence. We therefore chose to model p as only a function of time, allowing p to vary across years (unique intercepts per year) and within a year (2^{nd} order polynomial of date). Similarly, we allowed the local survival probability ϕ and colonization probability γ to vary across years. Covariates were specified through a logit link. Because no sites were visited in 2011, we set the detection probability p to 0 and specified that ϕ and γ be the mean of values estimated from the other years.

We coded our dynamic occupancy model in JAGS language and conducted the analyses using the R package "runjags" (Denwood 2016). All prior probabilities were selected to be uninformative. For the model, we ran three chains for 5,000 iterations, discarding the first 4,000 runs as burn-in and did not thin the retained samples. Convergence was assessed by visual inspection of the model trace and the Raftery-Lewis and Gelman-Rubin diagnostic tests implemented in the R package “coda” (Plummer et al. 2006). Final parameter estimates are presented as medians of the posterior probability distributions with 95% Bayesian credible intervals.

To assess the timing and number of site visits needed to detect true site occupancy by kestrels in our study system, we took the approach presented by Kery and Schaub (2012) by estimating the probability $P*$ to detect the species during n identical and independent site visits. We used the equation $P* = 1 – (1-p)^n$, where p was a detection probability estimated by the occupancy model. We developed multiple scenarios in which we assessed the effect of reducing the total number of site visits as well as varying the timing of these visits.

RESULTS

We detected kestrels at 83, 81, 82, 71, 65, and 75 nest box sites during 2008-2010 and 2012-2014, respectively. Modeled estimates of occupancy were quite similar to observed rates but trended slightly higher (Fig. 1). The difference was greatest during 2013 and 2014, both years with infrequent monitoring, when kestrels were observed at a few nest box territories but never detected using those nest boxes.

The probability of detecting kestrels at nest box territories varied across the season, with the highest detection probabilities during April and May (Fig. 2). Because detection probability varied so markedly across the breeding season, simply using an overall mean detection probability to determine the minimum number of site visits needed to detect kestrel presence at 95% confidence produced misleading results. Only 2 site visits would be needed to detect kestrels adequately if the detection probability were uniformly high (such as 0.893, Fig. 3A), but

3 site visits would often be necessary when accounting for seasonal changes in detection probability (Fig. 3B).

Two or three mid-season visits sufficed to adequately detect true kestrel presence (Fig. 4). More than three nest box inspections per season did not improve our estimates of nest box occupancy. For example, three inspections at monthly intervals beginning the second week of March (Fig. 4, scenario 3) was as effective as inspecting nest boxes twice as frequently (i.e., at 2-wk intervals rather than monthly intervals (Fig. 4, scenario 7).

Discussion

The common practice of monitoring American Kestrel nest boxes at monthly intervals appears to be sufficient to detect the percentage of nest box sites that are used by kestrels at a confidence level similar to that resulting from frequent (1-7 d) visits. We recommend three kestrel nest box visits during the breeding season in peninsular Florida coincident with mid-March, mid-April, and mid-to-late May to maximize detection of kestrel nests with the least amount of effort (see Fig. 4, scenario 3). The timing of those visits does not need to be exact, as long as monitoring visits are timed to straddle the peak period of egg laying (mean clutch initiation date = 2 April), as we have done in Florida. Our modeling results suggest that, in our study area at least, an early nest box inspection coincident with the onset of egg laying does not provide essential information for measuring occupancy. At the same time, it may be advisable not to begin monitoring too late in the nesting cycle, especially at northern latitudes where the annual onset of kestrel laying can vary in response to weather events (Bird and Palmer 1988). Females have lower breeding site fidelity than males in our kestrel population (Miller and Smallwood 2009), and early nest failures potentially could lead to relocation of breeding adults.

Investigators at other latitudes will need to adjust the timing of our recommendations to local nesting phenology, and the availability of long-term datasets provide opportunities to make informed choices. Long-term datasets have shown that the American Kestrel has shifted its breeding phenology in some regions, likely in response to climate change, and such shifts should be accommodated by adjustments in monitoring protocols (Powers et al. 2021, Callery et al. 2022). In addition, we encourage investigators to model the occupancy of kestrel territories as we have done rather than simply recording the percentage of nest boxes that contain nests, especially in years when fewer annual site visits are possible (Fig. 1). Information needed for an occupancy analysis can be collected with minimal effort, simply by recording the presence of any kestrels observed on nest-box territories while routinely checking nest boxes. If accurately tracking local kestrel population size and trends over time is a project goal, then investigators would benefit from using an occupancy approach because some proportion of a kestrel population will either not nest (Smallwood and Bird 2002) or will choose to nest in alternative nest sites (Brown and Collopy 2013, McClure et al. 2021). Observed use of nest boxes is affected by trends in availability of unmonitored alternative nest cavities (McClure et al. 2017a).

Nest-box programs for the American Kestrel are widely used and considered effective tools for research and monitoring. Remote technology, which obviates regular nest inspection visits, has recently been used to monitor kestrel nest boxes for research purposes (Kamm and Reed 2020, Boal et al. 2021), but that approach is not feasible or affordable for community science efforts across large spatial scales. Investigators often seek to maximize data collection by targeting only the most productive sites (e.g., Katzner et al. 2005). However, removing nest boxes from lower-quality territories (i.e., low occupancy and/or low reproductive output) to save staff resources also reduces the investigator’s ability to study kestrel ecology across a range of environmental conditions over time. Other project-specific concerns, such as maximizing the ability to band young or adults for demographic study, also may influence nest box visitation schedules and require additional effort. Clarity about the timing and scope of nest-box monitoring efforts can help maximize the efficiency of kestrel nest box research programs, while making unbiased assessments of kestrel population size and trend.

ACKNOWLEDGMENTS

We thank J. Smallwood and M. Collopy for their vision and leadership in originally establishing kestrel nest boxes in north-central Florida. Miller's research was supported by Florida's Nongame Wildlife Trust Fund and a State Wildlife Grant from the U.S. Fish and Wildlife Service. A. Fasoli and K. Deutsch assisted with data collection. Brown's research was supported by the Eastern Bird Banding Association, Florida Ornithological Society, Raptor Research Foundation, Sigma Xi, and the University of Nevada, Reno Program in Ecology, Evolution, and Conservation Biology. Earlier versions of the manuscript were improved by the comments of A. Cox and three anonymous reviewers.

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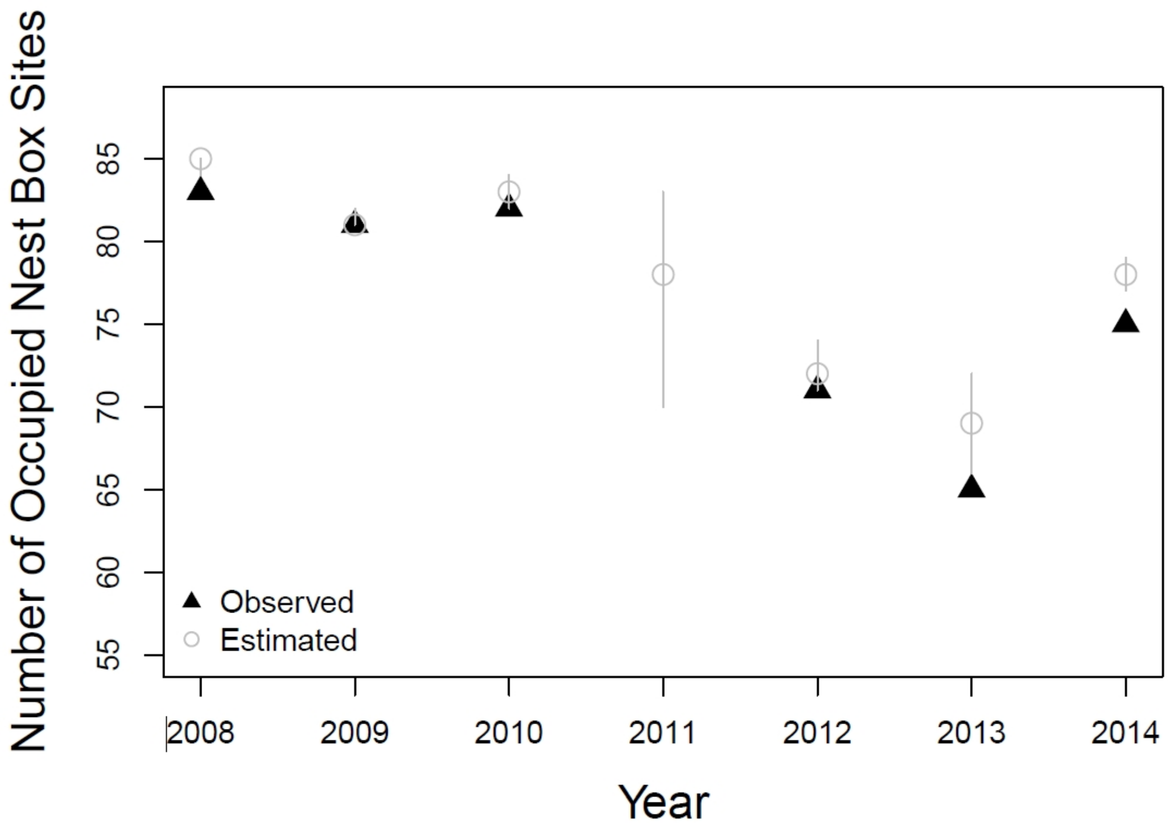
Figures.

Figure 1. Observed and estimated number of nest box sites occupied by American Kestrels in north-central Florida, USA, during 2008-2014. Black triangles indicate the maximum number of sites observed to be occupied by kestrels, and gray open circles show the mean number of sites occupied (gray lines show 95% Bayesian credible intervals) as estimated by a dynamic occupancy model. Nest boxes were visited frequently during 2008, 2009, and 2012, and infrequently during 2010, 2013, and 2014 (see Methods). No sites were visited in 2011.

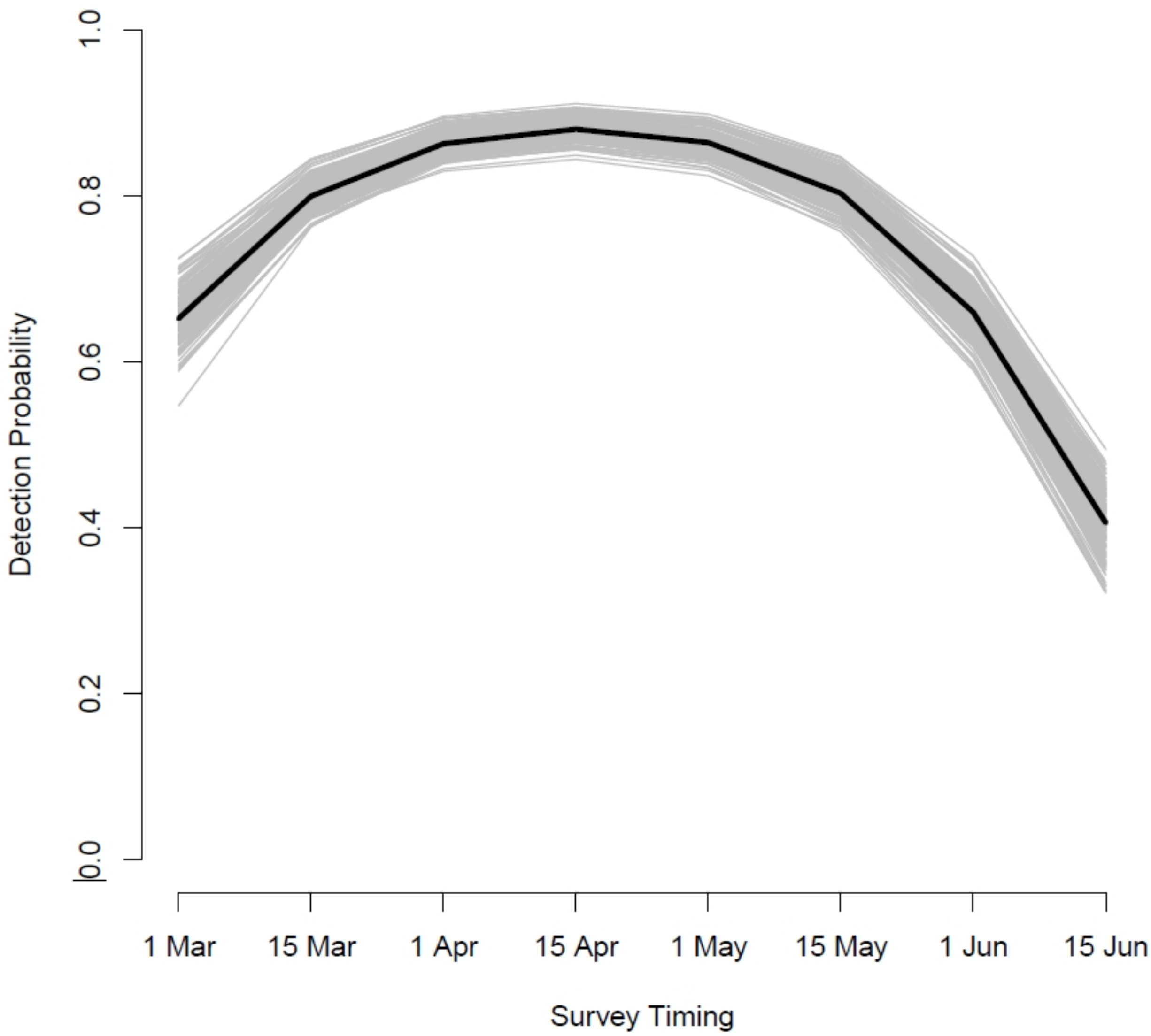
Figure 2. Probability of detecting American Kestrels at nest box sites in north-central Florida, USA varied across the breeding season. Illustrated in black is the mean detection probability during every bimonthly period from 1 March to 30 June in year 2 of the study. Gray lines indicate a random sample of 200 simulation results to illustrate variability.

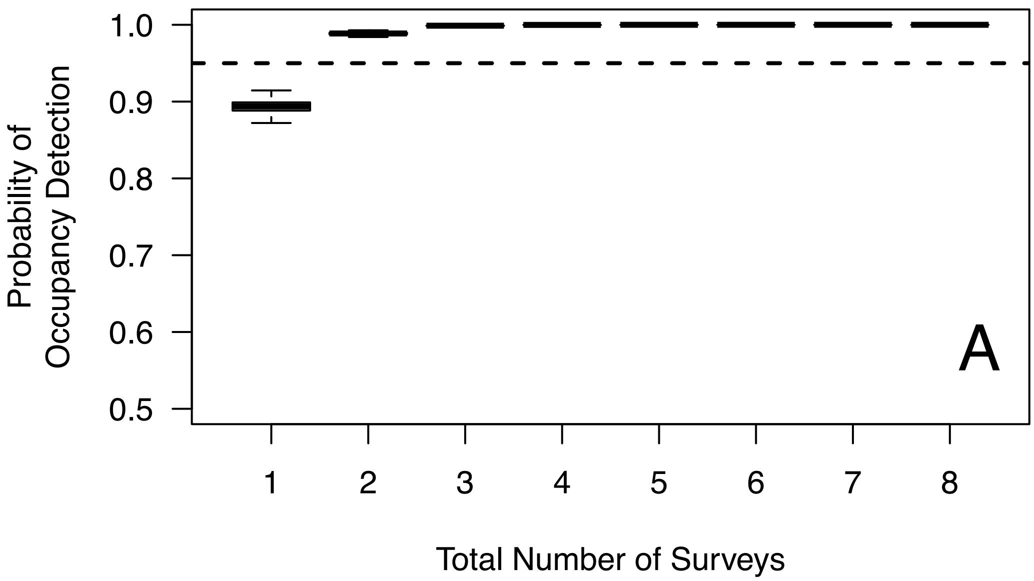
Figure 3. Effect of survey number on probability $P*$ of detecting kestrels at a site given their true occupancy as n number of visits increases. (A) suggests only 2 site visits needed to detect kestrels with ≥95% confidence without accounting for seasonal changes in detection probability. (B) illustrates at least 3 site visits are needed to detect kestrels with ≥95% confidence when accounting for date-specific detection probability, because early season detection probability was relatively low. Dashed line marks $P*$ at 0.95.

Figure 4. Multiple scenarios of survey timing and frequency with resulting effects on P* or the probability of detecting kestrels at a site given their true occupancy. Numbers at the top of each panel show the total number of site visits per scenario. Dashed line marks $P*$ at 0.95.

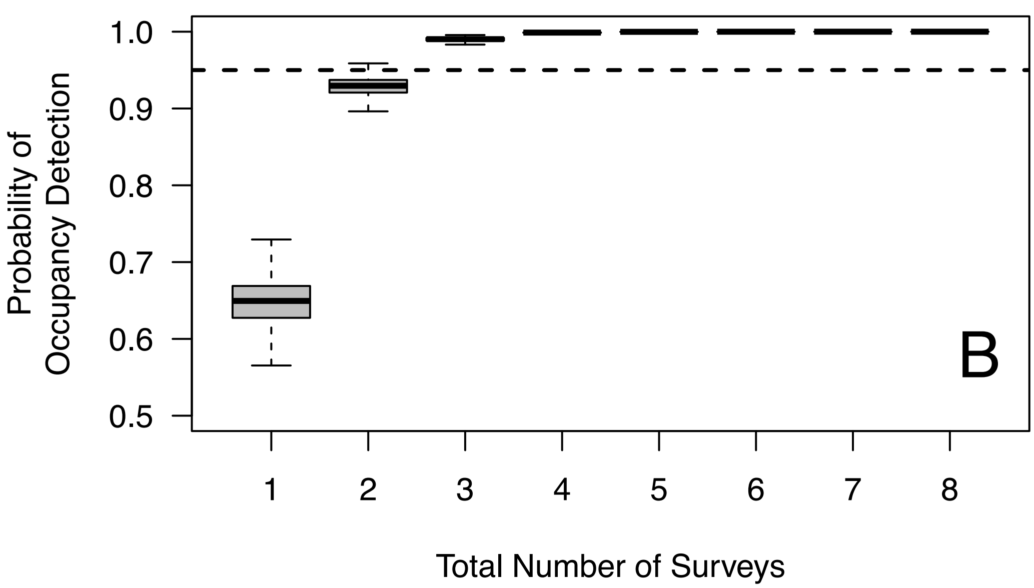


Number of Occupied Nest Box Sites
85
80
75
70
65
60
55
Observed
Estimated
2008
2009
2010
2011
2012
2013
2014
Year

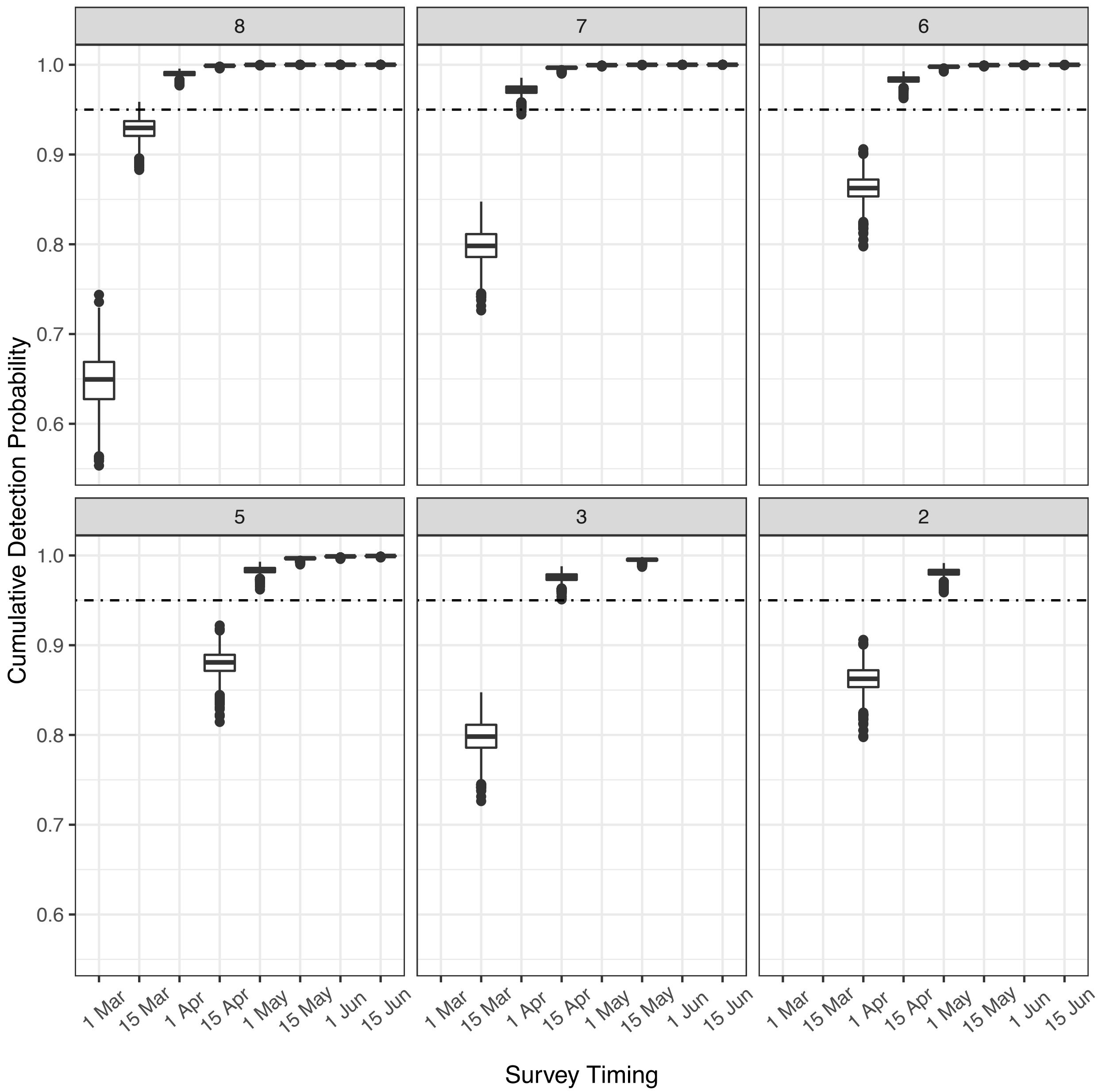

1.0
0.8
0.6
0.4
0.2
0.0
Detection Probability
1 Mar
15 Mar
1 Apr
15 Apr
1 May
15 May
1 Jun
15 Jun
Survey Timing



Probability of Occupancy Detection
1.0
0.9
0.8
0.7
0.6
0.5
A
1
2
3
4
5
6
7
8
Total Number of Surveys



Probability of Occupancy Detection
1.0
0.9
0.8
0.7
0.6
0.5
B
1
2
3
4
5
6
7
8
Total Number of Surveys


8
7
6
5
3
2
Cumulative Detection Probability
1.0
0.9
0.8
0.7
0.6
1 Mar
15 Mar
1 Apr
15 Apr
1 May
15 May
1 Jun
15 Jun
Survey Timing