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Review

The use of nest boxes to support bird conservation in commercially managed forests: A systematic review

Eliza K. Thompson *, Rodney J. Keenan, Luke T. Kelly

School of Agriculture, Food and Ecosystem Forest Sciences, Faculty of Science, The University of Melbourne, Parkville 3010, Victoria, Australia

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ABSTRACT

Nest boxes are widely used to supplement natural tree cavities used by fauna, particularly in “working lands” where large, old trees are cleared or harvested. Commercially managed forests comprise large areas of global forest cover and nest boxes provide an opportunity to encourage biodiversity in areas where trees are harvested before natural cavities form. Here, we used a systematic review to provide a global overview of the scientific literature on nest boxes and bird conservation within commercially managed forests. Our systematic review identified 76 studies exploring the influence of nest boxes on birds in commercially managed forests, ranging from studies of individual birds to whole communities. Insectivorous birds were the most common reported users of nest boxes, and studies that incorporate a before and after period provide one line of evidence that nest boxes enhance bird occupancy and survival. However, only a small number of bird species have been observed using nest boxes and most studies were conducted within pine-dominated forests in Europe and North America. We recommend future research to develop knowledge of a wider range of bird taxa and commercially managed forest types. Further, we advocate for testing different types of nest box designs, materials, and spatial arrangements to improve conservation outcomes. This will help to ensure nest boxes, in combination with ecological restoration and a suite of other conservation actions, enhance biodiversity and the ecosystem functions provided by birds, such as pest control.

1. Introduction

“Working lands”, such as farms, production forests and rangelands, are a significant proportion of the Earth’s land surface and can play a significant role in maintaining and enhancing biodiversity (Kremen & Merenlender, 2018). An emerging way to contribute to biodiversity conservation in these landscapes is through providing artificial habitats to compensate for modified or missing resources required by animals. For example, nest boxes are widely used to supplement natural tree cavities used by birds, particularly in areas where large, old trees have been cleared or harvested. Nest boxes have now been trialled to promote bird conservation in areas affected by agriculture (Rey Benayas et al., 2017; Shave, Shwiff, Elser, & Lindell, 2018) and, increasingly, by forestry (Zárybnická, Riegert, & Šťastný, 2015). Yet there is a need to understand when and where nest boxes are effective in boosting bird populations, and to synthesise and evaluate the evidence that nest boxes improve conservation outcomes in areas used for production of food, fibre, fuel, and forest products.

The global literature on nest boxes is large and fast-growing: a search of “nest box” AND “bird” in Web of Science yields more than 600 published papers, including 41 in 2022 alone. Substantial progress has been made in nest box research in only a few decades (Gibbons & Lindenmayer, 2002; Goldingay, Rohweder, & Taylor, 2020; Lindell, Eaton, Howard, Roels, & Shave, 2018). For example, studies of nest boxes indicate the importance of sound nest box construction design and construction for thermal stability (Griffiths et al., 2018), targeted positioning of nest boxes in the landscapes in relation to exposure to weather, climate and predation (Ardia, Pérez, & Clotfelter, 2006; Bailey & Bonter, 2017; Schwartz, Genouville, & Besnard, 2020), and the flow-on effects of nest boxes in attracting birds that perform ecosystem functions such as pest control (Mulyana, Priyambodo, Triwidodo, Hendarjanti, & Sahari, 2020; Peleg et al., 2018). Different types of studies, including those where next boxes have been deployed in areas subject to experimental manipulation, have also highlighted limitations of nest boxes: attraction of non-target species and pests (Charter, Izhaki, Mocha, & Kark, 2016; Stojanovic, Owens, Young, Alves, & Heinsohn, 2021), low occupancy of target species, time lags in occupancy (Lindenmayer, Crane, Blanchard, Okada, & Montague-Drake, 2016), and decay of nest

* Corresponding author.
E-mail address: elizat2@student.unimelb.edu.au (E.K. Thompson).

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boxes (Conner, Saenz, & Rudolph, 1995; Lindenmayer et al., 2009) (but see Goldingay, Thomas, & Shanty, 2018). While nest boxes in some forested landscapes are relatively well-studied, their usefulness in commercially managed forests subject to harvesting has received less attention.

Global forest cover is comprised of 93% (3.75 billion ha) of naturally regenerating forests with the remaining 7% (290 million ha) comprised of planted forest (FAO, 2020). Within these forest types, we focus on 'commercially managed forests' either as plantation forests or managed natural forests. Plantations are dominated by one, or few, tree species and are grown to produce fast-growing, tall, straight trees, leading to a relatively uniform vegetation structure. Managed natural forests are naturally regenerated areas that are modified by logging and other management actions. Commercially managed forests differ from other types of working lands, such as agricultural lands and rangelands in that they are dominated by a tree canopy until they are harvested (Wilson et al., 2006). While this canopy (and even temporary open areas with a shrub or understorey layer) can provide resources for native birds, in intensively-managed areas trees are usually harvested before natural tree cavities form (Cawsey & Freudenberger, 2008; Mawson & Cooper, 2015). This excludes cavity-dependent species and limits their conservation value (Lindenmayer et al., 2016).

Growing interest in the impacts of commercial activities on nature, including interest from local communities and financial investors, is driving some forest managers to consider options for enhancing biodiversity (Betts et al., 2021; Brockerhoff, Jactel, Parrotta, Quine, & Sayer, 2008). The ecosystem services provided by healthy populations of birds, and other insectivores, may also have benefits for the productivity and profitability of commercially managed forests. For example, by reducing insect pest populations that harm tree growth and condition (da Silva et al., 2022; Karp et al., 2013; Smith & Agnew, 2002). Forestry may therefore benefit from the presence of nest boxes. While large-scale nest box monitoring has occurred across commercially managed forests, there has been no systematic review of nest boxes and bird conservation

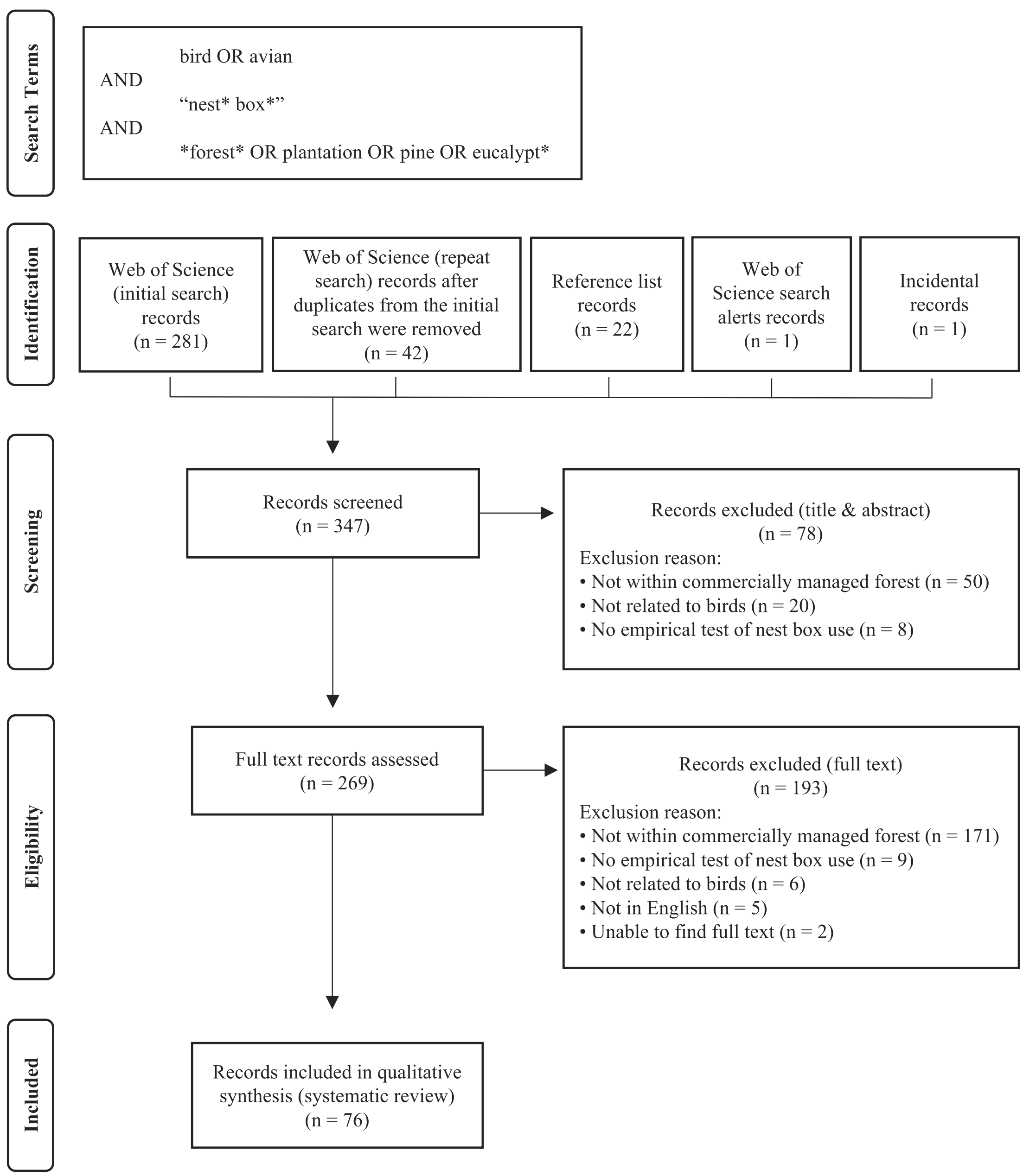

Fig. 1. Graphical representation of the systematic review process (modified from Haddaway et al., 2018).

within commercially managed forests. Systematic reviews provide a robust method to evaluate evidence for conservation outcomes from different actions or treatments and enable management decisions to be supported by accurate and up-to-date information. In this paper, we systematically reviewed the literature to address the following key questions:

1. What types of locations and bird responses to nest boxes have been studied in commercially managed forests?
2. Can nest boxes provide conservation value for birds within commercially managed forests?
3. What are the challenges and opportunities associated with the use of nest boxes in commercially managed forests?

Given the growing interest in improving natural values and biodiversity within forestry landscapes, we hope to support better decisions by forest managers through understanding where, when, and how nest boxes can improve the value of commercially managed forests for birds.

2. Material & methods

2.1. Search criteria

Our aim was to first identify peer-reviewed papers on bird use of nest boxes in commercially managed forests – the focal taxa, manipulation, and location. We systematically searched the Web of Science database using the keywords "bird" OR "avian", "*forest*" OR "plantation" OR "pine" OR "eucalypt*" and "nest* box*" (Fig. 1). The use of an asterisk allowed for word variations in the preceding or succeeding letters of the keyword. The initial search was executed on 21st May 2021. The search was repeated on 6th February 2023 to ensure the review submitted for publication captured the most recent literature.

We used the RepOrting standards for Systematic Evidence Syntheses (ROSES) to guide the systematic review and transparent reporting of methods (Table S1) (Haddaway, Macura, Whaley, & Pullin, 2018). To pass preliminary screening, papers needed to contain all three elements of the search terms: the focal taxa, manipulation, and location. The combined search included a window of publication from 1900 to 2023 and was restricted to papers written in English. Screening of records to pinpoint relevant papers began with reviewing paper titles and abstracts. Papers were excluded at this stage if summaries indicated that they did not measure bird associations with nest boxes in commercially managed forest landscapes. If a decision about inclusion or exclusion could not be made at the title or abstract level, the full text was screened to aid decision-making.

The initial literature search (May 2021) yielded 281 papers. After passing preliminary screening, each paper was read in full to check that it satisfied four criteria; i) the study was empirical (i.e., not a review or opinion piece); ii) the study assessed nest box use (by nest boxes we refer to artificially made structures, including nest boxes externally attached to trees and nest boxes carved into trees); iii) the study measured birds (either as the only taxa or in tandem with other taxa); and iv) the study was completed within a commercially managed forest (or a landscape containing a commercially managed forest). We also checked the reference lists of the 50 papers that passed the entire screening process, which yielded an additional 22 studies that met the criteria. The repeat search (February 2023) yielded 42 new papers, of which four passed preliminary screening. The final dataset of nest box studies for further analyses included 76 papers (Table S2).

We categorized each of the 76 papers by a range of attributes including: publication information (paper title, year of publication and journal name), study location and commercially managed forest type (country, tree species), study design (experimental design, study duration, sample size, nest box maintenance), bird responses (occupancy, relative abundance, measures of reproduction and survival, morphological traits, species richness), ecosystem services (pest control) and other taxa (nest box usage by other animal groups) (Table S2). Experimental design refers to one of four experimental designs including: Before-After-Control-Impact (BACI) where pre-treatment monitoring was undertaken and there was a control group that was also monitored, Before-After (BA) where only pre-treatment monitoring occurred but no control group, Control-Impact (CI) where no pre-treatment monitoring occurred but a control group was used for comparison to treatment and After-Only (AO) which had no pre-treatment monitoring or control group. We defined treatment as nest box installation within a commercially managed forest and a control group as a location within a commercially managed forest that did not contain nest boxes. Bird responses refer to the dependent variables reported by each study including species richness (number of species reported within the nest box area from dedicated census surveys), measures of reproduction and survival (parameters relating to breeding success), occupancy (presence of nesting material, egg or bird in a nest box), relative abundance (the number of individuals or pairs capable of breeding within an area regardless of species), and morphological traits (measured body measurements of nest box occupants which required handling). Such attribute groups were chosen based on the most frequently reported response variables from our screening as well as those variables related to our key questions. For data that were not directly stated or tabulated in the main text or supplementary material of a paper, we used PlotDigitizer Online App (https://plotdigitizer.com/app) to extract data from figures.

We examined the attributes of the 76 focal studies using two methods. To analyse where, how, and when studies were completed, we used summary statistics and graphical summaries to document the number and proportion of studies with different attributes. To qualitatively assess the influence of nest boxes on birds in commercially managed forests, we highlight and describe the five BACI studies identified that represent strong tests of the effect of nest boxes on birds.

3. Results

3.1. Year and publisher of study

Of the 76 studies, more were published between 2010 and 2019 (n = 29 studies) than other decades. The first empirical study was published in 1979, and when viewed on a continuum the number of studies is increasing linearly (Fig. S1). Research was most frequently published in four journals, namely Acta Ornithologica (n = 8), Forest Ecology and Management (n = 7), Ornis Fennica (n = 4) and Wilson Journal of Ornithology (n = 4).

3.2. Location and commercially managed forest type

The focal studies were distributed across 22 countries, with most studies occurring in Europe (n = 48) and North America (n = 16) (Fig. 2). In particular, Spain (n = 15) and the United States (n = 10) were the location of a high proportion of studies (Fig. 2). The remaining countries had six or less studies.

Most studies were completed in mixed species commercially managed forests (n = 54) compared to single species commercially managed forests (n = 21). Pine (*Pinus* spp.) or pine with other species was the most frequently studied type of commercially managed forest (n = 59) (Fig. 3) followed by commercially managed forests comprised of spruce (*Picea* spp.) (n = 27), birch (*Betula* spp.) (n = 17) and oak (*Quercus* spp.) (n = 11) (Fig 4; Table S2).

3.3. Experimental designs

Various study types were employed (Fig. 3). Most common were studies of nest boxes in commercially managed forests with no comparisons to a spatial or a temporal control without nest boxes (n = 49). A total of 27 studies compared areas of commercially managed forests with nest boxes to a control group. This included research that compared

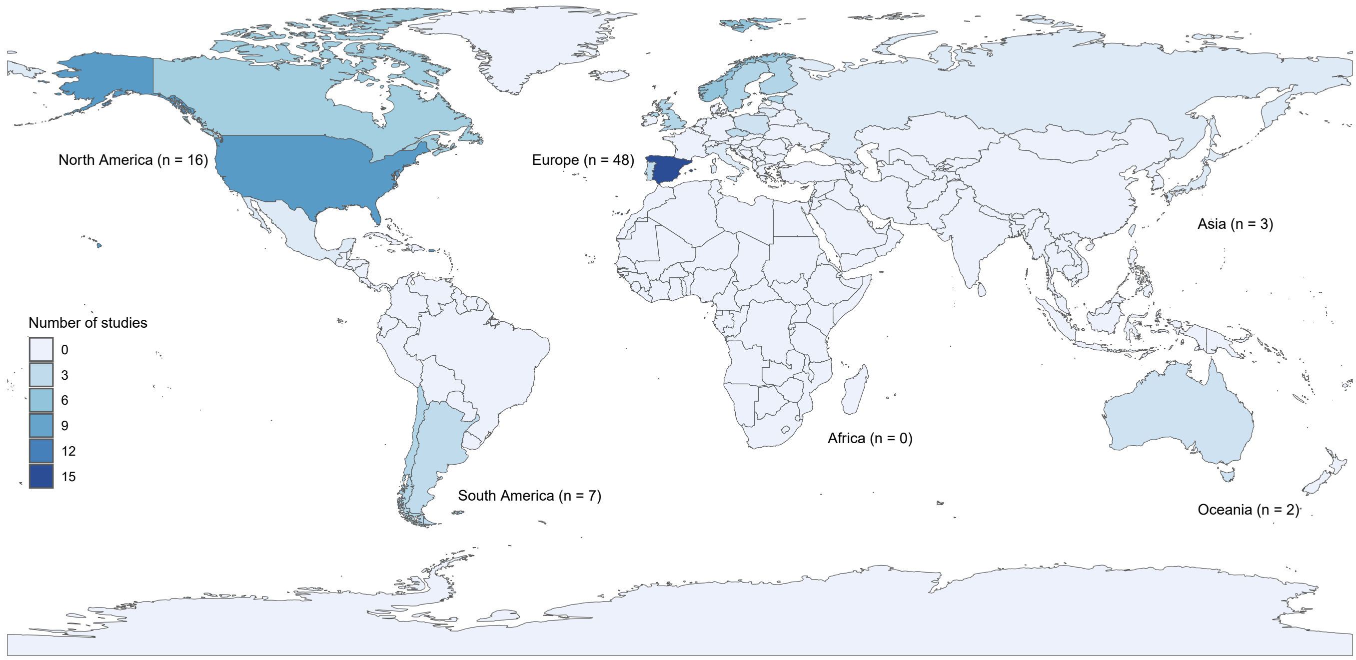

Fig. 2. The location of nest box studies for birds in commercially managed forests. Colour gradient represents the number of studies per country, with higher intensity of blue indicating more studies. Number in parentheses represents number of studies per continent.

areas of commercially managed forests with nest boxes to those areas without (i.e., a spatial control group) (n = 18) or that compared the same location before and after nest boxes were installed (i.e., a temporal control group) (n = 4). Five studies used a Before-After-Control-Impact design that included both spatial and temporal control groups (summarised in Table 1).

Study duration ranged from less than one year to 55 years, with a mean study duration of 7.6 years (Fig. 3). The sample size of nest boxes used per study ranged from 16 to 1900. Fourteen of 76 studies (18%) installed less than 100 boxes, 27 studies (36%) installed between 100 and 200 boxes, and 29 studies (38%) installed over 200 boxes. The number of nest boxes used within some studies varied over time, as nest boxes decayed, or arrangements were deliberately modified. After considering this temporal variation within studies, we calculated the average number of independent nest boxes installed per study as 272.

3.4. Measures of bird responsess

Fifty-five bird species were reported using nest boxes. The most common bird species observed using nest boxes were the great tit (*Parus major)* (n = 15 studies) and the Eurasian blue tit (*Cyanistes caeruleus)* (n = 12 studies). These two bird species were found across a range of commercially managed forest types including those comprised of pine, birch, and spruce in Europe. In North America, the most frequent nest box occupants were the Carolina wren (*Thryothorus ludovicianus)* (n = 5), eastern screech owl (*Megascops asio)* (n = 5) and great crested flycatcher (*Myiarchus crinitus)* (n = 5), while in South America the thorn-tailed rayadito (*Aphrastura spinicauda)* (n = 4) was the most frequently reported bird using nest boxes. Most studies investigated insectivorous birds (n = 62), followed by bird species that were carnivores (n = 26), granivores (n = 8), frugivores (n = 6), and omnivores (n = 6) (Fig. 3).

Occupancy was the most frequently used measure of bird response (n = 53). Detailed data on occupancy were available from 29 studies: the average occupation of nest boxes by birds within commercially managed forests was 29.3% (and ranged from 1% to 78%). Twenty-one studies reported the relative abundance of birds using nest boxes. Of the 21 studies, nine studies reported the relative abundance of a single species whereas 12 recorded the relative abundances of multiple species.

Other measures were of reproduction and survival (n = 48) and morphological traits (n = 19) (Fig. 3). Measures of reproduction and survival were mainly reported through clutch size (n = 36), laying date (n = 31) and the number of fledglings (n = 21). Body mass (n = 16) was the most reported morphological trait. Only seven studies reported the number of bird species where nest boxes were installed (i.e., species richness).

3.5. Qualitative synthesis of the impact of nest boxes on birds

We identified five BACI studies that reported bird responses to nest boxes in commercially managed forests. There were too few studies for meta-analysis. Instead, we provide a qualitative synthesis of this selection of empirical studies with strong design and highlight their key findings (Table 1). In summary, each of these five studies found a strong, positive effect of nest boxes on bird species responses. This included positive association between nest boxes and occupancy (n = 4), relative abundance (n = 4) and measures of reproduction and survival (n = 1).

4. Discussion

Systematic review revealed nest boxes in commercial forests managed for timber have been studied on five continents. There is growing evidence that nest boxes can provide supplementary habitat within commercially managed forests. In particular, evidence from studies that incorporate before and after treatment observations indicate that nest boxes within commercially managed forests can increase their value as habitat for birds. However, studies to date have only been conducted in a few types of commercially managed forests and focused on a narrow range of bird species and communities. Next, we discuss these results and highlight avenues for future research on nest boxes, and related actions and strategies for bird conservation in working lands.

4.1. Studies of species distribution and abundance

Occupancy of nest boxes was the most frequently reported measure of birds. Occupancy of nest boxes varied highly among studies: from 1%

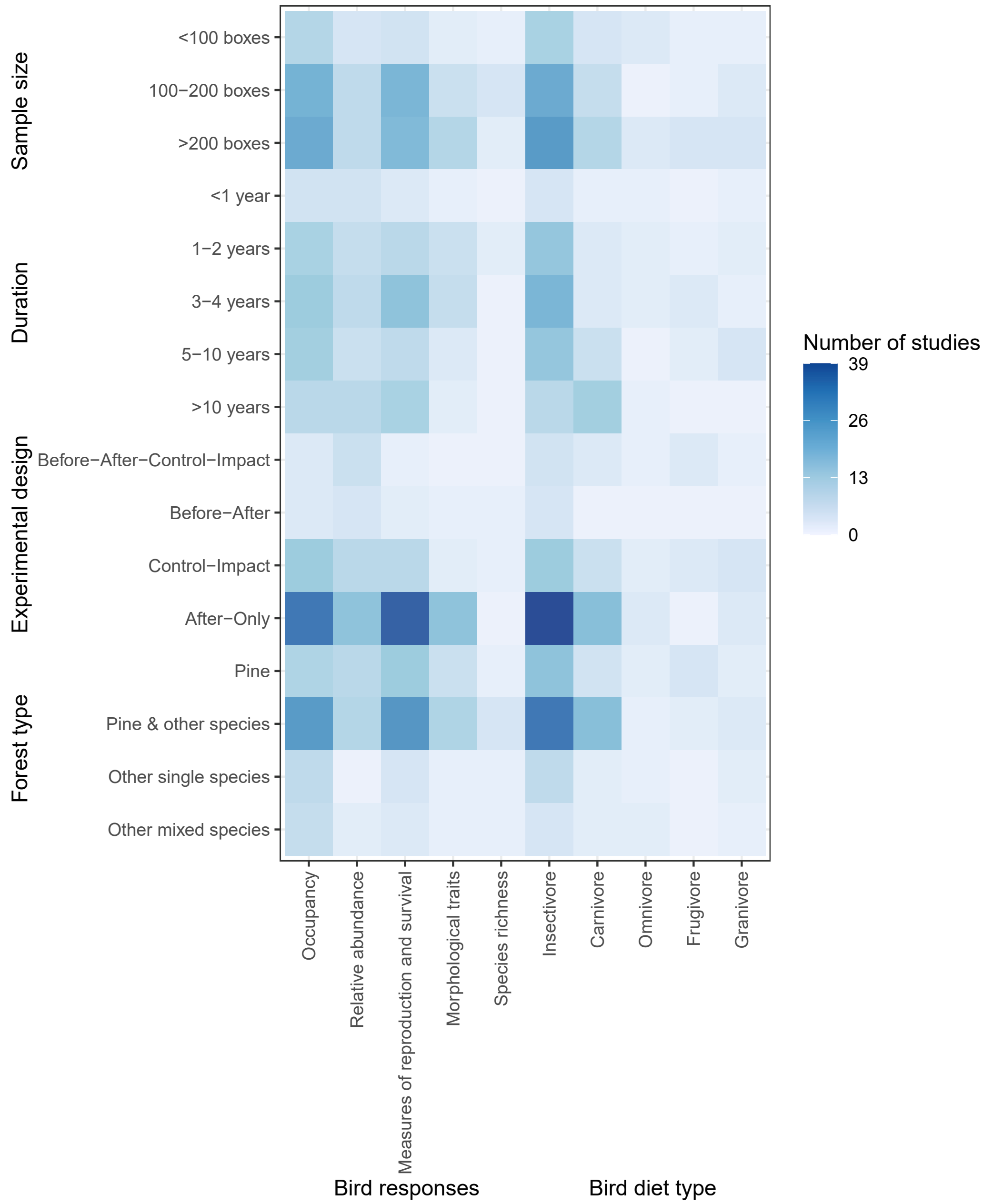

Fig. 3. Summary of studies assessing the effect of nest boxes for each bird response and diet type across commercially managed forest type, experimental design, duration, and sample size. Colour gradient represents the number of studies, with higher intensity of blue indicating more studies. Note: pine refers to either monocultural pine or multiple pine species within one commercially managed area. See Table S2 for term definitions.

(Dufour-Pelletier et al., 2020a) to 78% (Petty, Shaw, & Anderson, 1994). This highlights that the focal studies reported a range of effects and outcomes of nest box establishment on birds. In some cases, placing nest boxes within cavity-depleted commercially managed forests enabled birds to occupy such landscapes (Burgess, 2014; Dahlsten & Copper, 1979; Mathisen, Pedersen, Nilsen, & Skarpe, 2012; Petty et al., 1994). Further to this, some species (e.g., American kestrel (*Falco sparverius)* and great tit) have been shown to have higher rates of occupancy in nest boxes than natural cavities (Bortolotti, 1994; Maziarz, Wesołowski, Hebda, Cholewa, & Broughton, 2016). For example, within managed boreal forests of Canada, the nest box use rate of American kestrels was 49 – 62% compared to natural cavities of 5 – 15% (Bortolotti, 1994). In other cases, an effect of nest box installation was small or not detected (Cockle & Bodrati, 2013; Conner et al., 1995; Dufour-Pelletier et al., 2020b). Several factors were shown to influence occupancy including proximity to remnant vegetation (Kavanagh et al., 2010), nest box light penetration (Bortolotti, 1994), nest box depth (Summers & Taylor, 1996) and surrounding vegetation structure (Holt & Martin, 1997).

In addition to changes in occupancy, there is evidence that the relative abundance of birds is shaped by the addition of nest boxes. Across a 29-year period following nest box installation European pied flycatchers (*Ficedula hypoleuca)* increased in relative abundance across Scots pine (*Pinus sylvestris)* forests, from no pairs before nest box installation to 11.7 pairs/ha after nest box installation (Camacho, Martinez-Padilla, Canal, & Potti, 2019). In some cases, this increase in relative abundance can interact with reproduction and survival. Within maritime pine (*Pinus pinaster)* forests, when relative abundance of the great tit was lowest, a second breeding attempt occurred, yet as relative abundance increased, second breeding attempts decreased (Pimentel & Nilsson, 2007). Importantly, it can take time for bird population levels to change in response to nest boxes, and in several studies a long-term investment in maintenance and replacement was needed before bird

Fig. 4. Examples of bird species and commercially managed forests studied in relation to nest boxes. Tufted titmice (*Baeolophus bicolor)* (top left) increased in relative abundance and nesting attempts across slash pine (*Pinus elliottii)* forests in the United States (top right). Eurasian blue tits (*Cyanistes caeruleus)* (bottom right) bred successfully within artificially installed nest boxes in common beech (*Fagus sylvatica)* forests in Spain (bottom left). [Additional image credits: Andy Reago & Chrissy McClarren, CC BY 2.0 (https://creativecommons.org/licenses/by/2.0) (Tufted Titmouse). Riverbanks Outdoor Store from New Port Richey, FL, United States, CC BY 2.0 (https://creativecommons.org/licenses/by/2.0) (Slash pine plantation). I, Luc Viatour, CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0/) (Common beech forest plantation). Maximilian Dorsch / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0) (Eurasian blue tit).].

responses were observed (Camacho et al., 2019; Camprodon, Salvanya, & Soler-Zurita, 2008).

4.2. Nest boxes and bird demographic processes

Birds use nest boxes in commercially managed forests to roost and shelter in, and this has flow on effects for demographic processes such as reproduction and survival (Robles, Ciudad, & Matthysen, 2011). Such effects were demonstrated in Japanese cedar (*Cryptomeria japonica)* and Hinoki cypress (*Chamaecyparis obtusa)* forests, where higher fledgling success by crested tits (*Lophophanes cristatus)* occurred when they bred in nest boxes closer to patches of native vegetation (Kondo, Mizutani, & Hijii, 2017). This highlights that breeding success may be lower in commercially managed forests with no or few native vegetation elements within the landscape matrix. Thus, occupied nest boxes *per se* do not necessarily equate to high-quality habitat because their context within the landscape, such as proximity to natural forest remnants, is important (Demeyrier, Lambrechts, Perret, & Grégoire, 2016). Other factors important in determining the overall value of nest boxes in bird conservation include their location, spatial arrangement, age of surrounding vegetation, entrance hole size, and degree of predation.

Nest boxes installed higher in the tree canopy and at greater distances from the nearest neighbouring box resulted in earlier laying dates and higher mass of fledglings of the Eurasian blue tit (*Cyanistes caeruleus*) (Serrano-Davies, Barrientos, & Sanz, 2017). Survival rates of great tits in pine forests were higher when nest boxes were surrounded by immature vegetation compared to mature vegetation (Atienzar et al., 2010). Nest boxes with smaller entrance holes had higher hatching success compared to larger entrance holes in the Eurasian blue tit in Spain (Maícas, Bonillo, & Haeger, 2014). Predation led to lower survival in great crested flycatchers in the United States (Miller, 2002). Such measures of reproduction and survival are particularly useful indicators for assessing the effectiveness of nest boxes and can inform better design and implementation of nest boxes for conservation (Cowan et al., 2021; Goldingay, 2017; Larson, Eastwood, Buchanan, Bennett, & Berg, 2015).

4.3. Patterns in the location of studies and their focal bird taxa

This systematic review showed that nest box studies in commercially managed forests were biased in location and bird taxa. Most studies were conducted in commercially managed pine forests of the Northern Hemisphere, particularly within Spain and the United States. There were few studies in tree genera besides *Pinus*. The lack of studies on eucalypts (n = 5) was unexpected given that species within this genus are cultivated across many countries. For example, blue gum (*Eucalyptus globulus),* is cultivated across 24 countries (including the United States,

Table 1
Overview of nest box studies within commercially managed forests that used BACI experimental design.

Commercially managed forest type	Main findings	Study recommendations	Location	Reference
Mexican mountain pine (*Pinus hartwegii*)	Number of sightings of secondary cavity-nesting birds increased at sites with nest boxes compared to those without. On average, 12 of 80 nest boxes were occupied in commercially managed forests.	Addition of nest boxes and preservation of old stumps will promote bird conservation in Mexico.	Mexico	(Lima & Garcia, 2016)
Scots pine (*Pinus sylvestris*) Common Beech (*Fagus sylvatica*)	Between bird breeding seasons there was a significant increase in bird relative abundance and richness in plots with nest boxes compared to plots without nest boxes (between plots with and without nest boxes mean difference was 2.47 for abundance and 1.27 for species richness).	Practices that lead to an increase in the number of natural cavities should be encouraged e.g., not removing snags, and allowing some trees to complete their lifecycle and form cavities.	Spain	(Sanchez, Cuervo, & Moreno, 2007)
Slash pine (*Pinus elliottii*)	Increase in bird relative abundance (twofold in 1997 and threefold in 1998) and nesting attempts after nest boxes were added. Nine percent of nest boxes occupied.	Nest boxes should be installed to achieve high local densities of secondary cavity-nesting birds within recently burned commercially managed forests, with positive outcomes expected in the short-term.	United States	(Miller, 2010)
Laurel (Lauraceae) Guatambú (*Balfourodendron riedelianum*) Parana pine (*Araucaria angustifolia*) Bamboo (*Merostachys claussenii, Chusquea tenella* and *Guadua trinii*)	Positive effect of adding nest boxes on bird relative abundance for two species regardless of the number of natural cavities in the plot. Cavity-nesting birds occupied one or two of 15 nest boxes in each of the four treatment plots. In logged forest plots without nest boxes there were 0 nests/ha compared to plots with nest boxes where there were 1.2 nests/ha.	Forest certification should promote tropical timber management strategies that conserve large live cavity-bearing trees. Across production landscapes, the supply of tree cavities should be sufficient to maintain viable populations of cavity-nesting species.	Argentina	(Cockle, Martin, & Drever, 2010)
Ponderosa pine (*Pinus ponderosa*)	Increased relative abundance of birds on two of the three plots where nest boxes were established. Three of six species increased in relative abundance in areas with nest boxes installed.	Bird patterns surrounding nest boxes and natural cavities should be seen as multifaceted.	United States	(Brawn & Balda, 1988)

Kenya, China, France and Guatemala) (USDA, 2023). Even in Australia, where the Eucalyptus genus naturally occurs, only two studies were identified. Australia is home to a wide range of bird species that are dependent on natural tree cavities (Gibbons & Lindenmayer, 2002). Such species' geographical ranges overlap with millions of hectares of commercially managed forests, but they are underrepresented in our dataset, leaving a deficiency in our understanding of how nest boxes within commercially managed forests (of both locally grown and exotically grown tree species) can support a range of bird species.

As well as bias in the location and commercially managed forest species studied, most studies investigated a small selection of bird species, notably tits and flycatchers. Further, the number of species reported using nest boxes in each study was low. While some studies did employ a range of nest box designs to target multiple species, the highest number of birds shown to occupy nest boxes within one study was eight bird species (Maícas & Haeger, 1996). Of all studies of species that occupied nest boxes, all are classified as "Least Concern" according to the IUCN Red List of Threatened Species (IUCN, 2022). One interpretation is that nest box studies and application are not aiming to increase bird diversity *per se*, but rather to find out and support a single, or select few, target species. More comprehensive reporting on the status of all bird species occupying nest boxes (rather than just target species) will help improve understanding of the capacity nest boxes have in supporting bird diversity.

4.4. Opportunities for future research

Recent advances in nest box research show their ability to supplement natural commercially managed forests for birds amid land use changes, as well as provide indirect benefits to ecosystem services. A review of the global literature on birds and nest boxes has helped to identify several areas for improving nest box research in commercially managed forests. To establish a cause-and-effect relationship between nest boxes and birds, we advocate for the use of control groups, especially those incorporated into a BACI design. However, we acknowledge designs with both spatial and temporal controls are not always feasible. Other types of studies will also be important. For example, long-term research into the breeding ecology of birds requires careful observations of the demographics and life-histories of species.

We also urge future studies to provide sufficient detail on methodology to allow the study to be replicated and be used as a basis for synthesis across studies (also see Lambrechts et al., 2010; Møller, 1992; Wesoowski, 2011). Additional methodological details in research publications will help determine if poor nest box design selection (e.g., entrance size, wall thickness, construction materials) and placement (e.g., orientation, density and height) are contributing factors to low occupancy (Carstens, Kassanjee, Little, Ryan, & Hockey, 2019; Goldingay et al., 2020; Goldingay, Rueegger, Grimson, & Taylor, 2015; Lambrechts et al., 2012). In particular, box density may be an important contributor to box use. For example, Lima and Garcia (2016) placed nest boxes at a density higher than natural cavities (3 – 4.1/ha compared to 0.76 – 2.24/ha, respectively) whereas Miller (2010) placed nest boxes at a density lower than natural cavities (4/ha compared to 6.2 – 17.7/ha, respectively). This highlights that understanding the context and abundance of natural cavities within an area that nest boxes are placed will be crucial in understanding if nest boxes can be successful. Such understanding will be even more important as alternative nest box designs and technologies become more available (Quin et al., 2020; Parker et al., 2022). For example, studies that compare 3D printed nest boxes made from novel materials with traditional plywood designs, or that investigate the different placements of nest boxes within a commercially managed forest landscape matrix (e.g., near riparian areas or along forest edges) will provide important insights into the future use of nest boxes within commercially managed forests. Beyond design, technology and location, there is a need to understand the ecosystem services that may benefit plantation managers through encouraging birds that use nest boxes.

In attracting cavity-using birds, nest boxes may increase natural pest control by providing habitat for insectivorous birds. Insect pests are a frequent problem within plantations, usually managed through applying pesticide, which can be expensive and have impacts on non-target insect species. While most studies in our dataset investigate insectivorous birds, only six studies mention the potential for invertebrate pest control. If increased populations of insectivores can reduce insect pests, providing nest boxes for cavity-using insectivores could be economically attractive to plantation managers and reduce the amounts of pesticide used within these landscapes. For example, one study indicated great tits could reduce pest impacts within pine plantations (Mänd et al., 2005). The economic value of investing in nest boxes to increase populations of cavity-using insectivorous birds in commercially managed forests is an important area for future research.

5. Conclusions

A systematic review of the literature identified examples where placing nest boxes within commercially managed forests can contribute to conservation of target bird species. The effects of nest boxes varied with nest box design, placement, commercially managed forest type, landscape context and target bird species. Some studies indicated nest boxes did not improve conservation outcomes. For successful use of nest boxes to improve bird conservation in commercially managed forests, long-term planning and management are required, involving continuous replacement through timber harvest and regeneration cycles. Bird conservation in commercially managed forest landscapes, and in other working lands, will benefit from complementary actions and strategies including: maintaining and restoring natural habitat with the matrix of intensivly managed forests, as well as improving habitat quality within commercially managed forests.

CRediT authorship contribution statement

Eliza K. Thompson: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Rodney J. Keenan:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Luke T. Kelly:** Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are provided in the Supplementary Material

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Appendix A. Supplementary data

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