Conserving woodland birds:
the need for population data in evidence-based planning

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Declaration

This thesis is my own work, except where otherwise acknowledged

(see Preface and Acknowledgements).

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Preface

This thesis is structured as a series of connected papers that have been published or submitted for publication at the time of submission. These papers are listed below and are referred to by their roman numerals in the text.

I. Rayner L., Lindenmayer D.B., Gibbons P. & Manning A.D. (2014). Evaluating empirical evidence for decline in temperate woodland birds: A nationally threatened assemblage of species. *Biological Conservation*, 171, 145-155.

II. Rayner L., Gibbons P., Hutchinson, M. J., Lindenmayer D.B., Stein, J., Wood, J. & Manning A.D. (2014). The influence of weather on long-term population trends of birds in an endangered ecological community.

III. Rayner L., Lindenmayer D.B., Wood J.T., Gibbons P. & Manning A.D. (2014). Are protected areas maintaining bird diversity? *Ecography*, 37, 43-53.

IV. Rayner L., Evans, M. J., Gibbons P., Ikin K., Lindenmayer D.B. & Manning A.D. (2014). Avifauna and urban encroachment in time and space. *Diversity and Distributions*, 21, 428-440.

V. Rayner L., Gibbons P., Lindenmayer D.B. & Manning A.D. (2014). Conservation of temperate woodland birds: Lessons from long-term population monitoring and research.

All papers were intended as stand-alone pieces of work. For this reason, there is some repetition between chapters, for example in descriptions of the study area. In line with The Australian National University's College of Medicine, Biology and Environment guidelines for 'Thesis by Compilation', an Extended Context Statement has been provided at the beginning of this thesis. The Extended Context Statement is not intended to be a literature review, but rather a framework for understanding the links between research chapters.

I performed the majority of the work for the papers that form this thesis. This included data vetting and manipulation, statistical and spatial analyses, and writing. My supervisors, Adrian Manning, Philip Gibbons and David Lindenmayer, made substantial contributions to the conceptualisation of research and revision of manuscripts. The Canberra Ornithologist Group provided bird records that support my empirical research. Jeffrey Wood provided guidance on the use of regression splines and hierarchical generalised linear models in Papers II and III. Michael Hutchinson and John Stein assisted with the extraction of weather data in Paper II. Karen Ikin and Maldwyn Evans contributed to the conceptual development of ideas and assisted with functional trait analyses in Paper IV. The co-authors of each paper also provided comments during the revision of manuscripts.

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I am indebted to members of the Canberra Ornithologists Group whose passion and dedication over more than two decades is manifest in the incredible database that underpins this thesis. In particular, I thank Jenny Bounds for her fierce commitment to the Woodland Bird Monitoring Project and support of my research. I also thank Chris Davey, Niki Taws, Alison Rowell and Paul Fennell for valuable feedback and assistance. I am extremely grateful to Peter Milburn, Bruce Lindenmayer and Steve Holliday who shared with me their extraordinary bird wisdom, tolerated my 101 questions in the field, and helped connect me to the birds behind the numbers.

Thank you to the Fenner School of Environment and Society (The Australian National University) and the Environment and Planning Directorate (Australian Capital Territory Government) for financially supporting my research. My sincere thanks to the Fenner School Administration, HDR and IT teams - the unsung heroes – especially Cathy Gray, Diane Jakobasch, Kevin Mahoney, Amy Chen, Karl Nissen and Phil Greaves. In particular, I express my gratitude to the late Wendy Slater, who made the lives of Fenner HDR students so much easier and is sorely missed by many. Thanks also to Murray Evans, Margaret Kitchen and Richard Milner from the ACT Government for providing several opportunities to present my research to conservation managers and practitioners.

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Abstract

Arresting biodiversity loss is integral to protecting the intrinsic value of natural areas and the ecological services that are critical for human well-being. The important role that birds play in supporting a suite of ecosystem functions underpins the need to identify processes that drive long-term change in populations of this group. Indices of population change are frequently used to communicate important trend patterns for species. However, for such indices to assist the objectives of biological conservation and human development, a deeper understanding of the processes that drive population change is essential. Consequently, identifying factors that stress and pulse species populations has become a dominant theme in global conservation research.

Currently, there is concern for the persistence of birds throughout the temperate woodland regions of Australia. Native vegetation in these regions has been extensively cleared and modified since European settlement in the 1800's. Furthermore, ongoing threats to woodland extent and condition prevail, such as agricultural and urban expansion. In this thesis, I analyse an exemplary, volunteer-collected dataset to provide a detailed assessment of temperate woodland bird population trends over time, and the dominant factors influencing their persistence, in an important woodland region of Australia. My research shows that quantitative evidence for the decline of temperate woodland birds is limited, and that rigorous empirical research into the factors influencing woodland bird populations is needed to inform evidence-based conservation planning.

I identify significant temporal dependence in the response of woodland bird species, and functional trait groups, to three key regulatory factors: weather, reservation and urbanisation. My assessment and analysis of these factors incorporates 14 years of empirical field monitoring data, revealing important biological responses that would not be detected in short-term research. Specifically, I demonstrate that the temporal scale, and conditions experienced during the period of trend assessment, will exert a significant influence on the calculation of population indices and, in turn, the conservation implications inferred. I show that woodland bird species are resilient to severe drought. I reveal that the impact of protected areas and urban development on woodland birds are interactive, and can change through time. I provide empirical evidence that ecologically-informed reserve selection achieves better conservation outcomes for species, and that a previously untested metric of urban encroachment (rate of urban change) exerts a significant influence over species distributions in time and space.

These findings represent scientific evidence that can inform the planning of reserves, restoration activities, and ecological-sensitive urban design for birds occupying temperate woodland habitats. For this reason, I provide a synthesis of management implications and recommendations to enhance decision making for this threatened assemblage of species in Australia. In addition, the results presented in this thesis make an important contribution to the conservation science of managing declining populations. In particular, I present a novel tool for the evaluation of methods used in population trend assessment, as a means to improve future monitoring programs. In completing this work, I highlight the extraordinary contribution that citizen scientists can make, and have made, to conservation research.

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Extended context statement

Introduction

Few parts of the world are unaffected by biodiversity loss and the challenges associated with arresting species declines (Hoffman et al. 2010; WWF 2012; Dirzo et al. 2014). The growth of conservation biology as an applied discipline could be viewed as a response to the urgency of such challenges (Possingham & Shea 1999). However, with this growing field of research has come expansive debate on the accountability and defensibility of conservation investments for achieving true conservation progress (Ferraro & Pattanayak 2006; Svancara et al. 2005). Increasingly, authors have argued for improved systematic planning of conservation action (Possingham & Shea 1999; Margules & Pressey 2000; Brooks et al. 2004) and empirical assessment of conservation outcomes (Gaston et al. 2006, Taylor et al. 2011) to ensure timely and cost-effective biodiversity targets are met. It is now broadly acknowledged that future initiatives to conserve species populations should be evidence-based (Svancara et al. 2005).

Evidence-based conservation planning is urgently needed in areas subject to rapid land-use change (Jackson & Sax 2010). In particular, agricultural expansion and intensification represents the primary threat to terrestrial fauna populations (CBD 2010; Cunningham et al. 2013), and has been linked strongly to bird declines world-wide (BirdLife International 2013; Krebs et al. 1999; Ford et al. 2001; Newton 2004; Murphy 2003). Consequently, a diverse suite of conservation interventions, with significant associated costs, are undertaken to secure bird populations in these systems (Lindenmayer et al. 2012; McCarthy et al. 2012). The effectiveness of such interventions is crucially informed by monitoring national or continental biodiversity trends (Kleijn et al. 2011). However, it is a pervasive short-coming that adequate population monitoring data are not available for many species, and across many regions, where biodiversity is thought to be declining and conservation action is considered imperative (Collen et al. 2009; Mace et al. 2008).

One system where population data will be critical to effective conservation action is temperate woodland. Temperate woodland ecoregions are internationally-recognised as endangered due to high levels of land conversion and limited levels of formal protection (Hoekstra et al. 2005). This is certainly the case in Australia, where agricultural development is spatially concentrated in temperate zones, and has resulted in the loss of almost 90% of woodland vegetation (Lambert et al. 2000). This loss has had detrimental effects on associated biota (Lindenmayer et al. 2010), particularly birds (Robinson & Traill 1996; Reid 1999; Ford et al. 2001; Attwood et al. 2009), which are reported to be in national decline as a result (Recher 1999; Mac Nally et al. 2009; Ford 2011; Watson 2011). However, despite widespread concern, conservation research on this assemblage of species has rarely utilised long-term population monitoring data to examine factors affecting persistence. Indeed, Maron et al. (2005) found that Australian bird studies are typically conducted over a time period of less than 6 months.

There are a number of critical knowledge gaps in how to effectively conserve woodland bird populations that cannot be addressed with 'snapshot' studies (sensu Maron et al. 2005). This is because inter-annual variation in woodland bird populations is high (Mac Nally et al. 1996), making the extrapolation of short-term results to draw conclusions about long-term persistence potentially misleading (Maron et al. 2005; Porszt et al. 2012). In contrast, systematic monitoring data capture important information about population growth (trends) and fluctuation (variance). In turn, these data can assist the objectives of biological conservation by facilitating: (1) the calculation of long-term trend patterns to assess the likelihood of species persistence (Meir & Fagan 2000; Collen et al. 2009), (2) the identification of processes that pulse and stress populations (Siriwardena et al. 1998; Clavero & García-Berthou 2005; Potts et al. 2010; Rhodes et al. 2011), and (3) the evaluation of management interventions aimed to secure species persistence in perpetuity (Smith et al. 2005). Given the value of such outputs for evidence-based planning, the call has been made for further research on Australian temperate woodland birds utilising long-term population data (Reid 1999; Ford 2011). This thesis represents an important contribution toward that aim.

Overview of Aims

Previous studies have highlighted a lack of long-term population data used in research on Australian temperate woodland birds (e.g. Ford et al. 2001; Maron et al. 2005). However, a quantitative review of research on this assemblage of species is not available, despite numerous qualitative reviews and essays on their apparent decline (e.g. Robinson 1993; Robinson & Traill 1996; Recher 1999; Reid 1999; Ford et al. 2001; Ford 2011). In Paper I, I conducted an extensive systematic literature review to assess the growth, scope and rigour of studies investigating the conservation status of Australian temperate woodland birds. Specifically, I sought to consolidate the empirical evidence for decline in this assemblage of species. Further, there is a growing need to assess the inferential rigour of published population indices given their pertinence to evidence-based conservation policy and funding (Reading et al. 2010; Porszt et al. 2012). Therefore, as part of my review, I employ a novel scoring system to evaluate the inferential status of trend estimates reported in the literature for these species.

Based on the findings of my systematic review, the remainder of my thesis was designed to explore population dynamics in temperate woodland birds, and examine factors that are likely to influence their persistence over time. I selected three key regulatory factors for investigation: (1) weather, (2) reservation, and (3) urbanisation. These factors have been discussed previously in the literature with regard to the decline of woodland birds (Loyn & Menkhorst 2011), and their impacts measured in numerous short-term empirical studies (e.g. Mac Nally et al. 1996; Davis et al. 2013; Ikin et al. 2014). However, these three factors are expected to be temporally dynamic in their effects on species (Gaston et al. 2002; Maron et al. 2005). Thus, longitudinal data are vital for determining how these factors impact woodland bird populations over time, and whether those impacts are likely to assist or threaten long-term species persistence.

My investigation of these regulatory factors is presented as three empirical research papers (Papers II-IV) in this thesis. In Paper II, I investigate the influence of weather variability on the persistence of woodland birds in a modified landscape. I calculate population indices for 57 individual species, and quantify the effect of local- and broad-scale weather signals on species abundances through time, to determine if meteorological parameters explain significant long-term changes in population growth. Of particular interest to me was the effect of drought on population trends, as it has been suggested that droughts can interact with habitat loss to cause avifaunal collapse (Mac Nally et al. 2009). I took a novel approach in testing this effect on our study species, and examine closely the effect of sampling bias on the derivation of population estimates during- and post-drought.

Following the findings of Paper II, in Paper III, I examine the ecological effectiveness of a protected area network for maintaining woodland bird diversity. Studies that use long-term monitoring records to assess protected-area effectiveness are scarce (Gaston et al. 2006), meaning that the capacity for protected areas to ensure the persistence of species populations is poorly understood (Gaston et al. 2008). I explore differences in the conservation performance of reserves based on their period of enactment, and compare this to unprotected areas matched by key habitat attributes. I consider species functional trait responses, and reserve characteristics, in my evaluation of whether threatening processes are being abated or reduced for woodland birds in our study area.

Prompted by the findings of Paper III, in Paper IV, I investigate the effects of urbanisation on woodland birds occupying urban fringe habitats. Faunal communities occupying urban-adjacent habitats are assumed to change through time with ongoing development (Scott 1993). However, to date, this assumption has not been tested with empirical field monitoring data. I report individual species and trait-based responses to urbanisation over a period of marked change in urban growth, and determine whether the effects of encroachment are temporally dependent. That is, I test whether the rate of urban change had a distinct and significant effect on species inhabiting urban fringe ecosystems above that of spatial proximity alone.

In Paper V, I draw together the key findings of my empirical research and conclude with a synthesis of existing knowledge on long-term woodland bird responses to the three regulatory factors examined in this thesis. The chapter is intended as a management report that can be used by practitioners to improve conservation outcomes for birds dependent on temperate woodland habitats in Australia.

Methodology

All field monitoring sites used in my empirical papers were located in temperate woodland remnants of the Australian Capital Territory (ACT) in south-eastern Australia. Woodland remnants of the ACT are typically larger, more intact, and more adequately protected than woodlands found anywhere else in Australia (ACT 2004). However, all remnants have been perturbed by grazing, altered fire regimes and invasion by weeds and feral animals, reflecting substantial environmental modifications characteristic of this ecoregion. The type of temperate woodland found in the study region is box-gum grassy woodland, which is listed as critically endangered at the national level (ACT 2011).

All empirical research papers utilised a common longitudinal dataset of bird records, albeit with variable data abstractions depending on the specific aims of each paper. I sourced bird records from the Woodland Bird Monitoring Program undertaken by the Canberra Ornithologists Group. The program received professional statistical guidance during the design phase and throughout execution, ensuring a sound data collection framework. From the resulting database, I selected 92 permanent field sites, monitored between 1998 and 2012, that provided the highest temporal resolution of data for my empirical research. Sites were located in the sub-humid region of the ACT, on public and private land, on- and off-reserve, and at varying distances from urbanisation. Further details of the program, including survey effort, sampling protocol, specific site locations and related material, are provided in Papers II-IV.

I used a variety of statistical techniques for the analysis of species and spatial data in each paper. These techniques included Analysis of Variance (ANOVA; Underwood 1996), Generalised Linear Modelling (GLM; McCullagh & Nelder 1989), Hierarchical Generalised Linear Modelling (HGLM; Lee et al. 2006), Generalised Additive Modelling with regression splines (GAM; Wood & Augustin 2002), GROWEST Modelling (Nix 1981; Hutchinson et al. 2004); RLQ Analysis (Doledec et al. 1996) and Factorial Analysis on Mixed Data (FAMD; Husson et al. 2013). This required the use of two statistical packages, GENSTAT (VSN International; Payne 2009) and R (R Development Core Team; Venables & Smith 2010).

Summary of Outcomes

Paper I: Evaluating empirical evidence for decline in temperate woodland birds: A nationally threatened assemblage of species.

In Paper I, I revealed a paucity of research that can reliably detect population trends to draw conclusions about the persistence of woodland birds. I found that, while more than half of the reviewed articles acknowledged widespread declines in this assemblage of species, only 33 articles have directly measured change using population data. I found that the majority of these studies contained less than ten years of survey data and relied heavily on indirect or secondary data sources to derive trends, often with highly variable sampling protocols that were overlooked in the calculation of population indices. My novel scoring system, developed to assess the inferential rigour of population assessments, indicated that all currently available information on woodland bird population change is limited either by statistical methodology or the temporal coverage of population data. I demonstrated that population research on Australian temperate woodland birds is becoming more rigorous, however, strong long-term studies of change are rare.

Paper II: The influence of weather on long-term population trends of birds in an endangered ecological community.

In Paper II, I provided an up-to-date assessment of species population trajectories for woodland birds in the Australian Capital Territory, identifying five native species of immediate conservation concern. My analyses indicated highly variable, species-specific responses to modelled meteorological parameters. I identified the El Niño-Southern Oscillation as a strong influence on the regional abundances of 26 species, however there was no evidence to suggest that a severe drought threatened the long-term persistence of birds in our study system over the last 14 years. I concluded that trend patterns in woodland bird species can be strongly influenced by the length of, and climatic conditions associated with, the period of observation. In particular, I demonstrated bias toward the detection of declines where population data were collected during periods of declining or low rainfall.

Paper III: Are protected areas maintaining bird diversity?

In Paper III, I uncovered significant shortfalls in the conservation performance of multiple ACT reserves, and highlighted the value of off-reserve land for maintaining species persistence. I showed that species population trends differed between protected and unprotected areas, but also between protected areas established prior to and after fundamental changes to regional conservation policy that were made in 1995. I found that protected areas were less species rich than unprotected areas, with significant declines in species occurrence across sites protected prior to 1995. My investigation of trait relationships revealed that small, specialised and vulnerable species showed stronger associations with unprotected areas than protected areas. By examining the ecological attributes of reserves in this study system, I demonstrated that the conservation value of a protected area is strongly influenced by its physical characteristics and landscape context, and can diminish with changes in surrounding land use over time.

Paper IV: Avifauna and urban encroachment in time and space.

In Paper IV, I provided evidence that the response of species to urbanisation can change through time. I found that the occurrence of approximately half of the regions avifauna is strongly linked to the proximity of their habitat to urban fringe development. I classified species based on their response to urban proximity (as an *urban avoider* or *urban exploiter*) and identified life history traits characteristic of these groups. Importantly, I discovered that the rate of urban encroachment had a distinct effect on species occurrence over and above proximity alone, particularly during the construction of human infrastructure, and that the distance of these effects far exceeded those typically examined in urban gradient studies. I concluded that testing the response of species to urban change using long-term monitoring data provides critical insight into those taxa that are particularly vulnerable to urban-related disturbance.

Paper V: Conservation of temperate woodland birds: Lessons from long-term population monitoring and research.

In Paper V, I recommended management strategies to facilitate the persistence of temperate woodland birds in modified landscapes. These strategies are based on the key findings of my empirical chapters and other published long-term research. Management recommendations included: the collection of more detailed species movement data, enhanced protection of urban fringe habitats, increased conservation effort in productive landscapes with low urban land cover, and further investigation into the benefits of ecologically-sensitive urban design for woodland bird persistence. I highlighted new long-term evidence that confirms and challenges some key paradigms on how three globally relevant regulatory factors (i.e. weather, reservation, urbanisation) influence species population dynamics. In doing so, I have demonstrated the value of long-term empirical monitoring data for informing evidence-based conservation planning.

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I. Evaluating empirical evidence for decline in temperate woodland birds: A nationally threatened assemblage of species.

Despite numerous qualitative reviews and essays on the decline of Australian temperate woodland birds, a quantitative review of population research is not available. In this paper, I conducted an extensive systematic literature review to assess the growth, scope and rigour of studies investigating the conservation status of Australian temperate woodland birds. In doing so, I consolidate the empirical evidence for decline in this assemblage of species.

Rayner L., Lindenmayer D.B., Gibbons P. & Manning A.D. (2014) Evaluating empirical evidence for decline in temperate woodland birds: A nationally threatened assemblage of species. *Biological Conservation*, 171, 145-155

Abstract

Quantifying the population trends of species is crucial to achieving effective conservation action. However, deriving accurate and reliable indices of change is difficult due to the paucity and complexity of population data. There is a growing need to assess the inferential status of reported trend estimates given their pertinence to evidence-based conservation policy and funding. In this review, we used a simple scoring system to assess the rigour of population assessments using Australian temperate woodland birds as a case study. These birds are widely considered to be in severe and ongoing decline at a national scale. However, we found relatively few studies that report population trends for woodland birds in the existing conservation literature (44 articles, 9% of total) and only 33 articles (7% of total) that actually attempt to measure change using population data. While we identified strong signs that the inferential status of population research on temperate woodland birds is improving, we detected serious limitations in the temporal coverage and statistical analysis of population data used in the majority (80%) of trend assessments, compromising any long-term inference about population persistence. Despite these limitations, the decline of woodland birds is referenced in over half of all Australian woodland bird conservation studies (53%), with most of the information on woodland bird status (49% of citations) sourced from relatively few, predominantly qualitative, studies of change. The paucity of research that can reliably detect trends to draw conclusions about species persistence is a concerning issue for conservation practitioners and policy makers.

Introduction

Reducing rates of biodiversity loss relies heavily on our ability to track population trends (Collen et al. 2009). In particular, the detection of unwanted trends (e.g. native declines, invasive increases) is necessary for the diagnosis of ecosystems and species at risk (Meir and Fagan 2000), and can provide insight to the processes threatening biodiversity (Rhodes et al. 2011). Furthermore, quantifying population change in response to conservation interventions can enhance the adaptive capacity of management (Smith et al. 2005). Thus, monitoring population trends can make a significant contribution to the development of effective conservation (Lindenmayer and Likens 2010b).

In practice, quantifying trends of species' populations is fraught with challenges. Most prominent is a widespread lack of continuous, long-term survey data (Jenkins et al. 2003; Lindenmayer and Likens 2010a; Wilson et al. 2011). It is a pervasive short-coming that adequate population data are often not available for many species, and across many regions, where biodiversity is thought to be declining and conservation action is considered imperative (Collen et al. 2009; Mace et al. 2008). In an attempt to compensate for incomplete population data, studies often rely on historical records as evidence of change through time. While such studies frequently report interesting and informative differences, the conditions under which past and contemporary records were collected can vary (Holmes 2001). This is important because identifying sources of variability in population data is crucial for making sound inferences about species population growth (McNamara and Harding 2004).

Even where systematic and continuous population data are available, eliciting robust indices of change is not a trivial exercise. This is because population data are complex (Clark and Bjornstad 2004), with inherent variability presenting both a source of interest and error in analysis (McNamara and Harding 2004). For example, observed changes in year-to-year population size can be driven by unmeasured environmental factors (Amano et al. 2012; De Valpine 2003; Freckleton et al. 2006) or by statistical issues caused by sampling bias or error (Freckleton et al. 2006; Meir and Fagan 2000). Failing to account for either is likely to compromise the accuracy and reliability of long-term trend indices (McNamara and Harding

2004; Wilson et al. 2011). Indeed, some authors have explicitly demonstrated how failing to account for variation in population data can lead to tenuous, if not misleading, estimates of population change (e.g. Alford et al. 2001; Lonergan and Harwood 2003; Shapiro and Swain 1983).

Given these challenges, reviews of the empirical evidence behind documented trends in biota have proven useful for pinpointing the type and scope of data that limits understanding of species decline (e.g. Porszt et al. 2012; Reading et al. 2010). In this review, we examine the strength of inference that can be drawn from assessments of population decline in Australian temperate woodland birds. These birds are reported to be in severe (Mac Nally et al. 2009; Watson 2011), widespread (Recher 1999) and ongoing (Ford 2011) decline at a national scale, due primarily to extensive modification of their native habitat (Hobbs and Yates 2000). However, woodland birds are often highly mobile and exhibit large natural fluctuations in their abundances through space and time (Fleming 1992; Lindenmayer and Cunningham 2011; Mac Nally 1996; Manning et al. 2007). Given these factors, it is especially difficult to disentangle changes in population size driven by habitat alteration from those driven by environmental and demographic stochasticity (Emlen et al. 2003). This makes woodland birds an excellent case study for reviewing the issues associated with the quantification of long-term population trends. However, to date, a quantitative review approach has not been applied to the issue of Australian woodland bird conservation, despite numerous qualitative reviews and essays on their decline (e.g. Ford 2011; Ford et al. 2001; Recher 1999; Reid 1999; Robinson 1993; Robinson and Traill 1996).

Using this nationally threatened assemblage of species, we provide a quantitative approach for assessing the growth, scope and rigour of studies investigating decline. To establish the context for inference, we began our review by asking: (1) How pervasive has the acceptance of decline been in the ecological literature? And, (2) From where has the established knowledge of decline been derived? We then critically reviewed studies that directly investigate population change. Specifically, we asked: (3) What was the spatial coverage of population studies? (4) What was the temporal coverage of population studies? And, given the inherent variability of population data, (5) What proportion of studies allowed for rigorous inference about population decline? While our focus for this review is on Australian temperate woodland birds, our quantitative approach may be applied to any nation that seeks to define and counter species population declines, particularly in modified landscapes.

Background: Global bird declines and Australia's temperate woodlands

Tracking biodiversity loss is particularly important in areas subject to land-use change. The primary threat to terrestrial fauna populations is agricultural expansion and intensification (CBD 2010), which has been linked specifically to bird declines world-wide (BirdLife International 2013; Ford et al. 2001; Krebs et al. 1999; Newton 2004; Murphy 2003). Consequently, a diverse suite of conservation interventions, with significant associated costs, are undertaken to secure bird populations in these systems (Lindenmayer et al. 2012, McCarthy et al. 2012). The effectiveness of such interventions is crucially informed by monitoring national or continental biodiversity trends (Kleijn et al. 2011).

In Australia, land-use change has been particularly severe in temperate regions of the continent. Almost 90% of Australia's temperate woodlands have been cleared for agricultural development (Lambert et al. 2000). This has resulted in a loss of approximately 500,000 km^2 of native vegetation (Yates and Hobbs 1997); an area twice the size of the UK and larger than the state of California, USA. Disproportionately high rates of clearing (Fig. 1), coupled with poor representation in formally protected areas (Yates and Hobbs 2000), make ongoing threats to temperate woodland extent and condition a serious conservation concern (Lindenmayer et al. 2010a). Persisting woodland remnants in Australia now make a significant contribution to the global extent of this biome (Hoekstra et al. 2005). Thus, Australian temperate woodlands and associated biota are of global conservation significance.

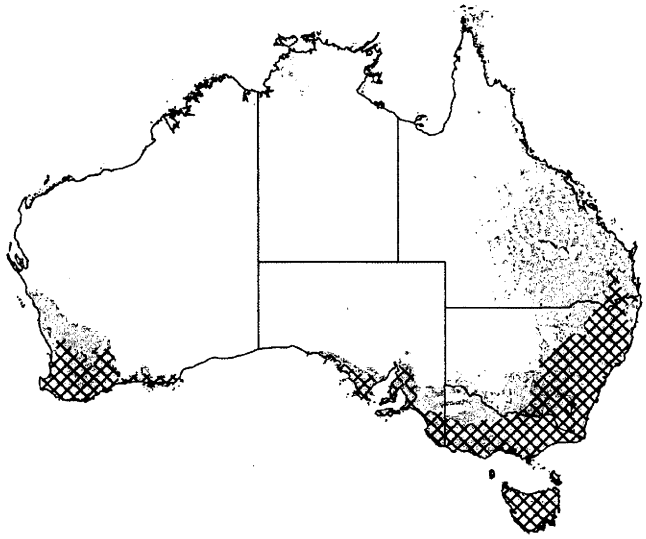

Figure 1. Clearing of native vegetation in Australia (shaded grey, NLWRA 2000) corresponds with the Australian temperate zone (cross-hatched, Stern et al. 2000).

Methods

Literature search

Our literature search was designed to capture all articles relevant to the conservation of woodland birds in Australia. We searched the scientific literature using three major electronic databases: Web of Science, CAB Abstracts and Zoological Record Plus (1945-2012, cut-off date Dec 30, 2012). We retrieved articles by screening the article topic (keywords or abstract) using the following automated search string: Australia* AND woodland* AND (bird* OR avifauna*) AND (conserv* OR declin* OR extinct*). Duplicates (n = 264) and references with indexing errors (n = 7) were removed, leaving 596 original articles (Fig. 2). We confirmed the relevance of these articles by manually screening the title and abstract. Articles that predominantly focussed on other taxa (e.g. mammals, n = 41), features (e.g. mistletoe, n = 29), biomes (e.g. rainforest, n = 50), countries (e.g. Britain, n = 7) or disciplines (e.g. statistics, n = 22) were excluded from the review, bringing the total number of articles to 447.

Data extraction

For these 447 articles, our review proceeded in two distinct phases. In Phase 1, we read all articles in full to determine which studies made reference to pre-existing woodland bird decline. During this process, we added 23 articles to the review that were found opportunistically or were highly cited among articles retrieved by the search string. A number of these articles were unpublished and sourced from "grey" literature, although an extensive review of that literature was not undertaken. This brought the total number of articles in Phase 1 of the review to 470 (Fig. 2). We extracted qualitative data from these papers to assess the prevalence of, and sources of information underpinning, statements acknowledging Australian woodland bird decline (research questions 1 and 2).

In Phase 2 of the review, we targeted articles that directly investigated changes in temperate woodland bird populations. We considered only those conducted in the temperate zone of Australia (Stern et al. 2000, Fig. 1) because these have been the woodlands and birds of greatest conservation concern (Watson 2011). Based on our reading in Phase 1, we identified 82 articles that satisfied this requirement. We refined this group of articles by excluding studies that: (1) reported only predictive trends based on short-term survey data or indirect measures of species abundance (e.g. expected abundance for a given value of vegetation cover, n = 15), (2) reported trends immediately following a disturbance event or substantial habitat manipulation thereby confounding long-term trend estimates (n = 13), or (3) contained only anecdotal data with no further supporting information (n = 2). Where multiple articles published results from the same dataset, we included only the most comprehensive study in the review (n = 8 articles excluded). We used the remaining articles (hereafter "*population studies*", n = 44) to examine the spatial and temporal coverage of trend assessments, as well as the strength of inference associated with reported population indices (research questions 3, 4 and 5; Fig. 2). Citations for the 470 articles included in this review are provided in Appendix A. Full references for the 44 population studies are provided in Appendix B.

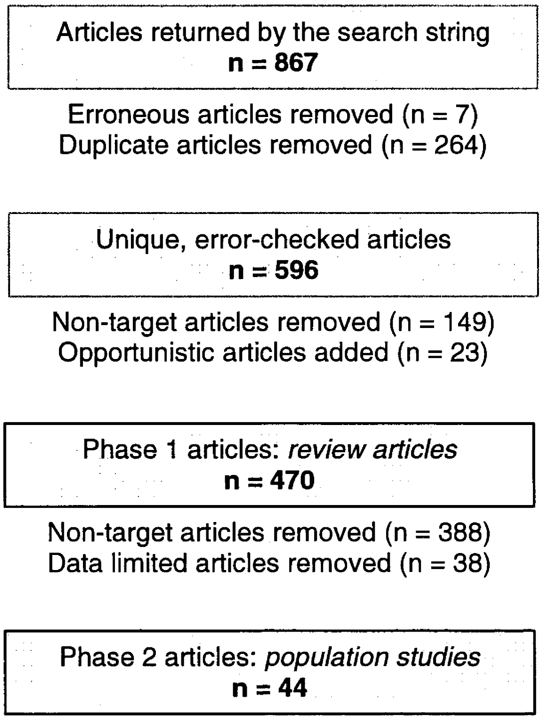

Figure 2. Flowchart illustrating the search protocol undertaken for this review.

Addressing research questions

How prevalent has the acceptance of woodland bird decline been in the literature?

We reported the number of studies that referenced a pre-existing decline in woodland bird populations as a proportion of all studies relevant to woodland bird conservation (n = 470). We used logistic regression (Generalized Linear Models with a logit link, McCullagh and Nelder 1989) to determine whether this proportion had significantly changed over time. When interpreting the results of this analysis, readers should be aware that observations were assumed to be independent despite a number of authors occurring on multiple studies. Therefore, results offer a simple measure of the prevalence of decline statements irrespective of their source or validity. We also reported the proportion of articles that indicated woodland bird decline as a motivation for their study aims, or utilised pre-existing classifications of declining species in their analyses.

From where has our knowledge of decline been derived?

From each review article, we recorded all instances where a paper was cited as providing evidence of woodland bird decline, for example, "*Many species of woodland birds have declined in numbers across southern Australia in recent decades (Ford et al. 2001)*" in Lollback et al. (2010). Not all references to population decline provided a citation but, where available, we tallied citations to provide a quantitative overview of articles that make the strongest contribution to our knowledge of woodland bird decline. Most often, there were multiple citations within a given article, such that the total number of tallied decline citations outnumbered the total number of articles that we reviewed.

What was the spatial coverage of population studies?

To provide an overview of the areas where woodland bird populations have been assessed, we noted the scale of research and mapped the survey locations of each population study that contained spatial references (mapping excluded reviews and state-wide or national assessments). Scale was defined as either: *Local* (< $1km^2$), *Landscape* ($1\text{-}100km^2$), *Regional* (multiple landscapes), or *Continental* (i.e. Australia-wide) following Fazey et al. (2005), and the boundary of survey data was estimated from site descriptions and coordinates (where available). We mapped survey locations against the distribution of cleared and remnant woodland vegetation (NLWRA 2000) to provide a crude depiction of habitat loss among studies and throughout the temperate woodland zone.

What was the temporal coverage of population studies?

From each population study, we extracted data on the temporal coverage of trend assessments. Where possible, we retrieved two values: (1) the time-span of the population dataset, from first population record to last, from which population trends have been derived (hereafter "*period of inference*") and (2) the number of years in which population survey data were actually collected (hereafter "*observation years*"). For each study, we calculated the number of observation years as a proportion of the period of inference.

What proportion of studies allowed for rigorous inference on bird decline?

We assigned each population study a score reflecting the inferential status of population trends reported by the study (hereafter "*inference score*"). Inference scores (0-15) were based on a proforma developed specifically for this review (Appendix C), but were informed by similar approaches in the conservation literature (e.g. Pullin and Knight 2003, Felton et al. 2010, Sato et al. 2013). Our proforma considers a set of simple, headline sources of variability known to influence the reliability and accuracy of long-term population indices (Meir and Fagan 2000; Szabo et al. 2012; Wilson 2011). These included: (1) type of trend assessment, (2) source of data, (3) generality of results, (4) temporal coverage, (5) statistical approach, and (6) confounding effects of weather (see Appendix C for full details of the proforma, including subject relevance and weighting). Articles with higher inference scores have controlled for more sources of uncertainty in trend estimates and, therefore, provide stronger inference of population change. To assist the interpretation of results, inference scores were summarised as "*casual*" (score 0-4), "*moderate*" (score 6-10) or "*rigorous*" (score 11-15).

It is important to note that inference scores only applied to the component of each study that examined long-term population trends. Not all articles classed as "population studies" in this review were designed to provide rigorous inference about long-term trends. Indeed, a number of these population studies provided information about long-term trend patterns as part of broader, or more directed, ecological questions. Our approach in this review has been to collect, to the best of our ability, all available information on woodland bird population trends to examine the empirical evidence for decline. Therefore, studies classified as "rigorous" in this review refer only to the rigour of population data and derived indices, and not to the study as a whole. Likewise, studies classified as "casual" in this review provide only weak inference of population change, but may be rigorous in addressing their specific study objectives.

In addition to summarising the results of our proforma, we used simple linear regression to assess whether inference scores (response variable) have changed over time. We also examined the relationship between inference scores and citation rates using Poisson regression (Generalized Linear Models with a logarithmic link, McCullagh and Nelder 1989) with citation rate and year as fixed effects.

Results

Our systematic review yielded 470 articles that were directly relevant to the conservation of Australian woodland birds. Articles were retrieved from a variety of sources, including science journals, books, technical reports and conference proceedings. The majority of articles came from peer-reviewed sources (93%), with large contributions from *Biological Conservation* (10%), *Emu* (8%), *Pacific Conservation Biology* (8%) and *Wildlife Research* (6%). However, *Wingspan* magazine (not peer-reviewed) also made a substantial contribution (4%). Population studies (n = 44) were identified from 20 sources, the majority being peer-reviewed (82%), with *Biological Conservation* contributing most studies (14%).

How prevalent has the acceptance of woodland bird decline been in the literature?

Reports of woodland bird decline have been made for over 50 years, with a number of unpublished, anecdotal reports documenting the local extirpation of species from wooded areas over time (e.g. Barnard 1925). However, serious concern for widespread population declines did not enter the ecological literature until the 1990s. Since then, the number of articles relevant to Australian woodland bird conservation has increased dramatically (Fig. 3a). Of the articles retrieved by our literature search, 96% have been released since 1990 (n = 456), 78% since 2000 (n = 341), and over half have been released since 2003 (56%, n = 266).

Of the 470 articles reviewed, 251 articles (53%) made a direct reference to pre-existing woodland bird decline. There has been an increase in the number of these articles over time with 98% published since 1990 (n = 247), 76% since 2000 (n = 191) and 60% since 2003 (n = 155, Fig. 3a). The proportion of all articles referencing decline has also increased over time (Wald = 13.87, $p < 0.001$, Fig. 3b) although this relationship was variable ($R^2 = 2.46$). We found that almost one quarter (22%) of all woodland bird studies cited population decline as a key driver of research, over half of which were published in the last decade. A further 34 articles have investigated the ecology of bird species identified as "decliners" in previous research. These results indicate that woodland bird decline is widely accepted in the conservation literature.

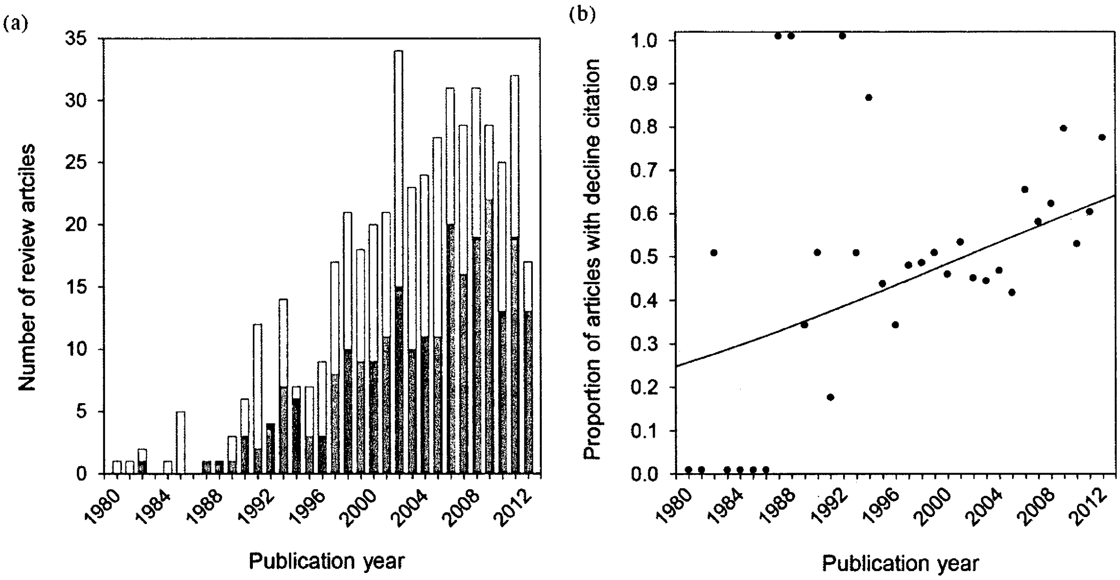

Figure 3. (a) The number of Australian woodland bird conservation articles that acknowledge (filled bars) or do not acknowledge (empty bars) pre-existing species declines with the corresponding year of publication. (b) The proportion of articles acknowledging woodland bird decline over time (black line) with 95% confidence intervals (shaded grey).

From where has our knowledge of decline been derived?

For each of the 470 articles reviewed, we recorded all references that were cited for providing evidence of woodland bird decline. From a total of 627 citations, we identified 195 independent references used to support population decline. The majority of these references (n = 137, 70%) were cited only once by a single study, accounting for less than one quarter (22%) of all citations. Eleven references were the source of almost half of all decline citations in the literature (49%, Table 1). Of these 11 references, only five utilise primary population data (usually in combination with secondary data sources) in trend assessments and only two of these studies assesse trends quantitatively. Three of the top 11 references, comprising 16% of all citations, are not peer-reviewed.

Table 1. Eleven references accounting for 49% (n = 309) of all decline citations. Full references for listed articles are provided in Appendix B.

Reference	**Study type**	**No. citations**	**% citations (cumulative)**	**Primary data?**	**Peer-review?**
Ford et al. 2001	Review	54	8.61 (8.61)	No	Yes
Reid 1999	Synthesis	53	8.45 (17.07)	Yes	No
Robinson and Traill 1996	Review	33	5.26 (22.33)	No	No
Barrett et al. 1994	Synthesis	27	4.31 (26.63)	Yes	Yes
Garnett and Crowley 2000	Action Plan	26	4.15 (30.78)	No	Yes
Recher 1999	Essay	26	4.15 (34.93)	No	Yes
Saunders 1989	Synthesis	22	3.51 (38.44)	Yes	Yes
Saunders and Ingram 1995	Bird Atlas	19	3.03 (41.47)	Yes	Yes
Barrett et al. 2003	Bird Atlas	17	2.71 (44.18)	Yes	Yes
Garnett 1992	Report	16	2.55 (46.73)	No	Yes
Robinson 1993	Essay	16	2.55 (49.28)	No	No

What was the spatial coverage of population studies?

Of the 44 population studies in our review, 33 provide details on the source of primary population data and 26 clearly define survey locations to allow mapping (Fig. 4). The number of studies conducted in each Australian state was roughly proportional to the amount of temperate woodland vegetation remaining within that state (Fig. 4). New South Wales (NSW), Victoria and Western Australia contributed 11, 9 and 6 studies respectively, while Queensland (QLD) and South Australia each provided two studies and the Australian Capital Territory provided one. Two studies took place across state borders. One of which, The New Atlas of Australian Birds (Barrett et al. 2003), examined population trends at the continental-scale and, therefore, includes temperate woodland, but is not specific to it. The majority of population studies were conducted at the regional scale (n = 20), with nine landscape-scale studies and only three local-scale studies (Appendix B). Most studies occurred predominantly in temperate eucalypt woodland vegetation; however, 11 studies included considerable samples of open forest and other woodland complexes (e.g. *Casuarina* spp., *Callitris* spp., *Acacia* spp.). All articles indicated that the region of study had been disturbed by clearing or the modification of bird habitat.

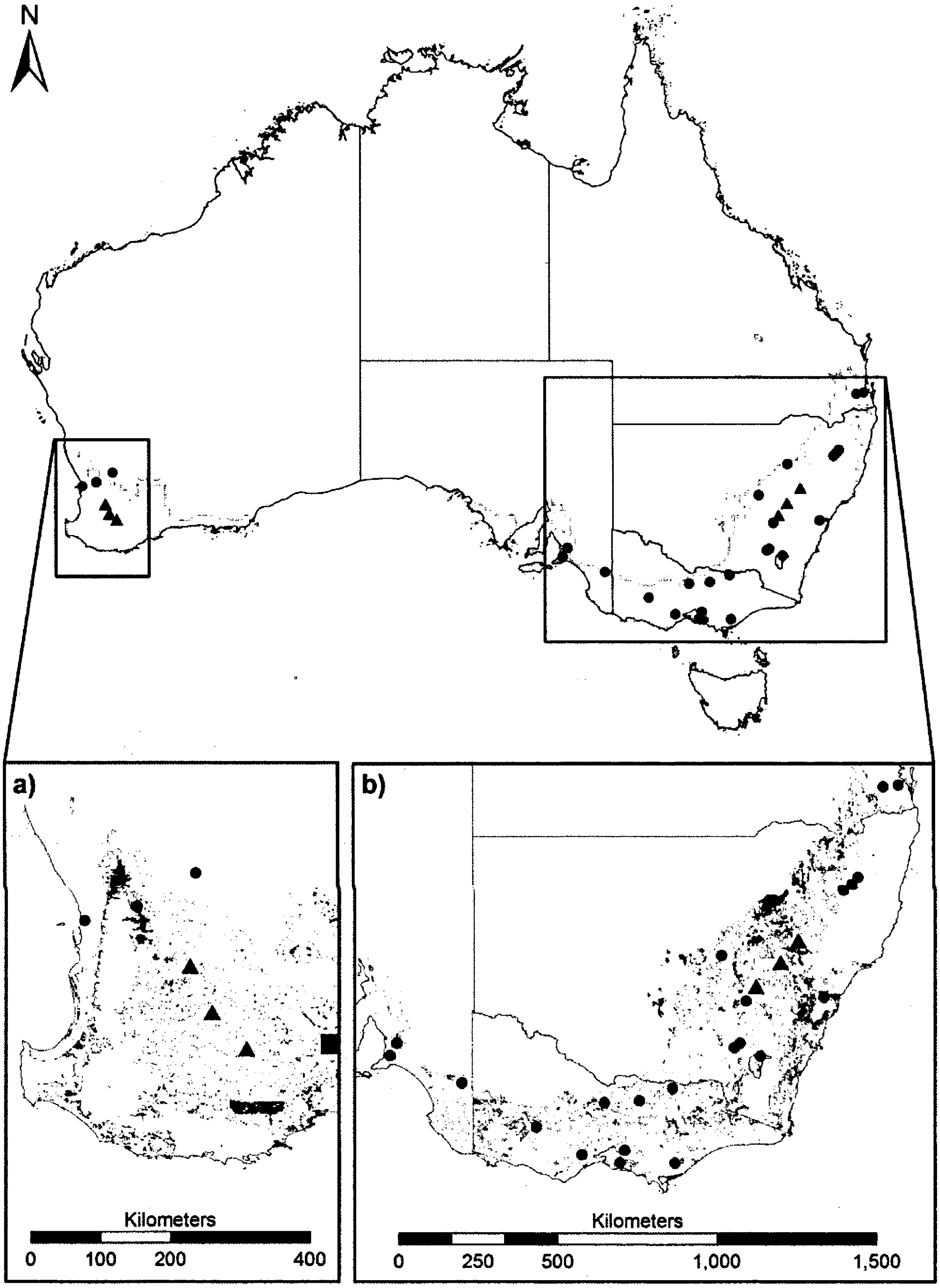

Figure 4. Location of 26 population studies (circles) occurring within the temperate zone of Australia (shaded grey). Survey locations are mapped for (a) south-western and (b) south-eastern Australia separately and illustrate the distribution of woodland vegetation prior to European settlement (light grey) and after clearing (dark grey) (NLWRA 2000). The general location of further 6 studies are shown (triangles), however these studies contain atlas data consisting of patchy sites with a much broader study region than is indicated.

What was the temporal coverage of population studies?

Of the 44 population studies in our review, 33 provided sufficient information about the temporal collection of survey data to assess coverage. The period of inference for reported trends could be retrieved for all 33 studies, however, the number of observation years had to be estimated for a third of population studies (n = 11, Appendix B). The period of inference varied substantially across population studies, ranging from 5 to 162 years, with a median of 25 years (substantially less than the mean: 38.4 years, Fig. 5). The number of observation years was less variable, ranging from 2 to 27 years, with a median of 8 years (nearing the mean: 9.3 years, Fig. 5). For the majority of population studies (n = 21), surveys occurred in less than half of the years from which trends were estimated. Ten studies reported population trends based on data collected from ten or more observation years, and five studies surveyed every year of the period of inference (Fig. 5).

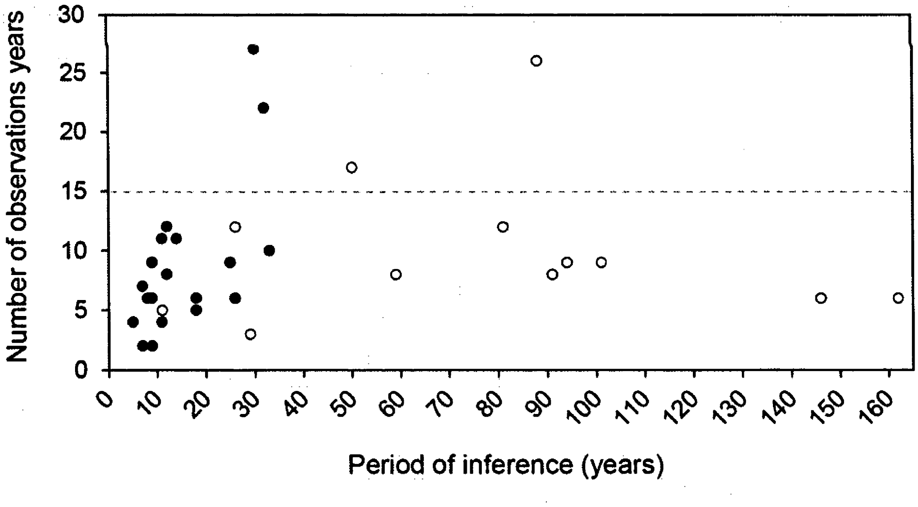

Figure 5. Interaction between the period of inference and the number of observation years for each study (circles). Filled circles represent studies where the number of observation years was clearly reported, empty circles represent studies where the number of observation years had to be estimated. The dashed line represents the approximate number of observation years required to elicit reliable trend estimates given by examples from the statistical literature (Holmes 2001; Hovestadt and Nowicki 2008; Swanson 1998).

What proportion of population studies allowed for rigorous inference of bird decline?

Inference scores ranged from 2 to 14 with a median of 6 (Appendix B), indicating that most assessments of population change (n = 22) provide moderate inference (score 5-10) about the long-term trends of woodland birds. Studies providing casual inference (score 0-4, n = 13) were typically reviews or essays (n = 11) that did not measure change directly using population data. Studies providing casual inference were characterised by: purely qualitative assessments of population change (e.g. a species is classed as less or more common), predominant use of secondary or anecdotal data, poorly- or un-defined temporal coverage, and the absence of any formal analysis (Table 2). At the other end of the scale, studies providing rigorous inference (score 11-15, n = 9) were characterised by quantitative assessments of population change (e.g. occurrence declined/increased by X percent), predominant use of primary data, a shorter period of inference (mean = 12 years) with a higher proportion of years surveyed (mean = 9 years), and formal analysis of data collected using systematic and structured survey protocols (Table 2). Rigorous studies typically examined trends during the period 1990-2010, four of which used volunteer-collected data.

Most population studies (79.5%) used indirect data sources (e.g. anecdotal records, historical bird lists, previously published surveys, atlas records) in assessments of population change. Population studies typically examined whole species assemblages, but five focussed on individual species, including the Brown Treecreeper (*Climacteris picumnus*), Carnaby's Cockatoo (*Calyptorhynchus funereus latirostris*), Grey-crowned Babbler (*Pomatostomus temporalis*) and Hooded Robin (*Melanodryas cucullata*). Roughly half of studies (47.7%) drew attention to the confounding effects of weather on reported population trends, however, only two studies attempted to examine these effects quantitatively (Table 2).

Table 2. Summary of inference scores for all studies combined, as well as for each inference class (*casual*, *moderate*, *rigorous*) separately. Tabulated values indicate the number of studies associated with each measure of inferential status. The weighting assigned to each measure, and used to calculate the inference score for each individual study, is presented in Appendix C.

	Casual **Score 0-4** **n = 13**	***Moderate*** **Score 6-10** **n = 22**	***Rigorous*** **Score 11-15** **n = 9**	**All studies** **Score 0-15** **n = 44**
Trend reporting				
Qualitative assessment	13	12	0	25
Quantitative assessment	0	10	9	19
Data source(s)				
Anecdotal	5	10	0	15
Secondary	12	11	2	25
Indirect primary/Primary	2	16	5	23
Primary only	0	6	4	10
Generality				
Single species	1	4	0	5
Species group	1	0	0	1
All species	11	18	9	38
Temporal coverage				
P.O.I. sampled < 0.5	13	18	1	21
P.O.I. sampled 0.5 - 0.8	0	3	3	6
P.O.I. sampled > 0.8	0	1	5	6
Observation years > 5	1	16	9	26
Observation years > 10	0	6	3	9
Study design				
Replicate sites	2	19	9	30
Repeat visits	1	16	9	26
Consistent method	0	3	8	11
Consistent effort	0	3	1	4
Data analysis				
Formal analysis	0	5	9	14
Measurement error	0	2	7	9
Weather				
Not considered	9	13	1	23
Qualitative assessment	4	8	7	19
Quantitative assessment	0	1	1	2

P.O.I. = period of inference

When considering each population study independently, we found a significant positive relationship between a study's inference score and the year of publication, indicating that population assessments are becoming more rigorous over time (Wald = 19.48, $p < 0.001$, $R^2 =$ 31.69, Fig. 6). When we examined the citation rates of each population study, we found a weak negative relationship between a study's inference score and the number of times that study had been cited (Wald = 5.50, p = 0.024, $R^2 = 13.08$). However, this relationship was not significant (Wald = 2.80, p = 0.102, $R^2 = 14.88$, Fig. 7) once the year of publication was included in the model (i.e. older publications have had more time to be cited).

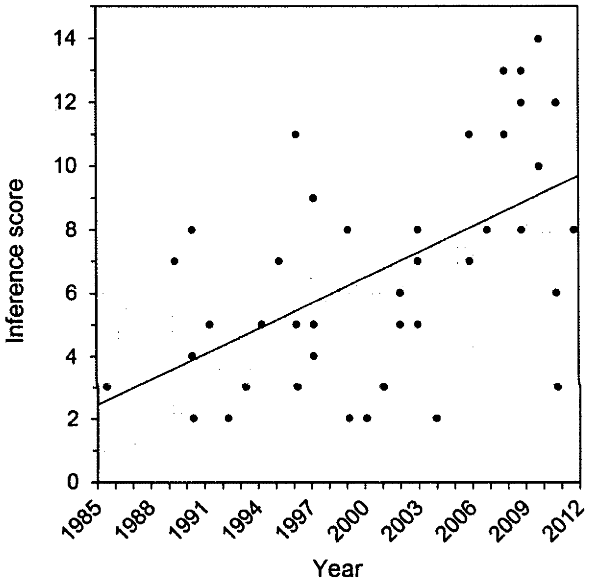

Figure 6. Results of linear regression showing significant increase in inference score over time (black line) with 95% confidence intervals (grey shading) for the 44 population studies examined.

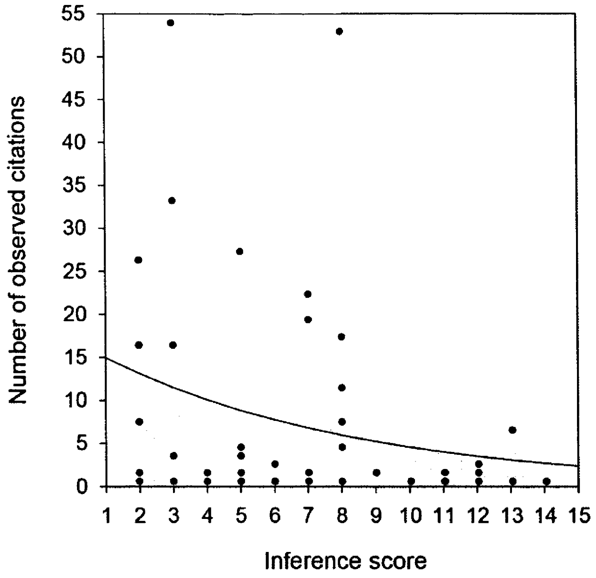

Figure 7. Results of Poisson regression showing a decline in citation rate with increasing inference score (black line) with 95% confidence intervals (grey shading) for the 44 population studies examined. The decline was not significant when the year of publication was included in the model.

Discussion

The results of our review indicate that, despite growing interest and widespread concern for the conservation of Australian woodland birds (as indicated by the increasing literature), relatively few rigorous, quantitative assessments of population change exist. Of the 470 articles that we reviewed, 44 report change in the population size of woodland bird species, of which only nine were able to provide rigorous inference about the trends they report. The spatial coverage of research was generally balanced across the distribution of remaining temperate woodland, with all studies representing typical woodland habitat in heavily degraded condition. The majority of studies (80%) contained less than ten years of survey data and relied heavily on indirect or secondary data sources to derive trends, often with highly variable sampling protocols that were overlooked in the calculation of population indices. Despite these limitations, the decline of woodland birds is referenced in over half of all Australian woodland bird conservation studies. Given the paucity of strong quantitative population research available from the empirical literature, it is unsurprising that the majority of cited information on woodland bird status (49% of citations) is sourced from reviews and syntheses of predominantly qualitative, short-term studies of change.

Challenges for woodland bird population research

Maintaining and improving spatio-temporal data quality

Understanding the dynamics of Australian woodland bird populations is made challenging simply by a limited capacity to adequately survey woodland areas across the range of many species. For example, the current Breeding Bird Atlas compiled by the British Trust for Ornithology has attracted over 17 000 online atlasers, providing comprehensive spatial coverage across Great Britain and Ireland (http://www.bto.org/volunteer-surveys/birdatlas/results). In Australia, the most recent national bird atlas, The New Atlas of Australian Birds (Barrett et al. 2003), represents a geographical area more than ten times the size of Great Britain and Ireland, but with less than half the number of atlasers (~7000). Even with such a concentrated mass effort, the spatial coverage of bird atlas records in Australia are typically biased toward coastal regions with high human population densities (Barrett et al. 2003). Our review showed that, while the spread of population studies is relatively balanced across the distribution of remaining temperate woodland vegetation, a number of population studies relied on secondary data sources to provide more spatially comprehensive estimates of population change (e.g. Barrett et al. 2007; Paton et al. 1994; Saunders and Ingram 1995).

More typically though, secondary data sources were utilised to compensate for poor temporal coverage in population data: a key resource gap encumbering the conservation of biodiversity all over the world (MEA 2005). But despite the contribution of secondary data, the majority of population studies evaluated in this review contained fewer than ten years of survey data. A number of authors argue that population data need to be a time series of 15-20 years before reliable estimates of population change can be inferred (Holmes 2001; Hovestadt and Nowicki 2008; Swanson 1998). This is because short-term datasets can underestimate long-term population variance (McNamara and Harding 2004), which is particularly relevant in countries such as Australia where marked variation in climate occur over long periods (discussed further below). This is particularly pertinent to trends derived from datasets where survey years are sparse (as was the case for many of the studies reviewed, Fig. 5,Table 2). Therefore, it would be unwise to assume that studies will provide stronger inference of population change simply because the period of inference is longer (Reside et al. 2011).

The heavy reliance on secondary data sources for both spatial and temporal coverage has its consequences for inference. Measurement errors, which stem from ignoring variation in sampling methods and effort, are more likely to occur in studies that combine multiple datasets collected by different individuals across space and time. Such errors have been shown to generate false patterns of annual variation in long-term datasets, compromising estimates of annual population growth (Freckleton et al. 2006; Hovestadt and Nowicki 2008; McNamara and Harding 2004). Inference scores calculated for this review considered efforts to control for measurement error, both in study design and statistical analysis, and revealed that only nine studies specifically addressed this issue (Table 2). This finding supports arguments from the broader literature that more attention should be paid to the effects of measurement error (Freckleton et al. 2006).

Challenges stemming from the use of secondary data sources do not mandate that such data are unsuitable for trend analysis (Jenkins et al. 2003, Szabo et al. 2012). In fact, formal analyses of community volunteer-collected bird records contributed three of the four most rigorous population studies identified in this review (Bounds et al. 2010; Reid and Cunningham 2008; Szabo et al. 2011).This demonstrates that secondary data have the potential to generate robust population estimates provided that features of the data, particularly its limitations and biases, are carefully considered in analysis (Szabo et al. 2012). It also highlights the importance of statistically-designed, long-term monitoring approaches (whether driven by research institutes or the motivated public) for detecting unwanted trends in biodiversity. Thus, it is of paramount importance that established monitoring programs are given adequate resources to continue to build long-term datasets (Lindenmayer and Likens 2010a).

Quantifying meteorological influences

The Australian climate is highly variable (McKeon 2006). In particular, rainfall exhibits very large interannual variability due to mechanisms associated with the El Niño-Southern Oscillation (Nicholls 1991; Nicholls et al. 1997). Numerous authors claim that such variability can influence the size and distribution of bird populations, particularly in response to drought conditions (Bennett and Ford 1997; Manning et al. 2007; Reid 1999; Reid 2000; Robinson 1993; Szabo et al. 2011; Woinarski and Catterall 2004). Furthermore, weather variability influences the availability of key avifaunal resources, for example food such as arthropods (Bell 1985) and nectar (Ford 1991). Many Australian birds are highly mobile and their movements are linked to areas where resources are optimal or more abundant (McGoldrick and Mac Nally 1998; Reid and Cunningham 2008; Schodde 1982), making their annual and seasonal abundances at a given location highly variable (Fleming 1992; Mac Nally 1996) and their total population size at any one point in time difficult to judge.

Since 1990, southeastern Australia has suffered the effects of two severe droughts, including one of the longest and most severe droughts on record (1991-1995 and 2001-2009, ABARES 2011; van Dijk et al. 2013). Studies that provide the strongest inference of population change have predominantly examined trends during this period (Fig. 6). While the potentially confounding effects of weather on population trends were frequently discussed among studies, such effects were rarely quantified (Table 2, but see Mac Nally et al. 2009). Thus, the impact that broad- and local-scale meteorological parameters have had, and will have, on the long-term trends of woodland birds is largely uncertain. With the severity and frequency of drought periods expected to increase with climate change (Recher et al. 2010), this relationship represents a major source of variability that should be addressed in future trend research.

Achieving effective conservation policy for birds

The loss of eucalypt woodland has been referred to as "*one of the most significant vegetation changes in Australian history*" (Yates and Hobbs 1997, p. 949), and little question remains as to whether Australian woodland birds have undergone historic declines. Indeed, it seems clear, from the many qualitative studies based on historical accounts of local extirpation, that woodland birds are neither as abundant nor as widespread as they once were. However, many authors argue that these declines are *ongoing* as result of an 'extinction debt' (e.g. Ford et al. 2009; Manning et al. 2012; Szabo et al. 2011). This implies that woodland birds are persisting in a non-equilibrial state (Mac Nally 1996) in which the impacts of environmental and demographic stochasticity may be heightened (Engen et al. 2001), particularly if a species is at serious and impending risk of extinction (Fagan and Holmes 2006). This scenario is not unique to Australia and further complicates the already challenging task of measuring change in threatened bird populations.

To effectively direct conservation efforts for birds we need to determine whether threats to persistence are ongoing and, if so, the relative importance of historic and recent land-use practices. In Australia, many landscapes are exhibiting dramatic increases in vegetative cover due to natural regeneration (Geddes et al. 2011, Cunningham et al. 2013). Such regenerating habitats have been shown to benefit birds, including a number of species of conservation concern (Lindenmayer et al. 2012). Further examples of birds adapting to landscape alteration exist, such as the breeding success of cover-dependent species in small patches (Fischer and Lindenmayer 2002; Zanette 2000) and the colonisation of birds in restoration plantings (Barrett et al. 2008; Cunningham et al. 2008; Lindenmayer et al. 2010b; Robinson 2006). These 'positive' scenarios of change are likely to temper ongoing declines in woodland avifauna in some landscapes, and offer hope for more widespread recovery in the future.

However, a large proportion of woodland landscapes are *not* regenerating naturally (Weinberg et al. 2011) and clearing pressures throughout much of the Australian temperate zone have not abated (e.g. Gibbons et al. 2008). In turn, the precautionary principle dictates that we should not base conservation policy on the assumption that 'positive' scenarios will lead to population-level recovery. The risks of falsely declaring "recovery" or underestimating rate of decline are manifold, especially in light of the small number and relatively recent publication of inferentially "rigorous" studies identified in our review.

While population research is progressing admirably toward more rigorous assessments, all currently available information on woodland bird trends is limited either by statistical methodology or temporal coverage. This is largely because flexible methods for modelling population data are relatively new (Clark and Bjornstad 2004) and most longitudinal or time-series datasets cover fewer than 15 observation years (Fig. 5). Continued population monitoring is, therefore, a priority. We need to know where to direct our restoration efforts to sustain extant populations and we need to know how to adapt those efforts to maximise conservation outcomes. Both of these goals necessitate reliable and accurate methods for monitoring and reporting population trends.

Conclusion

Eliciting population trends for many species is challenging, but is vital for good conservation policy. It is widely accepted that the treatment of natural and error-driven variability will determine the inferential status of long-term trend estimates. We argue that this relationship must be brought more prominently into our deliberations on global bird decline. We have shown that population research on Australian temperate woodland birds is becoming more rigorous. However, strong long-term studies of change are rare. The paucity of rigorous trend assessments has not subverted the notion that woodland birds are in severe and ongoing decline. We believe that the widespread citation of research that cannot reliably detect trends to draw conclusions about species persistence is a concerning issue for policy development (Boyd 2013). Given international concern for bird assemblages occupying regions of high land-use change, there is a pressing need to maintain the commitment to population monitoring to refine trend assessments and enhance the effectiveness of conservation activities. It is very encouraging that we found an increasing trend towards population studies that are inferentially rigorous. We hope that in coming years the rate of citations of this work shows a commensurate increase in support of evidence-based policy and practice.

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Appendix A

Table A1. Articles retrieved by the search string and included in the review (n = 470).

Authors	Year	Title	Source
Abbott	1998	Conservation of the forest red-tailed black cockatoo, a hollow-dependent species, in the eucalypt forests of Western Australia	Forest Ecology and Management
Abbott & Whitford	2001	Conservation of vertebrate fauna using hollows in forests of south-west Western Australia: strategic risk assessment in relation to ecology, policy, planning, and operations management	Pacific Conservation Biology
Abbott et al.	2011	Forestcheck: the response of birds to silviculture in jarrah (*Eucalyptus marginata*) forest	Australian Forestry
Abbott et al.	2003	Short-term logging and burning impacts on species richness, abundance and community structure of birds in open eucalypt forest in Western Australia	Wildlife Research
Alexander et al.	2002	Impacts of timber harvesting on mammals, reptiles and nocturnal birds in native hardwood forests of East Gippsland, Victoria: a retrospective approach	Australian Forestry
Amos et al.	2012	Predicting Landscape-Genetic Consequences of Habitat Loss, Fragmentation and Mobility for Multiple Species of Woodland Birds	PloS One
Antos & Bennett	2006	Foraging ecology of ground-feeding woodland birds in temperate woodlands of southern Australia	Emu
Antos & Bennett.	2005	How important are different types of temperate woodlands for ground-foraging birds?	Wildlife Research
Antos & White	2004	Birds of remnant vegetation on the Mornington Peninsula, Victoria, Australia: the role of interiors, edges and roadsides	Pacific Conservation Biology
Antos et al.	2008	Where exactly do ground-foraging woodland birds forage? Foraging sites and microhabitat selection in temperate woodlands of southern Australia	Emu
Armstrong & Nichols	2000	Long-term trends in avifaunal recolonisation of rehabilitated bauxite mines in the jarrah forest of south-western Australia	Forest Ecology and Management
Arnold, G. W.	2003	Bird species richness and abundance in wandoo woodland and in tree plantations on farmland at Baker's Hill, Western Australia	Emu
Arnold & Weeldenburg	1998	The effects of isolation, habitat fragmentation and degradation by livestock grazing on the use by birds of patches of gimlet *Eucalyptus salubris* woodland in the wheatbelt of Western Australia	Pacific Conservation Biology
Arnold & Weeldenburg	1990	Factors determining the number and species of birds in road verges in the wheatbelt of Western Australia.	Biological Conservation

Attwood et al.	2009	Declining birds in Australian agricultural landscapes may benefit from aspects of the European agri-environment model	Biological Conservation
Aumann	1989	Breeding parameters in the brown goshawk *Accipiter fasciatus* in south-eastern Australia.	Emu
Baker et al.	1997	Fire and its impact on avian population dynamics	Pacific Conservation Biology
Baker et al.	2002	The edge effect and ecotonal species: Bird communities across a natural edge in southeastern Australia	Ecology
Baker et al.	1998	Powerline easements through forests: a case study of impacts on avifauna	Pacific Conservation Biology
Banks & Bryant	2007	Four-legged friend or foe? Dog walking displaces native birds from natural areas	Biology Letters
Barea	2008	Nest-site selection by the Painted Honeyeater (*Grantiella picta*), a mistletoe specialist	Emu
Barea & Laurence	2012	Habitat influences on nest-site selection by the Painted Honeyeater (*Grantiella picta*): do food resources matter?	Emu
Barnard	1925	A review of the bird life on Coomooboolaroo Station, Duaringa district, Queensland, during the past fifty years.	Emu
Barnard	1934	Observations on the disappearance and probable cause of many of our native birds in central Queensland.	Queensland Naturalist
Barr et al.	2011	Thinning, fire and birds in Boola Boola State Forest, Victoria, Australia	Australian Forestry
Barrett et al.	2003	The New Atlas of Australian Birds	Birds Australia
Barrett & Davidson	2000	Community monitoring of woodland habitats - the Birds on Farms survey	Temperate eucalypt woodlands in Australia
Barrett et al.	2008	Colonisation of native tree and shrub plantings by woodland birds in an agricultural landscape	Wildlife Research
Barrett et al.	2007	Comparison of atlas data to determine the conservation status of bird species in New South Wales, with an emphasis on wood land-dependent species	Australian Zoologist
Barrett et al.	1994	Conservation of woodland birds in a fragmented rural landscape.	Pacific Conservation Biology
Bayly & Blumstein	2001	Pied Currawongs and the decline of native birds	Emu
Bennett	1993	Fauna conservation in box and ironbark forests: a landscape approach	Victorian Naturalist
Bennett & Ford	1997	Land use, habitat change and the conservation of birds in fragmented rural environments: a landscape perspective from the Northern Plains, Victoria, Australia.	Pacific Conservation Biology
Bennett & Radford	2009	Thresholds, incidence functions, and species-specific cues: responses of woodland birds to landscape structure in south-eastern Australia.	Conservation Biology Series

Bennett & Radford	2004	Landscape-level requirements for the conservation of woodland birds: are there critical thresholds in habitat cover?	Landscape ecology of trees and forests
Bennett & Watson	2011	Declining woodland birds - is our science making a difference?	Emu
Bennett et al.	2009	Ants as indicators for vertebrate fauna at a local scale: an assessment of cross-taxa surrogacy in a disturbed matrix	Biodiversity and Conservation
Berry	2008	Birds in four remnant bushland isolates and a garden and their importance to large isolated reserves in Perth	Western Australian Naturalist
Biggs et al.	2011	Landscape position predicts distribution of eucalypt feed trees for threatened black-cockatoos in the northern jarrah forest, Western Australia	Journal of the Royal Society of Western Australia
Bilney et al.	2011	Spatial ecology of sooty owls in south-eastern Australian coastal forests: implications for forest management and reserve design	Emu
Black et al.	2009	Distribution and habitats of the thick-billed grasswren, *Amytornis textilis*, subspecies *myall*	South Australian Ornithologist
Blackmore et al.	2010	The absence of sex-biased dispersal in the cooperatively breeding grey-crowned babbler	Journal of Animal Ecology
Blakers et al.	1984	The Atlas of Australian Birds	Book
BOCA	1993	Glossy black-cockatoos in South Australia	Bird Observer (Nunawading)
Boland	2004	Introduced cane toads *Bufo marinus* are active nest predators and competitors of rainbow bee-eaters *Merops ornatus*: observational and experimental evidence	Biological Conservation
Bonifacio et al.	2011	The effect of woody plant diversity and other stand and landscape factors on the diversity and abundance of birds using farm shelterbelts	Pacific Conservation Biology
Bounds et al.	2010	A statistical analysis of trends in occupancy rates of woodland birds in the ACT, December 1998 to December 2008: the ten-year data analysis	Canberra Bird Notes
Bowen et al.	2009	The age and amount of regrowth forest in fragmented brigalow landscapes are both important for woodland dependent birds	Biological Conservation
Bradby et al.	2011	The Great Western Woodlands. An introduction to the last, vast temperate woodland on earth	Wingspan
Brady & Noske	2010	Succession in Bird and Plant Communities over a 24-Year Chronosequence of Mine Rehabilitation in the Australian Monsoon Tropics	Restoration Ecology
Briggs et al.	2007	Structures of bird communities in woodland remnants in central New South Wales, Australia	Australian Journal of Zoology
Briggs et al.	2000	Wildlife in dry lake and associated habitats in western New South Wales	Rangeland Journal

Brigham et al.	1999	Foraging behaviour in relation to the lunar cycle by Australian Owlet-nightjars *Aegotheles cristatus*	Emu
Brooker	2002	The application of focal species knowledge to landscape design in agricultural lands using the ecological neighbourhood as a template	Landscape and Urban Planning
Brouwer & Garnett	1990	Threatened birds of Australia: An Annotated List	RAOU Report No. 68
Brown et al.	2003	A survey of the terrestrial vertebrate fauna of the Menindee Lakes, western New South Wales	Australian Zoologist
Burton & Olsen	2000a	Management of exotic pine plantations in northeast Queensland for goshawks	Australian Forestry
Burton & Olsen	2000b	Niche partitioning by two sympatric goshawks in the Australian wet tropics: Ranging behaviour	Emu
Cale	1990	The value of road reserves to the avifauna of the central wheatbelt of Western Australia	Proceedings of the Ecological Society of Australia
Calver & Dell	1998	Conservation status of mammals and birds in southwestern Australian forests. 2. Are there unstudied, indirect or long-term links between forestry practices and species decline and extinction?	Pacific Conservation Biology
Calver & Dell	1998	Conservation status of mammals and birds in southwestern Australian forests. 1. Is there evidence of direct links between forestry practices and species decline and extinction?	Pacific Conservation Biology
Cameron	2009	The influence of climate on glossy black-cockatoo reproduction	Pacific Conservation Biology
Cameron	2005	Group size and feeding rates of Glossy Black-Cockatoos in central New South Wales	Emu
Cameron	2006	Nesting habitat of the glossy black-cockatoo in central New South Wales	Biological Conservation
Catterall &Kingston	1993	Human populations, bushland distribution in south east Queensland and the implications for birds	Birds and their habitats: status and conservation in Queensland.
Catterall &Woinarski	2003	Birds of Coomooboolaroo, central Queensland, from 1873 to 1999	Sunbird
Catterall et al.	2010	Long-term dynamics of bird diversity in forest and suburb: decay, turnover or homogenization?	Diversity and Distributions
Catterall et al.	1991	Habitat use by birds across a forest-suburb interface in Brisbane: implications for corridors	Nature conservation 2: the role of corridors.
Catterall et al.	1997	Use of remnant forest habitat by birds during winter in subtropical Australia: patterns and processes	Pacific Conservation Biology
Catterall et al.	1998	Deforestation, urbanisation and seasonality: Interacting effects on a regional bird assemblage	Biological Conservation

Chan	2004	Effect of patch size and bird aggression on bird species richness: a community-based project in tropical/subtropical eucalypt woodland	Proceedings of the Royal Society of Queensland
Chapman & Kealley	2001	The birds of Kurrawang Nature Reserve - observations of avifaunal change in the eastern goldfields of Western Australia	CALMScience
Christensen & Abbott	1989	Impact of fire in the eucalypt forest ecosystem of southern Western Australia: a critical review	Australian Forestry
Clarke & Oldland	2007	Penetration of remnant edges by noisy miners (*Manorina melanocephala*) and implications for habitat restoration	Wildlife Research
Clarke & Schedvin	1999	Removal of bell miners *Manorina melanophrys* from *Eucalyptus radiata* forest and its effect on avian diversity, psyllids and tree health.	Biological Conservation
Clarke et al.	2002	Translocation of the socially complex black-eared miner *Manorina melanotis*: a trial using hard and soft release techniques	Pacific Conservation Biology
Cochran	1995	A small but beautiful bird. The forty-spotted pardalote. Recovery programme in Tasmania	Bird Observer (Nunawading)
Cody	2001	Bird diversity components in Australian *Eucalyptus* and north-temperate *Quercus* woodlands	Auk
Collard et al.	2009	Bird assemblages in fragmented agricultural landscapes: the role of small brigalow remnants and adjoining land uses	Biodiversity and Conservation
Conole, L. E.	2002	Local extinction and decline of birds in a woodland remnant at Inverleigh, Victoria	Corella
Cooney & Watson	2005	Diamond Firetails (*Stagonopleura guttata*) preferentially nest in mistletoe	Emu
Cooper & Walters	2002a	Independent effects of woodland loss and fragmentation on Brown Treecreeper distribution	Biological Conservation
Cooper & Walters	2002b	Experimental evidence of disrupted dispersal causing decline of an Australian passerine in fragmented habitat	Conservation Biology
Cooper et al.	2002	Landscape patterns and dispersal success: Simulated population dynamics in the brown treecreeper	Ecological Applications
Cousin	2004a	Habitat selection of the Western Yellow Robin (*Eopsaltria griseogularis*) in a Wandoo woodland, Western Australia	Emu
Cousin	2004b	Pounce site characteristics of the western yellow robin *Eopsaltria griseogularis*: the importance of assessing foraging microhabitat	Pacific Conservation Biology
Craig	2007	The ecology of the rufous treecreeper in the jarrah forest of south-western Australia and implications for its conservation and management	Australian Journal of Zoology
Craig	2002	Comparative ecology of four passerine species in Jarrah Forests used for timber production in southwestern Western Australia	Conservation Biology
Craig	2004	The value of unlogged buffers for vulnerable bird species in the jarrah forest of south-west Western Australia	Conservation of Australia's Forest Fauna (II)
Craig & Roberts	2005	The short-term impacts of logging on the jarrah forest avifauna in south-west Western Australia: implications for the design and analysis of logging experiments	Biological Conservation

Crates et al.	2011	The abundance and distribution of two species of fairy-wren in suburban and natural habitats	Emu
Crome & Francis	1993	Post World Heritage bird conservation problems in north east Queensland	Birds and their habitats
Crossen	1979	A new concept in park design and management	Biological Conservation
Cunningham & Olsen	2009	A statistical methodology for tracking long-term change in reporting rates of birds from volunteer-collected presence-absence data	Biodiversity and Conservation
Cunningham et al.	2008	The combined effects of remnant vegetation and tree planting on farmland birds	Conservation Biology
Curry	1991	The influence of proximity to plantation edge on diversity and abundance of bird species in an exotic pine plantation in north-eastern New South Wales	Wildlife Research
Czechura et al.	2011	Distribution, status and habitat of the red goshawk *Erythrotriorchis radiatus* in Queensland	Corella
Date et al.	2002	Impacts of logging, fire and grazing regimes on bird species assemblages of the Pilliga woodlands of New South Wales	Pacific Conservation Biology
Davey et al.	2006	Do exotic vertebrates structure the biota of Australia? An experimental test in New South Wales	Ecosystems
Davies	2010	Long-term indices of density of ten woodland passerines at Eyre Bird Observatory	Corella
Davis & Recher	2012	Use by Honeyeaters and Parrots of a Brown Mallet Plantation and an Arboretum at Dryandra Woodland, Western Australia, at a Time of Year When Few Other Nectar Resources Were Available	Western Australian Naturalist
Debus	1997	The barking owl in New South Wales	Australian Birds
Debus	1988	Search for red goshawk in New South Wales	Bird Observer (Nunawading)
Debus	2006a	The role of intense nest predation in the decline of scarlet robins and eastern yellow robins in remnant woodland near Armidale, New South Wales	Pacific Conservation Biology
Debus	2006d	Breeding-habitat and nest-site characteristics of scarlet robins and eastern yellow robins near Armidale, New South Wales	Pacific Conservation Biology
Debus	2008	The effect of noisy miners on small bush birds: an unofficial cull and its outcome	Pacific Conservation Biology
Debus et al.	2006b	Bird communities in remnant woodland on the New England tablelands, New South Wales	Pacific Conservation Biology
Debus et al.	2006c	Bird communities in remnant woodland on the upper north-west slopes of New South Wales	Australian Zoologist
Debus et al.	1993	The square-tailed kite *Lophoictinia isura* in New South Wales	Australian Birds
Dennings	2009	The malleefowl momentum	Wingspan

Dennis	2006	Status and distribution of the wedge-tailed eagle on the Fleurieu Peninsula, South Australia, in 2005	South Australian Ornithologist
Doerr et al.	2006	Habitat selection in two Australasian treecreepers: what cues should they use?	Emu
Dorrough et al.	2012	Differential responses of plants, reptiles and birds to grazing management, fertilizer and tree clearing	Austral Ecology
Dostine et al.	2001	Seasonal use of savanna landscapes by the Gouldian finch, *Erythrura gouldiae*, in the Yinberrie Hills area, Northern Territory	Wildlife Research
Dowling et al.	2003	Dispersal and recruitment of juvenile Red-capped Robins, *Petroica goodenovii*	Emu
Drew et al.	2002	Weddin catchment biodiversity assessment: a report for the TARGET project	Internal Report
Dudaniec et al.	2011	Genetic and morphological divergence in island and mainland birds: Informing conservation priorities	Biological Conservation
Egan et al.	1997	Historical and seasonal changes in the community of forest birds at Longneck Lagoon Nature Reserve, Scheyville, New South Wales	Corella
Ekert & Bucher	1999	Winter use of large-leafed privet *Ligustrum lucidum* (family: *Oleaceae*) by birds in suburban Lismore, New South Wales	Proceedings of the Linnean Society of New South Wales
Elliott et al.	2012	Landscape context affects honeyeater communities and their foraging behaviour in Australia: implications for plant pollination	Landscape Ecology
Ellis & Taylor	2013	Birds in remnant woodland vegetation in the Central Wheatbelt of New South Wales during the drought declared years 2005 to 2009	Australian Zoologist
Er et al.	1996	Importance of yellow box-Blakely's red gum woodland remnants in maintaining bird species diversity: inferences from seasonal data	Corella
Field et al.	2007	Making monitoring meaningful	Austral Ecology
Field et al.	2002	Estimating bird species richness: How should repeat surveys be organized in time?	Austral Ecology
Fischer & Lindenmayer	2002a	The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 1. Species composition and site occupancy patterns	Biodiversity and Conservation
Fischer & Lindenmayer	2002b	The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 2. Paddock trees as stepping stones	Biodiversity and Conservation
Fischer & Lindenmayer	2002c	Small patches can be valuable for biodiversity conservation: two case studies on birds in southeastern Australia	Biological Conservation
Fischer & Lindenmayer	2005a	Nestedness in fragmented landscapes: a case study on birds, arboreal marsupials and lizards	Journal of Biogeography
Fischer & Lindenmayer	2005b	Perfectly nested or significantly nested - an important difference for conservation management	Oikos

Fischer et al.	2010	Tree decline and the future of Australian farmland biodiversity	Proceedings of the National Academy of Sciences of the United States of America
Fisher	2001	Avifauna changes along a *Eucalyptus* regeneration gradient	Emu
Fisher & Goldney	1998	Native forest fragments as critical bird habitat in a softwood forest landscape	Australian Forestry
Fisher & Goldney	1997	Use by birds of riparian vegetation in an extensively fragmented landscape	Pacific Conservation Biology
Ford	1993	The role of birds in ecosystems: risks from eucalypt forest fragmentation and degradation	Birds and their habitats: status and conservation in Queensland.
Ford	1985	The bird community in eucalypt woodland and eucalypt dieback in the northern tablelands of New South Wales	Birds of eucalypt forests and woodlands
Ford	2011	The causes of decline of birds of eucalypt woodlands: advances in our knowledge over the last 10 years	Emu
Ford & Recher	1991	The dynamics of bird communities of eucalypt forests and woodlands in south-eastern Australia	Acta 20 Congressus Internationalis Ornithologici.
Ford et al.	1995	Birds in a degraded landscape - safety nets for capturing regional biodiversity	Nature conservation 4: the role of networks.
Ford et al.	2001	Why have birds in the woodlands of Southern Australia declined?	Biological Conservation
Ford et al.	2009	Extinction debt or habitat change? - Ongoing losses of woodland birds in north-eastern New South Wales, Australia	Biological Conservation
Ford & Howe	1980	The future of birds in the Mount Lofty Ranges	South Australian Ornithologist
Ford & Bell	1981	Density of birds in eucalypt woodland affected to varying degrees by dieback.	Emu
Ford & Pursey	1982	Status and feeding of the eastern spinebill *Acanthorynchus tenuirostris* at New England National Park, north-eastern NSW.	Emu
Ford	2011	Twinkling lights or turning down the dimmer switch? Are there two patterns of extinction debt in fragmented landscapes?	Pacific Conservation Biology
Fraser et al.	2003	Fire management experiment for the declining Partridge Pigeon, Kakadu National Park	Ecological Management and Restoration

Freeman	2006	Habitat requirements of the tooth-billed bowerbird	Bird Observer (Nunawading)
French	1999	Spatial variability in species composition in birds and insects	Journal of Insect Conservation
French et al.	2003	Nectarivorous bird assemblages in Box-Ironbark woodlands in the Capertee Valley, New South Wales	Emu
Freudenberger & Brooker	2004	Development of the focal species approach for biodiversity conservation in the temperate agricultural zones of Australia	Biodiversity and Conservation
Fulton & Majer	2006	The effect of recent chaining on birds in the eastern wheatbelt of Western Australia	Pacific Conservation Biology
Fulton et al.	2008	Road ecology from a road-side assemblage of forest birds in south-western Australia	Ornithological Science
Gardner	2004	Winter flocking behaviour of speckled warblers and the Allee effect	Biological Conservation
Gardner & Heinsohn	2007	Probable consequences of high female mortality for speckled warblers living in habitat remnants	Biological Conservation
Garnett	1992a	Rare birds and sustainable development	Wildlife Australia
Garnett	1992b	Threatened and extinct birds of Australia	Book
Garnett & Crowley	2000	The Action Plan for Australian Birds	Book
Goth & Vogel	2002	Chick survival in the megapode *Alectura lathami* (Australian brush-turkey)	Wildlife Research
Gould	2011	Does post-mining rehabilitation restore habitat equivalent to that removed by mining? A case study from the monsoonal tropics of northern Australia	Wildlife Research
Grey et al.	1998	Influence of the noisy miner *Manorina melanocephala* on avian diversity and abundance in remnant grey box woodland	Pacific Conservation Biology
Grey et al.	1997	Initial changes in the avian communities of remnant eucalypt woodlands following a reduction in the abundance of noisy miners, *Manorina melanocephala*	Wildlife Research
Grover & Slater	1994	Conservation value to birds of remnants of Melaleuca forest in suburban Brisbane	Wildlife Research
Hannah et al.	2007	Impacts of clearing, fragmentation and disturbance on the bird fauna of Eucalypt savanna woodlands in central Queensland, Australia	Austral Ecology
Hanspach et al.	2011	Conservation management of eastern Australian farmland birds in relation to landscape gradients	Journal of Applied Ecology
Harrisson et al.	2012	Fine-scale effects of habitat loss and fragmentation despite large-scale gene flow for some regionally declining woodland bird species	Landscape Ecology
Harwood & Mac Nally	2005	Geometry of large woodland remnants and its influence on avifaunal distributions	Landscape Ecology

Haslem & Bennett	2008a	Countryside elements and the conservation of birds in agricultural environments	Agriculture Ecosystems & Environment
Haslem & Bennett	2011	Countryside vegetation provides supplementary habitat at the landscape scale for woodland birds in farm mosaics	Biodiversity and Conservation
Haslem & Bennett	2008b	Birds in agricultural mosaics: The influence of landscape pattern and countryside heterogeneity	Ecological Applications
Heinsohn et al.	2003	Overlap and competition for nest holes among eclectus parrots, palm cockatoos and sulphur-crested cockatoos	Australian Journal of Zoology
Hines	2008	Some observations on the vertebrate fauna of Durikai State Forest, southeast Queensland, 2000-2008	Queensland Naturalist
Hingston & Black	1998	The short-term effects of fire and its intensity on avian abundance in *Eucalyptus pulchella* woodland	Tasmanian Naturalist
Hingston & Grove	2010	From clearfell coupe to old-growth forest: succession of bird assemblages in Tasmanian lowland wet eucalypt forests	Forest Ecology and Management
Hodgson et al.	2006	Comparison of foraging behaviour of small, urban-sensitive insectivores in continuous woodland and woodland remnants in a suburban landscape	Wildlife Research
Hogendyk	2008	Woody weeds and woodland birds. Invasive native species and declining woodland birds in western New South Wales - a rare case for clearing?	Wingspan
Holland-Clift et al.	2011	Impacts of an invasive willow *Salix rubens* on riparian bird assemblages in south-eastern Australia	Austral Ecology
Homan	2005	A survey of the vertebrate fauna of the Black Range, near Stawell	Victorian Naturalist
Howes & Maron	2009	Interspecific competition and conservation management of continuous subtropical woodlands	Wildlife Research
Howes et al.	2010	Bayesian Networks and Adaptive Management of Wildlife Habitat	Conservation Biology
Hsu et al.	2010	Avian assemblages in eucalypt forests, plantations and pastures in northern NSW, Australia	Forest Ecology and Management
Hudson et al.	1997	How useful are small but lightly treed suburban parks for forest birds in Brisbane?	Sunbird
Hughes	2003	Climate change and Australia: Trends, projections and impacts	Austral Ecology
Hume & Driessen	2010	The response of bird populations to fire in the Peter Murrell Reserves: initial survey	Tasmanian Naturalist
Huth & Possingham	2010	Basic ecological theory can inform habitat restoration for woodland birds	Journal of Applied Ecology
Ingwersen	2008	Resurrecting the warty-faced honeyeater: a behind the scenes look at what it takes to release a flock of captive-bred regent honeyeaters	Wingspan
Ingwersen & Tzaros	2011	Woodland birds: the next generation	Wingspan

James	2003	Response of vertebrates to fenceline contrasts in grazing intensity in semi-arid woodlands of eastern Australia	Austral Ecology
James et al.	1999	Provision of watering points in the Australian arid zone: a review of effects on biota	Journal of Arid Environments
Jansen & Robertson	2001	Riparian bird communities in relation to land management practices in floodplain woodlands of south-eastern Australia	Biological Conservation
Jansen & Robertson	2005	Grazing, ecological condition and biodiversity in riparian river red gum forests in south-eastern Australia	Royal Society of Victoria Proceedings
Johnson et al.	2007	Bird assemblages of a fragmented agricultural landscape and the relative importance of vegetation structure and landscape pattern	Wildlife Research
Jones & Bond	2010	Road barrier effect on small birds removed by vegetated overpass in South East Queensland	Ecological Management and Restoration
Joseph	2006	Presence-absence versus abundance data for monitoring threatened species	Conservation Biology
Kath et al.	2009	Interspecific competition and small bird diversity in an urbanizing landscape	Landscape and Urban Planning
Kavanagh & Stanton	2009	Conserving barking owls in the Pilliga Forests	Wingspan
Kavanagh	1991	The target species approach to wildlife management: gliders and owls in the forests of southeastern New South Wales	Conservation of Australia's Forest Fauna (II)
Kavanagh & Stanton	2002	Response to habitat fragmentation by the Powerful Owl *Ninox strenua*, Sooty Owl *Tyto tenebricosa*, Masked Owl *Tyto novaehollandiae* and other nocturnal fauna in southeastern Australia	Ecology and conservation of owls
Kavanagh & Stanton	2003	Bird population recovery 22 years after intensive logging near Eden, New South Wales	Emu
Kavanagh & Stanton	2005	Vertebrate species assemblages and species sensitivity to logging in the forests of north-eastern New South Wales	Forest Ecology and Management
Kavanagh et al.	2007	Eucalypt plantings on farms benefit woodland birds in south-eastern Australia	Austral Ecology
Kemmerer et al.	2008	High densities of bell miners *Manorina melanophrys* associated with reduced diversity of other birds in wet eucalypt forest: Potential for adaptive management	Forest Ecology and Management
Kemp & Kutt	2004	The vertebrate fauna of the Clemant State Forest Lowlands: a significant coastal woodland remnant in the southern wet tropics bioregion, Northeastern Queensland	Australian Zoologist
Kennedy	2003	A four-year study of a bird community in a woodland remnant near Moyston, western Victoria	Corella
Kennedy & Overs	2001	Foraging ecology and habitat use of the swift parrot on the south-western slopes of New South Wales	Corella
Kennedy & Tzaros	2005	Foraging ecology of the swift parrot *Lathamus discolor* in the box-ironbark forests and woodlands of Victoria	Pacific Conservation Biology

Kinross	2004	Avian use of farm habitats, including windbreaks, on the New South Wales Tablelands	Pacific Conservation Biology
Kinross & Nicol	2008	Responses of birds to the characteristics of farm windbreaks in central New South Wales, Australia	Emu
Kirkpatrick & Gilfedder	2000	Distribution, ecology and conservation status of lowland and subalpine woodlands in Tasmania	Temperate eucalypt woodlands in Australia
Koch et al.	2008	Hollow-using vertebrate fauna of Tasmania: distribution, hollow requirements and conservation status	Australian Journal of Zoology
Kutt & Fisher	2011	Increased grazing and dominance of an exotic pasture (*Bothriochloa pertusa*) affects vertebrate fauna species composition, abundance and habitat in savanna woodland	Rangeland Journal
Kutt & Martin	2010	Bird foraging height predicts bird species response to woody vegetation change	Biodiversity and Conservation
Kutt et al.	2012a	Do miners (*Manorina* spp.) affect bird assemblages in continuous savanna woodlands in north-eastern Australia?	Austral Ecology
Kutt et al.	2012b	Effect of small-scale woodland clearing and thinning on vertebrate fauna in a largely intact tropical savanna mosaic	Wildlife Research
Leach & Recher	1993	Use of roadside remnants of softwood scrub vegetation by birds in south-eastern Queensland	Wildlife Research
Leach	1996	Changes in populations of bird species in roadside softwood scrub remnants/farmland and open eucalypt forest in south-east Queensland, 1981-1993.	Pacific Conservation Biology
Leavesley et al.	2010	The effect of fire on birds of mulga woodland in arid central Australia	International Journal of Wildland Fire
Lee et al.	2010	Mine-site revegetation monitoring detects feeding by threatened black-cockatoos within 8 years	Ecological Management and Restoration
Lees & Smith	1999	Use of mature hoop pine plantation by the vulnerable black-breasted button-quail (*Turnix melanogaster*)	Australian Forestry
Lentini et al.	2011	Value of large-scale linear networks for bird conservation: A case study from travelling stock routes, Australia	Agriculture Ecosystems & Environment
Leslie	2005	Is the superb parrot *Polytelis swainsonii* population in Cuba state forest limited by hollow or food availability?	Corella
Lethbridge et al.	2009	Optimal restoration of altered habitats	Environmental Modelling & Software
Levin et al.	2009	Mapping forest patches and scattered trees from SPOT images and testing their ecological importance for woodland birds in a fragmented agricultural landscape	International Journal of Remote Sensing
Levin et al.	2007	Moving from Discrete to Continuous Landscape Metrics Using Remote Sensing: The Ecological Significance of Paddock Trees for Bird Richness	MODSIM 2007

Liddelow et al.	2002	Owls in the southwest forests of Western Australia	Ecology and conservation of owls
Lindenmayer et al.	2003	Birds in eucalypt and pine forests: landscape alteration and its implications for research models of faunal habitat use.	Biological Conservation
Lindenmayer & Cunningham	2011	Longitudinal patterns in bird reporting rates in a threatened ecosystem: Is change regionally consistent?	Biological Conservation
Lindenmayer & Ough	2006	Salvage logging in the montane ash eucalypt forests of the Central Highlands of Victoria and its potential impacts on biodiversity	Conservation Biology
Lindenmayer et al.	2010	The importance of temperate woodland in travelling stock reserves for vertebrate biodiversity conservation	Ecological Management and Restoration
Lindenmayer et al.	2002	Effects of forest fragmentation on bird assemblages in a novel landscape context	Ecological Monographs
Lindenmayer et al.	2008a	Temporal changes in vertebrates during landscape transformation: a large-scale "natural experiment"	Ecological Monographs
Lindenmayer et al.	2007	Farmland bird responses to intersecting replanted areas	Landscape Ecology
Lindenmayer et al.	2008c	Novel ecosystems resulting from landscape transformation create dilemmas for modern conservation practice	Conservation Letters
Lindenmayer et al.	2009	What makes an effective restoration planting for woodland birds?	Biological Conservation
Lindenmayer et al.	2003	How accurate are population models? Lessons from landscape-scale tests in a fragmented system	Ecology Letters
Lindenmayer et al.	2008b	Testing hypotheses associated with bird responses to wildfire	Ecological Applications
Lindenmayer et al.	2012a	Is biodiversity management effective? Cross-sectional relationships between management, bird response and vegetation attributes in an Australian agri-environment scheme	Biological Conservation
Lindenmayer et al.	2012b	Not All Kinds of Revegetation Are Created Equal: Revegetation Type Influences Bird Assemblages in Threatened Australian Woodland Ecosystems	PloS One
Lockwood & Robinson	1997	The grey crowned babbler *Pomatostomus temporalis* on the Mornington Peninsula - going, going, gone?	Victorian Naturalist
Lollback et al.	2010	Recruitment of the Black-chinned Honeyeater *Melithreptus gularis gularis* in a fragmented landscape in northern New South Wales, Australia	Corella
Low	1994	Invasion of the savage honeyeaters	Australian Natural History
Loyn	2000	Managing the forest matrix: regrowth forests as bird habitat	Conservation in production environments: managing the matrix.
Loyn	2004	Research for ecologically sustainable forest management in Victorian eucalypt forests	Conservation of Australia's Forest Fauna (II)

Loyn	2002b	Patterns of ecological segregation among forest and woodland birds in south-eastern Australia. (Special issue: Interspecific segregation and attraction in forest birds)	Ornithological Science
Loyn	1998	Birds in patches of old-growth ash forest, in a matrix of younger forest	Pacific Conservation Biology
Loyn & Kennedy	2009	Designing old forest for the future: old trees as habitat for birds in forests of mountain ash *Eucalyptus regnans*	Forest Ecology and Management
Loyn & Menkhorst	2011	The bird fauna of Melbourne: changes over a century of urban growth and climate change, using a benchmark from Keartland (1900)	Victorian Naturalist
Loyn et al.	2002a	Vertebrate fauna of Barmah Forest, a large forest of River Red Gum *Eucalyptus camaldulensis* on the floodplain of the Murray River	Victorian Naturalist
Loyn et al.	2007	Eucalypt plantations as habitat for birds on previously cleared farmland in south-eastern Australia	Biological Conservation
Loyn et al.	2001	Modelling landscape distributions of large forest owls as applied to managing forests in north-east Victoria, Australia	Biological Conservation
Loyn et al.	2002	Modelling distributions of large forest owls as a conservation tool in forest management: a case study from Victoria, southeastern Australia	Ecology and conservation of owls
Loyn, Richard H	1997	Effects of an extensive wildfire on birds in far eastern Victoria.	Pacific Conservation Biology
Luck	2002a	The habitat requirements of the rufous treecreeper (*Climacteris rufa*). 1. Preferential habitat use demonstrated at multiple spatial scales	Biological Conservation
Luck	2003	Differences in the reproductive success and survival of the rufous treecreeper (*Climacteris rufa*) between a fragmented and unfragmented landscape	Biological Conservation
Luck	2002b	The dynamics and conservation of a spatially subdivided avian population in a fragmented landscape	Pacific Conservation Biology
Luck & Korodaj	2008	Stand and landscape-level factors related to bird assemblages in exotic pine plantations: implications for forest management	Forest Ecology and Management
Mac Nally	1999	Habitat fragmentation and habitat loss	Australian Biologist
Mac Nally	2007a	Consensus weightings of evidence for inferring breeding success in broad-scale bird studies	Austral Ecology
Mac Nally	2001	'Mesoscale' experimental investigation of the dependence of riparian fauna on floodplain coarse woody debris	Ecological Management and Restoration
Mac Nally & Bennett	1997a	Species-specific predictions of the impact of habitat fragmentation: Local extinction of birds in the box-ironbark forests of central Victoria, Australia	Biological Conservation

Mac Nally & Horrocks	2000b	Landscape-scale conservation of an endangered migrant: the Swift Parrot (*Lathamus discolor*) in its winter range	Biological Conservation
Mac Nally & Horrocks	2007b	Inducing whole-assemblage change by experimental manipulation of habitat structure	Journal of Animal Ecology
Mac Nally & Horrocks	2002a	Relative influences of patch, landscape and historical factors on birds in an Australian fragmented landscape	Journal of Biogeography
Mac Nally & McGoldrick	1997b	Landscape dynamics of bird communities in relation to mass flowering in some eucalypt forests of central Victoria, Australia	Journal of Avian Biology
Mac Nally et al.	2000a	Forecasting the impacts of habitat fragmentation. Evaluation of species-specific predictions of the impact of habitat fragmentation on birds in the box-ironbark forests of central Victoria, Australia	Biological Conservation
Mac Nally et al.	2002c	How well do ecosystem-based planning units represent different components of biodiversity?	Ecological Applications
Mac Nally et al.	2009	Collapse of an avifauna: climate change appears to exacerbate habitat loss and degradation	Diversity and Distributions
Mac Nally et al.	2010	Are Replanted Floodplain Forests in Southeastern Australia Providing Bird Biodiversity Benefits?	Restoration Ecology
Mac Nally et al.	2002d	Nestedness in fragmented landscapes: birds of the box-ironbark forests of south-eastern Australia	Ecography
Mac Nally et al.	2002b	Experimental evidence for potential beneficial effects of fallen timber in forests	Ecological Applications
Mac Nally et al.	2000c	The conservation value of mesic gullies in dry forest landscapes: avian assemblages in the box-ironbark ecosystem of southern Australia	Biological Conservation
MacDonald & Kirkpatrick	2003	Explaining bird species composition and richness in eucalypt-dominated remnants in subhumid Tasmania	Journal of Biogeography
MacDonald et al.	2005	The birds of retained vegetation corridors: a pre- and post-logging comparison in dry sclerophyll forest in Tasmania	Forest Ecology and Management
MacDonald et al.	2002	Bird assemblages in wildlife habitat strips in a Tasmanian plantation matrix	Pacific Conservation Biology
MacHunter et al.	2006	Bird declines over 22 years in forest remnants in southeastern Australia: Evidence of faunal relaxation?	Canadian Journal of Forest Research
Majer et al.	2003	Trunk invertebrate faunas of Western Australian forests: implications for global warming	Ecological Management and Restoration
Major et al.	2001	Influence of remnant and landscape attributes on Australian woodland bird communities	Biological Conservation
Major et al.	1999a	Age structure and density of red-capped robin populations vary with habitat size and shape	Journal of Applied Ecology
Major et al.	1999b	Elevated rates of predation on artificial nests in linear strips of habitat	Journal of Field Ornithology
Manning & Lindenmayer	2009	Paddock trees, parrots and agricultural production: an urgent need for large-scale, long-term restoration in south-eastern Australia	Ecological Management and Restoration

Manning et al.	2006	Multi-scale site and landscape effects on the vulnerable superb parrot of south-eastern Australia during the breeding season	Landscape Ecology
Manning et al.	2011	Integrating research and restoration: the establishment of a long-term woodland experiment in south-eastern Australia	Australian Zoologist
Maron	2007b	Agricultural intensification and loss of matrix habitat…	Biological Conservation
Maron	2008	Size isn't everything: the importance of small remnants to the conservation of woodland birds in Australia	Australian Field Ornithology
Maron	2007a	Threshold effect of eucalypt density on an aggressive avian competitor	Biological Conservation
Maron	2005b	Agricultural change and paddock tree loss: implications for an endangered subspecies of Red-tailed Black-Cockatoo	Ecological Management and Restoration
Maron & Kennedy	2007c	Roads, fire and aggressive competitors: determinants of bird distribution in subtropical production forests	Forest Ecology and Management
Maron & Lill	2005a	The influence of livestock grazing and weed invasion on habitat use by birds in grassy woodland remnants	Biological Conservation
Maron & Lill	2006	Intraspecific variation in detection of bird-habitat relationships: declining birds in southern Australian woodlands	Pacific Conservation Biology
Maron & Lill	2004b	Discrimination among potential buloke *Allocasuarina luehmannii* feeding trees by the endangered south-eastern red-tailed black-cockatoo *Calyptorhynchus banksii graptogyne*	Wildlife Research
Maron et al.	2005c	Temporal variation in bird assemblages: How representative is a one-year snapshot?	Austral Ecology
Maron et al.	2004a	Can the biotic nestedness matrix be used predictively?	Oikos
Maron et al.	2011	Relative influence of habitat modification and interspecific competition on woodland bird assemblages in eastern Australia	Emu
Maron et al.	2012	Distribution and individual condition reveal a hierarchy of habitat suitability for an area-sensitive passerine	Biodiversity and Conservation
Martin & McIntye	2007	Impacts of livestock grazing and tree clearing on birds of woodland and riparian habitats	Conservation Biology
Martin & Possingham	2005a	Predicting the impact of livestock grazing on birds using foraging height data	Journal of Applied Ecology
Martin et al.	2005b	The power of expert opinion in ecological models using Bayesian methods: Impact of grazing on birds	Ecological Applications
Martin et al.	2006	Is landscape context important for riparian conservation? Birds in grassy woodland	Biological Conservation
Martin et al.	2004	The value of habitat reconstruction to birds at Gunnedah, New South Wales	Emu
McCarthy et al.	2000	Testing spatial PVA models of Australian treecreepers (Aves: *Climacteridae*) in fragmented forest	Ecological Applications
McCarthy et al.	1994	Use and abuse of wildlife models for determining habitat requirements of forest fauna	Australian Forestry

McCarthy et al.	1999	Uncertainty in assessing the viability of the powerful owl *Ninox strenua* in Victoria, Australia	Pacific Conservation Biology
McGinness et al.	2010	Woodland bird declines in the Murray-Darling Basin: are there links with floodplain change?	Rangeland Journal
McLean et al.	2005	Breeding success and timing of nesting by forest birds on the northern tablelands of New South Wales, Australia	Corella
Mikami et al.	2010	Bowers of the Great Bowerbird *Chlamydera nuchalis* remained unburned after fire: is this an adaptation to fire?	Journal of Ethology
Milledge	2004	Large owl territories as a planning tool for vertebrate fauna conservation in the forests and woodlands of eastern Australia	Conservation of Australia's Forest Fauna (II)
Milledge et al.	1991	'Barometers of change': the distribution of large owls and gliders in mountain ash forests of the Victorian central and their potential as management indicators	Conservation of Australia's Forest Fauna (I)
Miller & Cale	2000	Behavioral mechanisms and habitat use by birds in a fragmented agricultural landscape	Ecological Applications
Montague-Drake et al.	2009	Factors affecting site occupancy by woodland bird species of conservation concern	Biological Conservation
Montague-Drake et al.	2011	A reverse keystone species affects the landscape distribution of woodland avifauna: a case study using the Noisy Miner (*Manorina melanocephala*) and other Australian birds	Landscape Ecology
Mooney	1997	Habitat and seasonality of nesting masked owls in Tasmania	Birds Australia Monograph
Mooney	1998	Status and conservation of raptors in Australia's tropics	Journal of Raptor Research
Mooney	2000	Appearance vs performance; managing endangered Tasmanian wedge-tailed eagles in forestry operations	Raptors at Risk
Mooney & Taylor	1996	Value of nest site protection in ameliorating the effects of forestry operations on wedge-tailed eagles in Tasmania	Raptors in human landscapes
Moore	1992	Conservation biology of the southern cassowary	North Queensland Naturalist
Moore	2007	Population ecology of the southern cassowary *Casuarius casuarius johnsonii*, Mission Beach north Queensland	Journal of Ornithology
Morris & Wooller	2001	The structure and dynamics of an assemblage of small birds in a semi-arid eucalypt woodland in south-western Australia	Emu
Munks et al.	2004	The importance of adaptive management in 'off-reserve' conservation for forest fauna: implementing, monitoring and upgrading swift parrot *Lathamus discolor* conservation measures in Tasmania	Conservation of Australia's Forest Fauna (II)
Munro et al.	2010	Bird's Response to Revegetation of Different Structure and Floristics - Are "Restoration Plantings" Restoring Bird Communities?	Restoration Ecology
Murphy	1999	The conservation value of small woodland remnants on the New South Wales south western slopes: a case study from Wagga Wagga	Australian Zoologist
Neave & Norton	1998	Biological inventory for conservation evaluation. 4. Composition, distribution and spatial prediction of vegetation assemblages in southern Australia	Forest Ecology and Management

Neave et al.	1996c	Biological inventory for conservation evaluation 3. Relationships between birds, vegetation and environmental attributes in southern Australia	Forest Ecology and Management
Neave et al.	1996a	Biological inventory for conservation evaluation 1. Design of a field survey for diurnal, terrestrial birds in southern Australia	Forest Ecology and Management
Neave et al.	1996b	Biological inventory for conservation evaluation .2. Composition, functional relationships and spatial prediction of bird assemblages in southern Australia	Forest Ecology and Management
Nelson & Morris	1994	Nesting requirements of the yellow-tailed black-cockatoo, *Calyptorhynchus funereus*, in *Eucalyptus regnans* forest, and implications for forest management	Wildlife Research
Nichols et al.	2003	Long-term trends in faunal recolonization after bauxite mining in the jarrah forest of southwestern Australia	Restoration Ecology
Oldland et al.	2009	Habitat preferences of the noisy miner (*Manorina melanocephala*) - a propensity for prime real estate?	Austral Ecology
Oliver	2001	Activity budget of the regent honeyeater, *Xanthomyza phrygia*, in northern New South Wales	Australian Journal of Zoology
Oliver	2000	Foraging behaviour and resource selection of the regent honeyeater *Xanthomyza phrygia* in northern New South Wales	Emu
Oliver	1998b	The importance of insects and lerp in the diet of juvenile regent honeyeaters, *Xanthomyza phrygia*: implications for the conservation of an endangered woodland bird	Wildlife Research
Oliver et al.	1998a	Breeding success and nest site selection of the regent honeyeater *Xanthomyza phrygia* near Armidale, New South Wales	Emu
Oliver et al.	1999	Habitat of the Regent honeyeater *Xanthomyza phrygia* and the value of the Bundarra-Barraba region for the conservation of avifauna	Pacific Conservation Biology
Oliver	1998	The breeding behaviour of the endangered regent honeyeater, *Xanthomyza phrygia*, near Armidale, New South Wales.	Australian Journal of Zoology
Oliver et al.	1998b	Spatial fidelity of plant, vertebrate, and invertebrate assemblages in multiple-use forest in eastern Australia.	Conservation Biology.
Olsen et al.	2005	The state of Australia's birds 2005: Woodlands and Birds	Wingspan
Palmer & Bennett	2006	Riparian zones provide for distinct bird assemblages in forest mosaics of south-east Australia	Biological Conservation
Parker & Oliver	2008	A spring snapshot. Have tree fencing and tree planting yielded the expected outcomes for woodland birds in the central Murray catchment of New South Wales?	Wingspan
Parker et al.	2007	A survey of large forest owls in state forests of south-western New South Wales, Australia	Australian Zoologist
Parker et al.	2011	Such is the birding life. A weekend in Kelly Country chasing threatened woodland birds	Wingspan
Parkinson et al.	2002	Differential macrohabitat use by birds on the unregulated Ovens River floodplain of southeastern Australia	River Research and Applications

Parsons et al.	2008	The vegetation requirements of Superb Fairy-wrens (*Malurus cyaneus*) in non-urban edge and urbanised habitats	Emu
Pascoe et al.	2008	Detection of owls, owlet nightjars and arboreal mammals in edge environments of Cape Otway, south-western Victoria	Royal Society of Victoria Proceedings
Paton et al.	2004	Birdscaping the environment: restoring the woodland systems of the Mt Lofty region, South Australia	Conservation of Australia's Forest Fauna (II)
Pavlova et al.	2012	Genes and song: genetic and social connections in fragmented habitat in a woodland bird with limited dispersal	Ecology
Peake et al.	1993	The masked owl *Tyto novaehollandiae* in Victoria	Australian Bird Watcher
Pearce & Ferrier	2001a	The practical value of modelling relative abundance of species for regional conservation planning: A case study	Biological Conservation
Pearce & Minchin	2001b	Vegetation of the Yellingbo Nature Conservation Reserve and its relationship to the distribution of the helmeted honeyeater, bell miner and white-eared honeyeater	Wildlife Research
Pearce et al.	1994	Habitat selection by helmeted honeyeaters	Wildlife Research
Pearce et al.	2001c	An evaluation of the predictive performance of distributional models for flora and fauna in north-east New South Wales	Journal of Environmental Management
Pearce et al.	1995	Niche overlap and competition for habitat between the helmeted honeyeater and the bell miner	Wildlife Research
Pepper	1997	A survey of the south Australian glossy black-cockatoo (*Calyptorhynchus lathami halmaturinus*) and its habitat	Wildlife Research
Piper & Catterall	2006	Is the conservation value of small urban remnants of eucalypt forest limited by increased levels of nest predation?	Emu
Piper & Catterall	2004	Effects of edge type and nest height on predation of artificial nests within subtropical Australian eucalypt forests	Forest Ecology and Management
Platt & Lill	2006	Composition and conservation value of bird assemblages of urban 'habitat islands': do pedestrian traffic and landscape variables exert an influence?	Urban Ecosystems
Pocock & Lawrence	2005	How far into a forest does the effect of a road extend? Defining road edge effect in eucalypt forests of south-eastern Australia	Online
Possingham & Possingham	1997	Habitat use and abundance of dryland birds in heritage areas in the upper south east of South Australia	South Australian Ornithologist
Price et al.	2009	Continuum or discrete patch landscape models for savanna birds? Towards a pluralistic approach	Ecography
Priday	2010	Beyond the 'woody remnant' paradigm in conservation of woodland birds: habitat requirements of the Hooded Robin (*Melanodryas cucullata cucullata*)	Emu
Prober & Smith	2009	Enhancing biodiversity persistence in intensively used agricultural landscapes: A synthesis of 30 years of research in the Western Australian wheatbelt	Agriculture Ecosystems & Environment
Proust	2006	Restoration of woodland bird habitat at Cowra	Wingspan

Radford & Bennett	2004	Thresholds in landscape parameters: occurrence of the white-browed treecreeper *Climacteris affinis* in Victoria, Australia	Biological Conservation
Radford & Bennett	2007	The relative importance of landscape properties for woodland birds in agricultural environments	Journal of Applied Ecology
Radford & Bennett	2006	Factors affecting patch occupancy by the white-browed treecreeper *Climacteris affinis* in an agricultural landscape in north-west Victoria, Australia	Pacific Conservation Biology
Radford & Bennett	2005	Terrestrial avifauna of the Gippsland Plain and Strzelecki Ranges, Victoria, Australia: insights from Atlas data	Wildlife Research
Radford et al.	2005	Landscape-level thresholds of habitat cover for woodland-dependent birds	Biological Conservation
Razeng & Watson	2012	What do declining woodland birds eat? A synthesis of dietary records	Emu
Recher	1999	The state of Australia's avifauna…	Australian Zoologist
Recher	1990	A review of current ideas of the extinction…	Proceedings of the Ecological Society of Australia
Recher	1985	Eucalypt Forests, Woodlands and Birds: An Introduction	Birds of eucalypt forests and woodlands
Recher	1991b	The conservation and management of eucalypt forest birds: resource requirements for nesting and foraging	Conservation of Australia's Forest Fauna (I)
Recher	2004	Eucalypt forest birds: the role of nesting and foraging resources in conservation and management	Conservation of Australia's Forest Fauna (II)
Recher	2006a	A hypothesis to explain why the south-western subspecies of the Crested Shrike-tit (*Falcunculus frontatus leucogaster*) is rare and declining	Emu
Recher	1997	Impact of wildfire on the avifauna of Kings Park, Perth, Western Australia	Wildlife Research
Recher & Davis	2002	Foraging profile of a salmon gum woodland avifauna in Western Australia	Journal of the Royal Society of Western Australia
Recher & Majer	2006b	Effects of bird predation on canopy arthropods in wandoo *Eucalyptus wandoo* woodland	Austral Ecology
Recher & Serventy	1991	Long term changes in the relative abundances of birds in King's Park, Perth, Western Australia	Conservation Biology
Recher et al.	2002a	Comparative foraging ecology of five species of ground-pouncing birds in western Australian woodlands with comments on species decline.	Ornithological Science
Recher et al.	1985	Foraging patterns of breeding birds in eucalypt forest and woodland of southeastern Australia	Australian Journal of Ecology

Recher et al.	1991a	Ecological association of habitats and bird species during the breeding season in southeastern New South Wales	Australian Journal of Ecology
Recher et al.	2007	Conservation inverted: birds in the great western woodlands	Wingspan
Reid	2008b	Results from a bird monitoring project in the Cowra Region of NSW	Internal Report
Reid	2010	The Cowra woodland birds program - nine years on	Wingspan
Reid	1999	Threatened and declining birds in the NSW sheep-wheat belt, Part I	Internal Report
Reid	2000	Threatened and declining birds in the NSW sheep-wheat belt, Part II	Internal Report
Reid & Cunningham	2008	Statistical Analysis of the Cowra Woodland Birds Program's Bird Database	Internal Report
Reid	1997	Behaviour, voice and breeding of the mistletoebird *Dicaeum hirundinaceum* in arid woodland.	Victorian Naturalist
Reside et al.	2011	Incorporating low-resolution historic species location data decreases performance of distribution models	Ecological Modelling
Robinson	1991	Threatened birds in Victoria…	Victorian Naturalist
Robinson	1993	Vale Toolern Vale: the loss of our woodland birds	Wingspan
Robinson & Traill	1996	Conserving woodland birds in the wheat and sheep belts of southern Australia	Wingspan
Robinson	2006	Is revegetation in the Sheep Pen Creek area, Victoria, improving grey-crowned babbler habitat?	Ecological Management and Restoration
Robinson et al.	2006	Grey-crowned babbler: conservation in Victoria - fifteen years on. Woodland restoration is giving these engaging yahoos a fighting chance	Wingspan
Robinson & Paull	2009	Comparative evaluation of suburban bushland as foraging habitat for the glossy black-cockatoo	Corella
Rogers & Close	2008	Breeding and observed habitat preference of the scarlet-chested parrot *Neophema splendida* in Yumbarra Conservation Park	South Australian Ornithologist
Rowley & Chapman	1991	The breeding biology, food, social-organisation, demography and conservation of the Major Mitchell or Pink Cockatoo, *Cacatua leadbeateri*, on the margin of the Western Australian wheat-belt	Australian Journal of Zoology
Saunders	1989	Changes in the avifauna of a region…	Biological Conservation
Saunders	1993	A community-based observer scheme to assess avian responses to habitat reduction and fragmentation in south Western Australia	Biological Conservation
Saunders & Curry	1990	The impact of agricultural and pastoral industry on birds in the southern half of Western Australia: past, present and future.	Proceedings of the Ecological Society of Australia

Saunders & Ingram	1998	Twenty-eight years of monitoring a breeding population of Carnaby's cockatoo	Pacific Conservation Biology
Saunders & Ingram	1995	Birds of Southwestern Australia: an atlas of changes in distribution and abundance of the wheatbelt fauna	Book
Saunders et al.	1985	The effects of clearing for agriculture on the distribution of cockatoos in the southwest of Western Australia	Birds of eucalypt forests and woodlands
Saunders	1990	Problems of survival in an extensively cultivated landscape: the case of Carnaby's cockatoo *Calyptorhynchus funereus latirostris*.	Biological Conservation
Seddon et al.	2003	Relationships between bird species and characteristics of woodland remnants in central New South Wales	Pacific Conservation Biology
Seddon et al.	2009	Biodiversity benefits of alley farming with old man saltbush in central western New South Wales	Animal Production Science
Selwood et al.	2009	Native bird breeding in a chronosequence of revegetated sites	Oecologia
Shanahan et al.	2011a	The influence of patch area and connectivity on avian communities in urban revegetation	Biological Conservation
Shanahan et al.	2011b	Foraging height and landscape context predict the relative abundance of bird species in urban vegetation patches	Austral Ecology
Shelly	1998	Preliminary fauna survey of belah and cypress/box woodland near West Wyalong NSW and recommendations for forest management	Australian Forestry
Shelly	1998	Survey of vertebrate fauna and habitats in a cypress pine-ironbark forest in central-west New South Wales.	Australian Zoologist
Sherren et al.	2011	Lessons from visualising the landscape and habitat implications of tree decline-and its remediation through tree planting-in Australia's grazing landscapes	Landscape and Urban Planning
Shoo	2006	Detecting climate change induced range shifts: where and how should we be looking?	Austral Ecology
Smith	1994	A critical analysis of the factors responsible for the decline of the superb lyrebird *Menura novaehollandiae* in Sherbrooke Forest, Victoria	Australian Bird Watcher
Smith	1992	The tragedy of Sherbrooke	Bird Observer (Nunawading)
Smyth & Pavey	2001	Foraging by the endangered black-breasted button-quail (*Turnix melanogaster*) within fragmented rainforest of an agricultural landscape	Biological Conservation
Smyth et al.	2002	Comparative influence of forest management and habitat structural factors on the abundances of hollow-nesting bird species in subtropical Australian eucalypt forest	Environmental Management
Soderquist & Gibbons	2007	Home-range of the powerful owl (*Ninox strenua*) in dry sclerophyll forest	Emu
Soderquist et al.	2002	Habitat quality in powerful owl (*Ninox strenua*) territories in the Box-Ironbark Forest of Victoria, Australia	Ecology and conservation of owls

Stagoll et al.	2010	Using bird-habitat relationships to inform urban planning	Landscape and Urban Planning
Stone et al.	2008	Forest canopy health and stand structure associated with bell miners (*Manorina melanophrys*) on the central coast of New South Wales	Australian Forestry
Straw	1998	Homebush Bay. A win for the birds	Wingspan
Szabo et al.	2012a	Adapting global biodiversity indicators to the national scale: A Red List Index for Australian birds	Biological Conservation
Szabo et al.	2011	Paying the extinction debt: woodland birds in the Mount Lofty Ranges, South Australia	Emu
Szabo et al.	2012b	A comparison of estimates of relative abundance from a weakly structured mass-participation bird atlas survey and a robustly designed monitoring scheme	Ibis
Tassicker et al.	2006	The effects of vegetation structure on the birds in a tropical savanna woodland in north-eastern Australia	Rangeland Journal
Taylor & Kirsten	1999	Barking owls: woodland survivors	Wingspan
Taylor & Haseler	1995	A piece of the puzzle: a reply to McCarthy et al. (1994)	Australian Forestry
Taylor et al.	2008	Edge geometry influences patch-level habitat use by an edge specialist in south-eastern Australia	Landscape Ecology
Thomas	2009	Regent Honeyeater Habitat Restoration Project Lurg hills, Victoria	Ecological Management and Restoration
Thomson et al.	2007	Predicting bird species distributions in reconstructed landscapes	Conservation Biology
Tidemann	1987	Gouldian finches in the wild	Bird Keeping in Australia
Todd	2006	The monkey-faced owls of Awaba: a plea for the forests of Awaba and their sad-faced owls, threatened	Wingspan
Tolsma et al.	2010	The Likely Impacts of Prescribed Fire on the Flora and Fauna of Box-Ironbark Remnants	Royal Society of Victoria Proceedings
Towerton et al.	2008	The potential for remote cameras to monitor visitation by birds and predators at malleefowl mounds	Ecological Management and Restoration
Traill & Duncan	2000	Status of birds in the New South Wales temperate woodlands region	Internal Report
Traill et al.	1996	Current and past status of the birds of Chiltern	Australian Bird Watcher
Traill	1999	For whom the bellbird tolls.... Woodlands	Wingspan
Traill	1991	Box-ironbark forests: tree hollows, wildlife and management	Conservation of Australia's Forest Fauna (II)
Traill	1993	Forestry, birds, mammals and management in box and ironbark forests	Victorian Naturalist

Trollope et al.	2009	The response of ground and bark foraging insectivorous birds across an urban-forest gradient	Landscape and Urban Planning
Tubelis et al.	2007	The peninsula effect on bird species in native eucalypt forests in a wood production landscape in Australia	Journal of Zoology
Tubelis et al.	2004	Novel patch-matrix interactions: patch width influences matrix use by birds	Oikos
Valentine et al.	2012	Effects of a short fire-return interval on resources and assemblage structure of birds in a tropical savanna	Austral Ecology
Valentine et al.	2007	Burning season influences the response of bird assemblages to fire in tropical savannas	Biological Conservation
Van Polanen et al.	2004	Bird communities of some urban bushland fragments: implications for conservation	Australian Field Ornithology
Vesk & Mac Nally	2006	The clock is ticking - Revegetation and habitat for birds and arboreal mammals in rural landscapes of southern Australia	Agriculture Ecosystems & Environment
Vesk et al.	2008	Time lags in provision of habitat resources through revegetation	Biological Conservation
Walters et al.	1999	The ecological basis of sensitivity of brown treecreepers to habitat fragmentation: a preliminary assessment	Biological Conservation
Wapstra & Doran	2004	Observations on a nesting hollow of yellow-tailed black cockatoo, and the felled tree that hosted it, in north-eastern Tasmania	Tasmanian Naturalist
Wardell-Johnson & Williams	2000	Edges and gaps in mature karri forest, south-western Australia: logging effects on bird species abundance and diversity	Forest Ecology and Management
Wardell-Johnson et al.	2005	A review of eucalypt dieback associated with bell miner habitat in south-eastern Australia	Australian Forestry
Watson	2011	A productivity-based explanation for woodland bird declines: poorer soils yield less food	Emu
Watson et al.	2000	The avifauna of severely fragmented, buloke *Allocasuarina luehmanni* woodland in western Victoria, Australia	Pacific Conservation Biology
Watson et al.	2005	Bird community responses to habitat fragmentation: how consistent are they across landscapes?	Journal of Biogeography
Watson et al.	2003	Woodland fragmentation is causing the decline of species and functional groups of birds in southeastern Australia	Pacific Conservation Biology
Watson et al.	2001	An assessment of the focal-species approach for conserving birds in variegated landscapes in southeastern Australia	Conservation Biology
Weaver	1982	Breeding habitats and status of the golden-shouldered parrot *Psephotus chrysopterygius*, in Queensland	Emu
Webb	2008	Swift parrot breeding season survey report - 2007/08	Internal Report
Westcott	1999	Counting cassowaries: what does cassowary sign reveal about their abundance?	Wildlife Research
Westphal & Possingham	2003b	Applying a decision-theory framework to landscape planning for biodiversity: Follow-up to Watson et al	Conservation Biology

Westphal et al.	2007	Optimizing landscape configuration: A case study of woodland birds in the Mount Lofty Ranges, South Australia	Landscape and Urban Planning
Westphal et al.	2003a	Effects of landscape pattern on bird species distribution in the Mt. Lofty Ranges, South Australia	Landscape Ecology
Williams & Ley	1993	Northern NSW Group saving the regent honeyeater	Wingspan
Williams et al.	2001	Recovery of bird populations after clearfelling of tall open eucalypt forest in Western Australia	Journal of Applied Ecology
Wilson & Recher	2001	Foraging ecology and habitat selection of the Yellow-plumed Honeyeater, *Lichenostomus ornatus*, in a Western Australian woodland: implications for conservation	Emu
Wilson & McCulloch	1998	Bird of Belah woodlands	Bird Observer (Nunawading)
Wintle et al.	2005	Fauna habitat modelling and mapping: a review and case study in the Lower Hunter Central Coast region of NSW	Austral Ecology
Woinarski	1993	Australian tropical savannas, their avifauna, conservation status and threats	Birds and their habitats
Woinarski & Braithwaite	1993	The distribution of terrestrial vertebrates and plants in relation to the vegetation and habitat mapping schemes in stage III of of Kakadu National Park	Wildlife Research
Woinarski & Fisher	1995	Wildlife of lancewood *Acacia shirleyi* thickets and woodlands in northern Australia. 2. Comparisons with other environments of the region (*Acacia* woodlands, *Eucalyptus* savanna woodlands and monsoon rainforests)	Wildlife Research
Woinarski & Tidemann	1991	The bird fauna of a deciduous woodland in the wet-dry tropics of northern Australia	Wildlife Research
Woinarski & Fisher	1995	Wildlife of lancewood (*Acacia shirleyi*) thickets and woodlands in Northern Australia. 1. Variation in vertebrate species composition across the environmental range occupied by lancewood vegetation in the Northern Territory.	Wildlife Research
Wood	1996	Bird assemblages in a small public reserve and adjacent residential area at Wollongong, New South Wales	Wildlife Research
Wykes	1985	The helmeted honeyeater and related honeyeaters of Victorian woodlands	Birds of eucalypt forests and woodlands
Yen et al.	2011	To what are woodland birds responding? Inference on relative importance of in-site habitat variables using several ensemble habitat modelling techniques	Ecography
Yeoman & Mac Nally	2005	The avifaunas of some fragmented, periurban, coastal woodlands in south-eastern Australia	Landscape and Urban Planning
Zanette	2000	Fragment size and the demography of an area-sensitive songbird	Journal of Animal Ecology

Appendix B

Table B1. Articles defined as 'population studies' in this review (n = 44). Table abbreviations: 'POI' is the period of inference in years, 'OY' is the number of observation years, 'IS' is the inference score. Scale abbreviations: 'Lo' is local, 'La' is landscape, 'Re' is regional, 'Co' is continental. 'DD' indicates deficient data. Values that were estimated due to inadequate reporting are denoted with an asterisk (*).

Citation	Scale	POI	OY	IS
Arnold, G. W., 2003. Bird species richness and abundance in wandoo woodland and in tree plantations on farmland at Baker's Hill, Western Australia. Emu. 103, 259-269.	La	29	3	5
Barrett, G.W., Ford, H.A., Recher, H.F., 1994. Conservation of woodland birds in a fragmented rural landscape. Pac. Conserv. Biol. 1, 245-256.	La	11	5*	5
Barrett, G., Silcocks, A., Barry, S., Cunningham, R., Poulter, R., 2003. *The New Atlas of Australian Birds*. Bird Australia (Royal Australasian Ornithologists Union), Melbourne.	Co	25	9	8
Barrett, G.W., Silcocks, A.F., Cunningham, R., Oliver, D.L., Weston, M.A., Baker, J., 2007. Comparison of atlas data to determine the conservation status of bird species in New South Wales, with an emphasis on woodland-dependent species. Aust. Zool. 34, 37-77.	Re	25	9	8
Bounds, J., Taws, N., Cunningham, R., 2010. A statistical analysis of trends in occupancy rates of woodland birds in the ACT, December 1998 to December 2008: the ten year data analysis. Canberra Bird Notes. 35, 158-192.	Re	11	11	14
Brouwer, J., Garnett, S., 1990. *Threatened birds of Australia: An Annotated List.* RAOU Report No. 68. Royal Australasian Ornithologists Union, Melbourne.	*DD*	*DD*	*DD*	2
Catterall, C.P., Cousin, J.A., Piper, S., Johnson, G., 2010. Long-term dynamics of bird diversity in forest and suburb: decay, turnover or homogenization? Divers. Distrib. 16, 559-570.	La	18	5	10
Conole, L.E., 2002. Local extinction and decline of birds in a woodland remnant at Inverleigh, Victoria. Corella. 26, 41-46.	La	50	17*	6
Cooper, C. B., Walters, J. R., 2002. Independent effects of woodland loss and fragmentation on Brown Treecreeper distribution. Biol. Conserv. 105, 1-10.	Re	7	2	6
Cunningham, R., Olsen, P., 2009. A statistical methodology for tracking long-term change in reporting rates of birds from volunteer-collected presence-absence data. Biodiv, Conserv. 18, 1305-1327.	Re	9	9	12
Date, E.M., Ford, H.A., Recher, H.F., 2002. Impacts of logging, fire and grazing regimes on bird species assemblages of the Pilliga woodlands of New South Wales. Pac. Conserv. Biol. 8, 177-195.	Re	94	9*	5
Egan, K.H., Farrell, J.R., Pepper-Edwards, D.L., 1997. Historical and seasonal changes in the community of forest birds at Longneck Lagoon Nature Reserve, Scheyville, New South Wales. Corella. 21, 1-16.	Lo	30	27	9
Ellis, M.V., Taylor, J.E., 2013. Birds in remnant woodland vegetation in the central wheatbelt of New South Wales during the drought declared years 2005-2009. Aust. Zool. 36, 332-348.	Re	33	10	8

Ford, H. A., Barrett, G. W., Saunders, D. A., Recher, H. F., 2001. Why have birds in the woodlands of Southern Australia declined? Biol. Conserv. 97, 71-88.	*DD*	*DD*	*DD*	3
Ford, H.A., Walters, J.R., Cooper, C.B., Debus, S.J.S., Doerr, V.A.J., 2009. Extinction debt or habitat change? - Ongoing losses of woodland birds in north-eastern New South Wales, Australia. Biol. Conserv. 142, 3182-3190.	Re	32	22	8
Ford, H. A., 2011. The causes of decline of birds of eucalypt woodlands: advances in our knowledge over the last 10 years. Emu. 111, 1-9.	*DD*	*DD*	*DD*	3
Garnett, S., 1992. *Threatened and extinct birds of Australia.* RAOU Report No. 82. Royal Australasian Ornithologists Union and Australian National Parks and Wildlife Service, Melbourne.	*DD*	*DD*	*DD*	2
Garnett, S. T., Crowley, G. M., 2000. *The Action Plan for Australian Birds.* Environment Australia, Canberra.	*DD*	*DD*	*DD*	2
Kennedy, S.J., 2003. A four-year study of a bird community in a woodland remnant near Moyston, western Victoria. Corella. 27, 33-44.	Lo	5	4	7
Leach, G.J., 1996. Changes in populations of bird species in roadside softwood scrub remnants/farmland and open eucalypt forest in south-east Queensland, 1981-1993. Pac. Conserv. Biol. 2, 232-243.	La	12	12	11
Lindenmayer, D.B., Cunningham, R.B., MacGregor, C., Crane, M., Michael, D., Fischer, J., Montague-Drake, R., Felton, A., Manning, A., 2008. Temporal changes in vertebrates during landscape transformation: a large-scale "natural experiment". Ecol. Monog. 78, 567-590.	Re	8	6	12
Lindenmayer, D.B., Cunningham, R.B., 2011. Longitudinal patterns in bird reporting rates in a threatened ecosystem: Is change regionally consistent? Biol. Conserv. 144, 430-440.	Re	12	8	11
Lockwood, D., Robinson, D., 1997. The grey crowned babbler Pomatostomus temporalis on the Mornington Peninsula - going, going, gone? Vic. Nat.t 114, 269-277.	Re	101	9*	5
Loyn, R.H., Menkhorst, P.W., 2011. The bird fauna of Melbourne: changes over a century of urban growth and climate change, using a benchmark from Keartland (1900). Vic. Nat. 128, 210-232.	La	162	6*	6
Mac Nally, R., Bennett, A.F., Thomson, J.R., Radford, J.Q., Unmack, G., Horrocks, G., Vesk, P.A., 2009. Collapse of an avifauna: climate change appears to exacerbate habitat loss and degradation. Divers.Distrib. 15, 720-730.	Re	14	11	13
MacHunter, J., Wright, W., Loyn, R., Rayment, P., 2006. Bird declines over 22 years in forest remnants in southeastern Australia: Evidence of faunal relaxation? Canadian J. For. Res. 36, 2756-2768.	Re	26	6	11
Paton, D. C., Carpernter, G., Sinclair, R. G., 1994. A second bird atlas of the Adelaide region. Part 1: Changes in the distribution of birds: 1974-75 vs 1984-85. S. Aust. Ornit. 31, 151-193.	Re	11	4	5
Paton, D. C., Rogers, D. J. and Harris, W. 2004. Birdscaping the environment: restoring the woodland systems of the Mt Lofty region, South Australia. In Lunney, D. (ed.) *Conservation of Australia's Forest Fauna* (second edition). Royal Zoological Society of New South Wales, Sydney.	*DD*	*DD*	*DD*	2
Possingham, M. L., Possingham, H. P., 1997. Habitat use and abundance of dryland birds in heritage areas in the upper south east of South Australia. S. Aust. Ornit. 32, 145-160.	La	18	6	4
Recher, H. F., 1999. The state of Australia's avifauna: a personal opinion and prediction for the new millenium. Aust. Zool. 31, 11-27.	*DD*	*DD*	*DD*	2

Recher, H. F., Serventy, D. L., 1991. Long term changes in the relative abundances of birds in King's Park, Perth, Western Australia. Conserv. Biol. 5, 90-102.	Lo	59	8*	5
Reid, J. R. W., 1999. *Threatened and declining birds in the New South Wales Sheep-Wheat Belt: Part I. Diagnosis. characteristics and management. Consultancy report to NSW National Parks and Wildlife Service.* CSIRO Wildlife and Ecology, Canberra.	Re	26	12*	8
Reid, J.R.W., Cunningham, R.B., 2008. *Statistical analysis of the Cowra Woodland Birds Program's Bird Database: Trends in individual bird species and composite indices, with brief comments on their relevance to monitoring and evaluation and setting targets for habitat management and restoration. A report to Birds Australia and the Lachlan CMA.* Fenner School (ANU) and CSIRO Sustainable Ecosystems, Canberra.	Re	7	7	13
Robinson, D., 1993. Vale Toolern Vale: the loss of our woodland birds. Wingspan. 9, 1-3, 20-21.	*DD*	*DD*	*DD*	3
Robinson, D., Traill, B. J., 1996. Conserving woodland birds in the wheat and sheep belts of southern Australia. Wingspan (supplement). 6, 1-16.	*DD*	*DD*	*DD*	3
Robinson, D., 2006. Is revegetation in the Sheep Pen Creek area, Victoria, improving Grey-crowned Babbler habitat? Ecol. Manag. Restor. 7, 93-104.	Re	9	6	7
Saunders, D. A., Curry, P. J., 1990. The impact of agricultural and pastoral industry on birds in the southern half of Western Australia: past, present and future. Proc. Ecol. Soc. Aust. 16, 303-321.	La	81	12*	8
Saunders, D. A., Ingram, J., 1995. *Birds of Southwestern Australia: an atlas of changes in distribution and abundance of the wheatbelt fauna.* Surrey Beatty & Sons, Sydney.	Re	91	8*	7
Saunders, D. A., 1989. Changes in the avifauna of a region, district and remnant as a result of fragmentation of native vegetation: the wheatbelt of western Australia. A case study. Biol. Conserv. 50, 99-135.	Re	88	26*	7
Saunders, D. A., 1990. Problems of survival in an extensively cultivated landscape: the case of Carnaby's cockatoo Calyptorhynchus funereus latirostris. Biol. Conserv. 54, 277-290.	La	9	2	4
Saunders, D. A., Rowley, I., Smith, G. T.,1985. The effects of clearing for agriculture on the distribution of cockatoos in the southwest of Western Australia. In Keast, A., Recher, H. F., Ford, H., Saunders, D. A., (eds.). *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation, Management.* Chipping Norton: Surrey Beatty. pp. 309-321.	*DD*	*DD*	*DD*	3
Szabo, J.K., Vesk, P.A., Baxter, P.W.J., Possingham, H.P., 2011. Paying the extinction debt: woodland birds in the Mount Lofty Ranges, South Australia. Emu. 111, 59-70.	Re	9	9	12
Traill, B. J., Collins, E., Peake, P., Jessup, S., 1996. Current and past status of the birds of Chiltern – a box-ironbark forest in north-eastern Victoria. Aust. Bird Watcher. 16, 309-326.	Re	146	6*	5
Traill, B. J., Duncan, S., 2000. *Status of birds in the New South Wales temperate woodlands region.* Consultancy report to the New South Wales National Parks and Wildlife Service. Australian Woodlands Conservancy, Victoria, Australia.	*DD*	*DD*	*DD*	2

Appendix C

Table C1. Proforma used to evaluate the inferential status of each population study included in the review. Each individual inference measure was assigned a weighting (see column: 'Weight') that was used to calculate the inference score for each article. Table abbreviations: 'POI' is the period of inference in years, 'Obs.years' is the number of observation years.

Inference measure	Description	Weight
Trend reporting	*How have authors assessed population change?*	*/1*
Qualitative assessment	Reported trends were based on qualitative measures of population change, e.g. species X became more or less common.	0
Quantitative assessment	Reported trends were based on quantitative measures of population change, e.g. reporting rate of species declined by X over Y years.	1
Data source(s)	*From where have survey data used in the assessment of population change been sourced?*	*/2*
Anecdotal	Population data included published and unpublished anecdotes of population change without any information on data collection.	0
Secondary	Population data included the results of published studies of population change without access to raw survey data.	1
Indirect primary/Primary	Population data included raw survey data collected for (1) a previous ecological study (indirect), or (2) for the reviewed study (primary).	1
Primary only	Population data included only raw survey data collected specifically for the purposes of the study reviewed.	2
Generality	*How generally applicable is the assessment of population change to the conservation of woodland bird species?*	*/1*
Target species	Trends were reported for only one or two targeted species.	0
Species group	Trends were reported for a group of species that share common traits, for example cockatoos or species of conservation concern.	1
All species	Trends were reported for all species that were encountered during surveys (includes studies that apply a minimum detection cut-off).	1
Temporal coverage	*What is the temporal coverage of surveys during the period of trend assessment?*	*/4*
POI sampled < 0.5	Low coverage: surveys were conducted in less than 50% of the years for which trends were assessed	0
POI sampled 0.5 - 0.8	Moderate coverage: surveys were conducted in 50-80% of the years for which trends were assessed	1
POI sampled > 0.8	High coverage: surveys were conducted in more than 80% of the years for which trends were assessed	2
Obs. years > 5	At least 5 years of survey data were used to account for temporal variability in species occurrence.	1
Obs. years > 10	At least 10 years of survey data were used to account for temporal variability in species occurrence.	1

Study design	*What features of the study design have favoured inference about population change?*	*/4*
Replicate sites	Trend estimates derived for a given study area were based on surveys conducted at multiple sites within that area.	1
Repeat visits	Trend estimates derived for a given period of inference were based on sites that were surveyed more than once in an observation year.	1
Consistent method	Trend estimates derived for a given period of inference were based on multiple surveys that used a consistent sampling protocol.	1
Consistent effort	Trend estimates derived for a given period of inference were based on multiple surveys that were conducted evenly through time.	1
Data analysis	*How were surveys analysed to provide indices of population change?*	*/2*
Formal analysis	Reported trends were established from formal statistical analyses of survey data.	1
Survey error	Statistical analyses accounted for variation in sampling method (e.g. protocol or effort) over time when deriving trends.	1
Weather	*Have studies considered the confounding effects of weather in assessments of population change?*	*/1*
Not considered	Weather was not considered in trend assessment.	0
Qualitative assessment	Weather was considered qualitatively in trend assessment, e.g. rainfall in year X may have influenced trend pattern observed for species Y.	1
Quantitative assessment	Weather variables were measured quantitatively to examine the influence it had on population change	1

II. The influence of weather on long-term population trends of birds in an endangered ecological community.

Rigorous assessments of long-term population change are rare for Australian temperate woodland birds. Robust population indices are urgently needed to inform evidence-based conservation planning for this assemblage of species. Further, to assist the objectives of biological conservation, a deeper understanding of the processes that drive population change is essential. In this paper, I quantify the effect of weather variability on the persistence of woodland birds in a modified landscape, paying particular attention to the effects of drought.

Rayner L., Gibbons P., Hutchinson, M. J., Lindenmayer D.B., Stein, J., Wood, J. & Manning A.D. (2014). The influence of weather on long-term population trends of birds in an endangered ecological community.

Abstract

Observed trends in populations of native biota can be confounded with or explained by weather variability. Weather variability therefore needs to be rigorously considered in decision-making. We calculated trends in abundance for 57 bird species over 14 years and assessed the influence of weather variability on those trends. Our results showed that fewer native bird species were declining (n = 5) than might be expected from the existing literature. We also observed no change or an increase in some species of birds identified to be of conservation concern in other regions. Our analyses showed highly variable, species-specific responses to the modelled meteorological parameters, but we nevertheless identified the El Niño-Southern Oscillation (ENSO) as a strong influence on the regional abundances of 26 species. This association was reinforced in a comparison of population trends during and after drought. The group of species we analysed in detail excluded a number of potentially vulnerable birds whose detection was too low for robust trend estimates to be calculated. We found a bias toward the detection of declines where population data were collected during periods of declining or low rainfall. Despite significant effects of ENSO on population dynamics, we found no evidence that a severe drought threatened species persistence over the observation period. However, it should not be assumed that relationships between drought and species persistence will be innocuous in the future, as climate change is expected to exacerbate the dry phase of ENSO and may increase pressure on species whose abundances are suppressed during drought.

Introduction

Arresting biodiversity loss is integral to the protection of ecosystem function (Hooper et al. 2012), including services critical for human well-being and prosperity (Cardinale et al. 2012). Indices of species population change are frequently used to quantify biodiversity loss and help communicate important trend patterns (e.g. Baillie et al. 2010; WWF 2012). However, for such indices to assist the objectives of biological conservation and human development, a deeper understanding of the processes that drive population change is essential (Siriwardena et al. 1998). Identifying drivers of species decline has become a dominant theme in global conservation research (e.g. Clavero and García-Berthou 2005; Potts et al. 2010).

The important role that birds play in supporting a suite of ecosystem functions (Wenny et al. 2011) underpins the need to identify processes that drive long-term change in populations of this group. This is particularly relevant in regions subject to land-use change where declines in bird abundances are frequently documented (Attwood et al. 2009; Marzluff 2001). In these regions, studies have focused heavily on anthropogenic disturbances to explain declines, such as habitat loss (Kerr and Deguise 2004), fragmentation (Rueda et al. 2013) and interactions with non-native species (Beckerman et al. 2007). However, climatic variation is a primary determinant of faunal population dynamics (Stenseth et al. 2002) and can influence the nature and severity of anthropogenic threats to species (Cox et al. 2013; Mantyka-Pringle et al. 2012). Conversely, anthropogenic threats have the potential to alter regional climates (McAlpine et al. 2007) to which populations of species will respond.

With growing concern for the impacts of climate change on biodiversity (IPCC 2013), quantifying meteorological effects on species that are part of threatened ecological communities is needed to underpin effective conservation (Mantyka-Pringle et al. 2012). There is a strong case for this in the temperate zone of Australia, where climate is highly variable (Steffen et al. 2009), landscape responses to climate can be rapid (McAlpine et al. 2007), and inter-annual bird abundances fluctuate markedly (Lindenmayer and Cunningham 2011). Furthermore, land conversion in the temperate zone of Australia has been extensive (Yates et al. 2000) and many bird species are reported to be in severe and ongoing decline (Mac Nally et al. 2009). Of particular concern are those species occupying woodland habitats (Ford 2011) as these areas have been selectively cleared for grazing and cropping.

In a review of the literature dedicated specifically to threatened bird assemblages in the temperate zone, Rayner et al. (2014a) found that patterns of population change are frequently attributed to climatic variability, but that the effect of such variability on longitudinal trends is rarely quantified. Indeed, empirical evidence on how temperate woodland birds respond to meteorological variability is largely limited to short-term studies that investigate weather-driven resource pulses (e.g. Barea and Watson 2007; McGoldrick and Mac Nally 1998). While such studies have provided important information about habitat quality and resource limitation, questions remain over how species respond to prolonged weather events (e.g. drought, Ford 2011), and what role climate plays in apparently declining woodland bird populations (Chambers et al. 2005; Recher et al. 2010).

The aim of our study was to investigate the influence of weather variability on the persistence of woodland birds in a modified landscape. We used bird records collected over a 14-year period, capturing one of the most severe droughts in Australian history (2001-2009) and some of the highest rainfall events that followed. Specifically, we asked: (1) What is the effect of local weather, and broad-scale weather signals, on the abundances of individual bird species? (2) Do these meteorological effects explain significant changes in population growth? And (3) How did the drought, and subsequent high rainfall years, influence trend indices derived for individual species? We focused our assessment on individual species to assist conservation decision-making by identifying species with concerning long-term trend patterns, as well as species that may be susceptible to future climate change.

Methods

Study region

Our study area comprised a 20 km x 40 km area (bounded by -35.1°, 149.3° and -35.6°, 148.9°) in the sub-humid region of the Australian Capital Territory, south-eastern Australia. The area has a cool wet climate with soil moisture availability being highest in winter and spring

(Hutchinson et al. 2005). Annual mean temperatures range from 6 to 16°C. Mean summer temperatures across the observation period ranged from 19 to 22°C (maximum = 31°C), while mean winter temperatures ranged from 6 to 7°C (minimum = -1°C). Annual precipitation is approximately 630 mm (monthly rainfall averages range from 38.4 to 67.4 mm; BOM 2013).

The dominant vegetation type in the study area is temperate eucalypt woodland. These woodlands once covered vast areas of the Australian continent, but have been heavily cleared since European settlement in the mid-1800s (Lindenmayer et al. 2010). Some large intact remnants remain, but most have been perturbed by grazing, altered fire regimes, and invasion by weeds and feral species. Urbanisation presents ongoing threats to woodland extent in the region and significant challenges for protecting the ecological integrity of remnants on the urban fringe (Ikin et al. 2013; Rayner et al. 2014b).

Bird surveys

We obtained bird records for this study from a citizen-based monitoring project run by the Canberra Ornithologists Group. We used data from 92 permanent field sites located in temperate grassy woodland (n = 86) or dry forest contiguous with temperate grassy woodland (n = 6). Sites were dominated by eucalypt tree species, including *Eucalyptus blakelyi*, *E. melliodora*, *E. bridgesiana* and *E. macroryncha*. Several sites were located in peri-urban reserves of strict legal protection.

Sites were surveyed every year for 14 years from 1999 to 2012. Surveys were 10-minute point-counts conducted seasonally (four surveys/site/year) with no changes to survey protocol and little appreciable variation in effort. During surveys, observers counted all birds seen or heard within a 50m radius. Further information on site and survey characteristics is provided in Cunningham and Rowell (2006).

Data exclusion

Prior to trend calculation, we applied data exclusion criteria to ensure meaningful statistical analyses of population change. We excluded the following: (1) *Water birds* because surveys were concentrated on woodland habitat. (2) *Species that occurred in less 1% of surveys* as they provided insufficient data for trend calculation. (3) *Sites that did not contain at least three repeat observations of a species over the 14-year period* to ensure that trend indices were derived using sites where species were known to reoccur. And (4) *Seasons that contained less than 5% of a species' total abundance* to ensure that trend indices for migratory birds were derived using seasons when species occur in the study area. Exclusion criteria left 57 species suitable for trend analysis. We provide a list of these species, with the number of sites and the seasons included in trend calculations, in Appendix A.

Calculating trend indices

We used hierarchical generalised linear modelling (*HGLMs*; Lee et al. 2006) to derive trend indices from abundance data for each species. Exploratory data summaries revealed high intra- and inter-year variability. We fitted cubic regression splines to the time-series data for each individual bird species, setting knots at the terciles of the study period (Cunningham and Olsen 2009). We then fitted HGLMs with the spline parameters and 'season' as fixed effects to obtain a smoothed trend index for each bird species. We used an overdispersed Poisson distribution with a logarithmic link function. We accounted for dependence resulting from site- and time-specific variations in abundance by including 'site' and 'time' as random effects. We included the effects of surveys within a year for each site as random effects to control for small variations in sampling effort. All random effects were gamma distributed with a logarithmic link function. Finally, we fitted a linear trend with season and the same random effects to estimate long-term population change (increase, no change, decline) over the study period. We have presented smoothed trend indices and linear trend lines with 95% confidence intervals to assist inference.

Weather data

We examined both local weather (using individual weather features) and broad-scale weather signals (using climate indices) for their effects on long-term bird abundances. Individual weather features can provide a direct link to local-scale, short-term changes in abundance (Stenseth et al. 2003) and are frequently used to investigate bird-weather relationships (e.g. Stevens and Watson 2013). However, it is sometimes the *combination* of weather features captured by broad-scale climate indices that best predict ecological processes driving population change (Hallett et al. 2004).

We investigated four weather features (temperature, rainfall, soil moisture and plant growth index) and two climate indices (raw and normalised Southern Oscillation Index, '*SOI*' and '*nSOI*') in our study (Table 1, Fig. 1). Both climate indices are measures of El Niño-Southern Oscillation activity ('*ENSO*'). We obtained all weather variables as monthly anomalies from 1998-2012 means and averaged over seasonal and annual time steps for analysis. We accounted for potential delays in species responses to weather by analysing seasonally summarised variables with lags of 0, 3, 6, 9 and 12 months, and annually summarised variables with lags of 0, 12 and 24 months, prior to each survey.

Linking trends to weather

We used HGLMs to identify weather variables that explained significant variation in the long-term trend patterns of individual species. In fitting these models, we considered a suite of measures of ENSO, but pre-selected weather features by examining correlation coefficients between lagged weather features and the Pearson residuals of abundance derived from seasonal survey data. We used residual abundances because the detection of most species (n = 50) was significantly related to season (Appendix A). Therefore, examining abundances with the seasonal effect removed was likely to highlight weather features relevant to long-term change rather than inter-annual variability. All weather variables added to HGLMs were significantly correlated with individual species' residual abundances at $p < 0.05$. Weather variables included in the final species models were refined using backwards stepwise selection. We used stepwise selection as a simple method for eliminating terms that were correlated with species abundances, but did not make a significant contribution to the model.

To examine the effect of weather on population estimates, we compared linear trend indices before and after adding weather parameters to the model. We compared trends in terms of direction (Δ slope) and precision (Δ error).

Table 1. Variables used to investigate relationships between weather and long-term bird abundances. Weather features and climate indices covered the time period 1998-2011 and 1998-2012 respectively. All GROWEST models assumed a mesotherm temperature index. "NCAR" is the National Centre for Atmospheric Research.

Variable	Description and source method	Reference
Weather features		
Temperature (mean, max, min)	Site estimates derived from elevation dependent interpolations of weather station data using thin plate smoothing splines	Hutchinson 2004; Kesteven and Landsberg 2004
Rainfall (mean, total, sqrt)	Site estimates derived from elevation dependent interpolations of weather station data using thin plate smoothing splines	Hutchinson 2004; Kesteven and Landsberg 2004
Soil moisture index	Site estimates derived from GROWEST by a simple water balance model using monthly rainfall and pan evaporation	Hutchinson et al. 2004; Nix 1981
Plant growth index	Site estimates derived from GROWEST by combining the soil moisture index with temperature and solar radiation indices to summarise weather conducive to plant growth	Hutchinson et al. 2004; Nix 1981
Climate indices		
SOI	Broad-scale measure of the Southern Oscillation Index	NCAR:www.cgd.ucar.edu/cas/catalog/climind/
*n*SOI	Broad-scale measure of the Southern Oscillation Index derived using normalisation factors based upon annual means to maximise the signal-to-noise ratio	NCAR:www.cgd.ucar.edu/cas/catalog/climind/; Trenberth 1984

Effects of drought on trends

We explored the effects of the Millennium Drought (2001-2009; van Dijk et al. 2013) on long-term trends in species abundance. To do this, we compared trends in birds derived from the entire time-series (1999-2012) with data until the end of the drought (1999-2010).

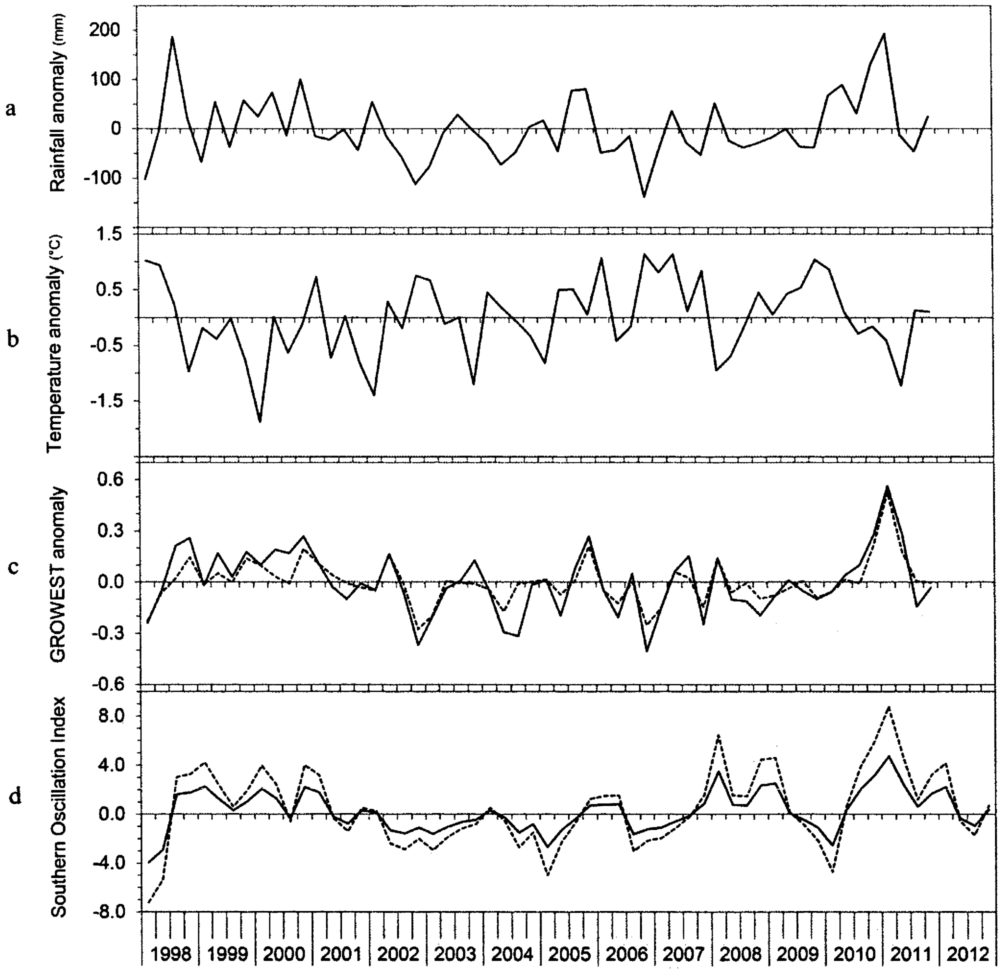

Figure 1. Seasonal values of weather in the study area from 1998-2012. Plots show anomalies in (a) total rainfall, (b) mean temperature and (c) soil moisture index (solid) and plant growth index (dashed) and seasonal means of (d) SOI (solid line) and nSOI (dashed).

Results

Long-term trends in abundance

Our longitudinal bird dataset comprised 4,750 surveys spanning 14 years from 1999 to 2012. From counts of 65,413 individuals, we quantified long-term population change for 57 bird species (Appendix A). For 39 species, we found no significant temporal trend. The remaining 18 species showed significant trend patterns over the study period: 12 with increasing linear trends, and six with declining linear trends (Table 2). Two of these species were introduced to Australia, the increasing Common Starling and declining Common Myna. We show examples of long-term trends for six species in Fig. 2. We provide trend statistics for all species in Appendix A.

Table 2. Species showing significant linear trends in population growth during the study period (1999-2012). Significance tests were set at $p < 0.05$. Species are listed in order of prevalence (i.e. the number of surveys present). "Surveys" is the number of surveys in which a species was detected, "Obs" is the number of observed individuals, and "Sites" is the number of sites where a species was detected. Asterisks (*) denote introduced species.

Species	**Survey**	**Obs.**	**Sites**	**Linear trend**		
				Slope	**S.E.**	**P**
Increasers						
Weebill	1603	3971	85	0.007	0.003	0.008
Australian Magpie	1494	3047	91	0.007	0.002	< 0.001
Galah	1142	2958	67	0.013	0.002	< 0.001
Noisy Miner	894	3008	36	0.011	0.003	< 0.001
Sulphur-crested Cockatoo	753	1817	60	0.016	0.003	< 0.001
Superb Fairy-wren	739	2740	43	0.007	0.003	0.010
Common Starling*	706	3408	34	0.009	0.004	0.028
Australian Raven	507	903	50	0.015	0.004	< 0.001
Magpie Lark	310	579	28	0.009	0.004	0.036
Crested Pigeon	275	534	19	0.035	0.005	< 0.001
White-eared Honeyeater	198	231	19	0.031	0.008	< 0.001
Brown-headed Honeyeater	169	459	15	0.027	0.009	0.002
Decliners						
Striated Thornbill	519	1820	45	-0.010	0.004	0.011
Mistletoebird	296	369	24	-0.020	0.008	0.008
Scarlet Robin	277	404	31	-0.013	0.005	0.012
Common Myna*	237	736	15	-0.038	0.007	< 0.001
Grey Shrike-thrush	155	172	12	-1.138	0.306	0.002
Tree Martin	154	616	10	-0.068	0.012	< 0.001

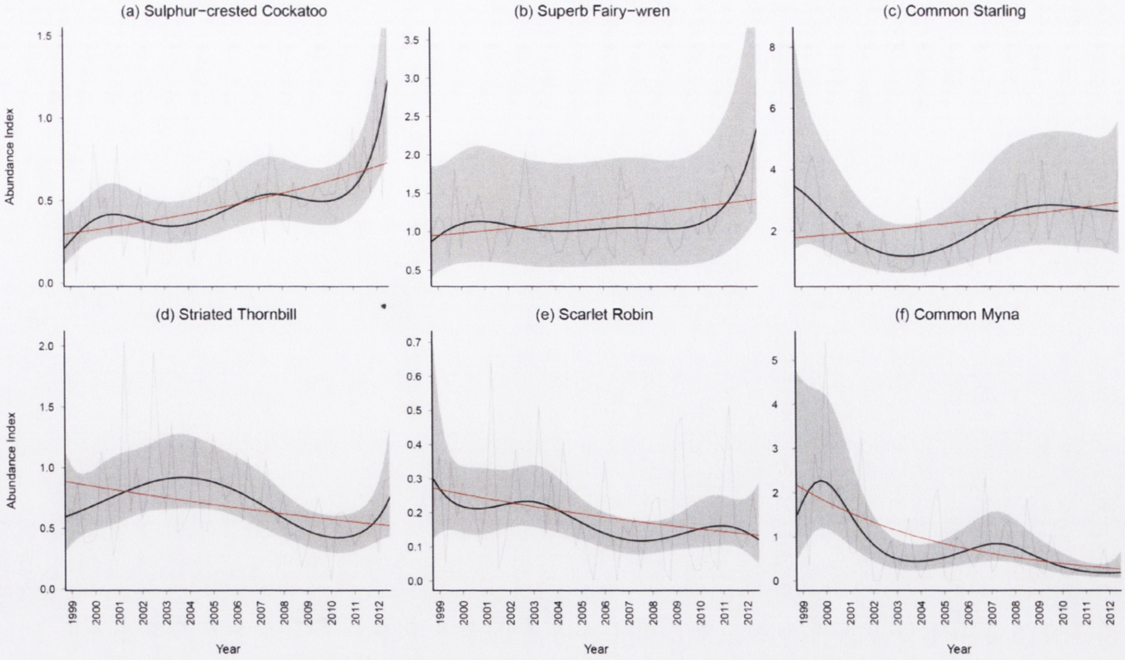

Figure 2. Examples of three increasing (a-c) and three declining (d-f) species, including two introduced species (c and f). Plots show smoothed trend indices (bold line) with 95% confidence intervals (shaded grey), the expected (mean) number of birds per season (dotted line) and the calculated linear trend (red line). All trends displayed are significant at $\alpha = 0.05$. Note: Y axes are scaled to best visualise trend patterns and vary between species.

Bird responses to weather

We identified 34 species whose long-term trends in abundance were significantly influenced by weather. Of these 34 species, SOI was a significant predictor in the models of 26 species, and local weather explained a significant amount of variation for 17 species (9 species responded to a combination of both). Temperature was the most influential local weather feature in the models (13/17 species) indicating a positive association with altitudinal and summer migrants and an inverse relationship with most resident species (6/9 species). However, SOI was the strongest predictor of long-term abundances for most species (18/34 species) showing predominantly positive associations with abundance (12/18 species). Importantly, SOI was also the most common predictor of long-term abundances for species with significant temporal trends (10/13 species), all of which were resident species with the exception of the Tree Martin (Table 3). Further details of each individual species' association with weather are provided in Appendix B.

Effects of weather on trend estimates

Additional variance in population trends for 27 species was explained by weather. In most cases (21 species), adjusting models for weather effects improved the precision of trend estimates, although this effect was usually small (Δ error < 0.001 for 16 species). However, improved precision resulted in three additional species exhibiting significant trend patterns (Increasers: Australian King-parrot and Speckled Warbler, Decliner: Welcome Swallow) that were not previously identified (Table 3; Fig. 3a-c). For these three species, local weather features were more important than broad-scale weather variation. In contrast, improved precision also resulted in the trends of two species no longer being significant (Table 3; Fig. 3d, e). For these two species, SOI was most important.

Adjusting models for weather effects also altered the slope of trend lines for five species (Δ slope > error). Slopes were more positive for four species (Common Bronzewing, Golden Whistler, Varied Sittella, Grey Shrike-thrush) indicating predominantly unfavourable weather conditions during the study period, and more negative for one species (Sacred Kingfisher) indicating predominantly favourable weather conditions during the study period. However, while linear trends were significantly altered for all of these species, only the Grey Shrike-thrush exhibited a significant long-term trend (decline; Fig. 3f). Details of model comparisons are provided in Appendix C.

Table 3. Weather variables significantly associated with increasing or declining bird species from 1999-2012. Only species with significant weather predictors and significant increasing or declining trends are shown. † denotes species that showed significant temporal trends only after models were adjusted for the effects of weather variability. Species in italics showed non-significant trends after adjusting for the effects of weather variability. Asterisks (*) denote introduced species.

Common name	**Predictor (lag)**	**HGLM**			
		Est.	**SE**	**Wald**	**P**
Increasers					
Weebill	Mean annual SOI (24)	-0.142	0.040	12.34	< 0.001
*Common Starling**	*Mean annual SOI*	*0.215*	*0.063*	*11.66*	*< 0.001*
Magpie Lark	*Mean annual SOI*	*0.144*	*0.069*	*4.44*	*0.035*
White-eared Honeyeater	Mean annual SOI	0.213	0.093	5.27	0.022
Brown-headed Honeyeater	Mean annual SOI (24)	-0.191	0.083	5.37	0.020
Australian King-Parrot†	Maximum spring temperature	0.44	0.019	5.51	0.019
Speckled Warbler†	Mean seasonal temperature	0.097	0.036	7.07	0.008
Decliners					
Striated Thornbill	Mean seasonal moisture	-0.980	0.235	17.41	< 0.001
	SOI (12)	-0.095	0.034	7.68	0.006
Scarlet Robin	SOI (9)	0.117	0.055	4.46	0.035
Common Myna*	Mean annual SOI	0.429	0.142	9.16	0.002
Grey Shrike-thrush	Maximum autumn temperature	-0.044	0.007	35.54	< 0.001
	SOI	-0.275	0.093	8.69	0.003
Tree Martin	Mean annual SOI (24)	-0.291	0.106	7.53	0.006
Welcome Swallow†	Mean seasonal temperature (3)	-0.106	0.031	11.66	< 0.001
	Total annual rainfall	0.001	0.001	5.14	0.023

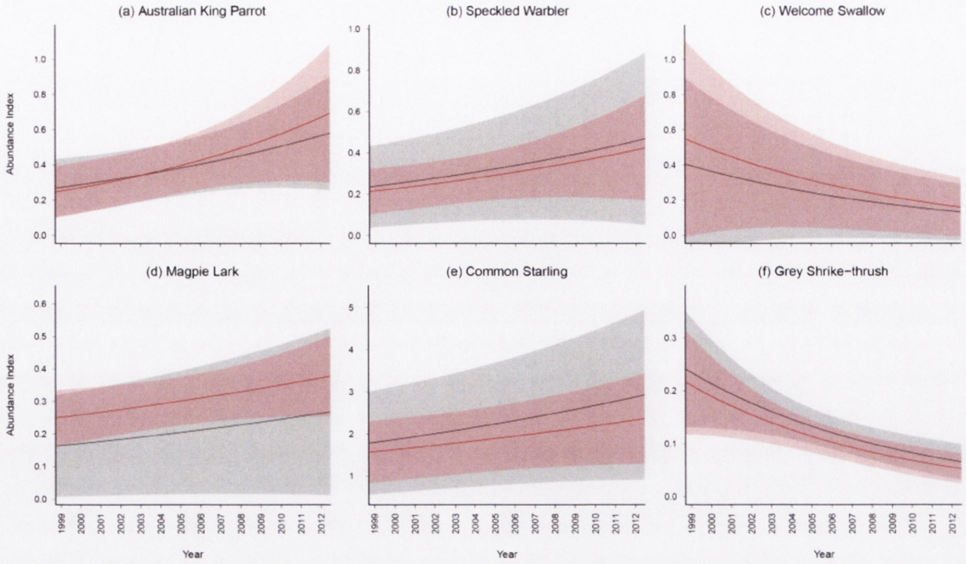

Figure 3. Trend indices for six species with (red) and without (grey) the effects of weather included in the model. Solid lines represent the linear trend for the time-series of each species and shaded areas represent 95% confidence intervals about the linear trend index for each species. All trends displayed are significant at α = 0.05.

Effects of drought on trend patterns

Excluding survey data from post-drought years (2010 to 2012) significantly altered trend indices that were derived from the full time-series of survey data (1999-2012) for a quarter of the study species (14 species, Table 4). Most species went from an increasing trend to no temporal change (4 species, e.g. Superb Fairy-wren, Fig. 4a) or from no temporal change to a declining trend (5 species, e.g. Willie Wagtail, Fig. 4b) when post-drought survey data were excluded. Three species that showed no overall change across the full time-series of survey data were increasing prior to 2010, and two species that showed declines across the full time-series of survey data were stable prior to 2010.

Almost all species whose trends were more negative with the exclusion of post-drought data showed significant positive associations with either rainfall or SOI (8 species, Appendix B). Conversely, two species whose trends were more positive with the exclusion of post-drought data showed negative associations with SOI. This indicates that drought may be augmenting trend indices for these species. However, four species did not respond significantly to rainfall or SOI and are, therefore, more likely to be responding (in most cases negatively) to other environmental drivers (Table 4).

Table 4. Species with trend indices that were altered by the exclusion of post-drought survey data. Trend changes are based on the significance of the linear trend lines derived for each species. We provide P-values for the linear trend lines in parentheses. Asterisks (*) denote introduced species.

Common name	**Full time-series 1999-2012** **Linear trend (p)**	**Drought only 1999-2009** **Linear trend (p)**	**Relationship to SOI or rainfall?**
Positive trend change			
Australian Magpie	Increase (< 0.001)	No change (0.193)	Positive
Common Starling*	Increase (0.028)	No change (0.183)	Positive
Crimson Rosella	No change (0.836)	Decrease (0.045)	Positive
Grey Currawong	No change (0.546)	Decrease (0.034)	Positive
Welcome Swallow	No change (0.054)	Decrease (0.017)	Positive
White-eared Honeyeater	Increase (< 0.001)	No change (0.744)	Positive
Willie Wagtail	No change (0.391)	Decrease (0.010)	Positive
Superb Fairy-wren	Increase (0.010)	No change (0.654)	None
Negative trend change			
Common Bronzewing	No change (0.484)	Increase (0.032)	Negative
Striated Thornbill	Decrease (0.011)	No change (0.096)	Negative
Australian King-Parrot	No change (0.072)	Increase (0.036)	None
Mistletoebird	Decrease (0.008)	No change (0.691)	None
White-winged Chough	No change (0.062)	Increase (0.049)	None

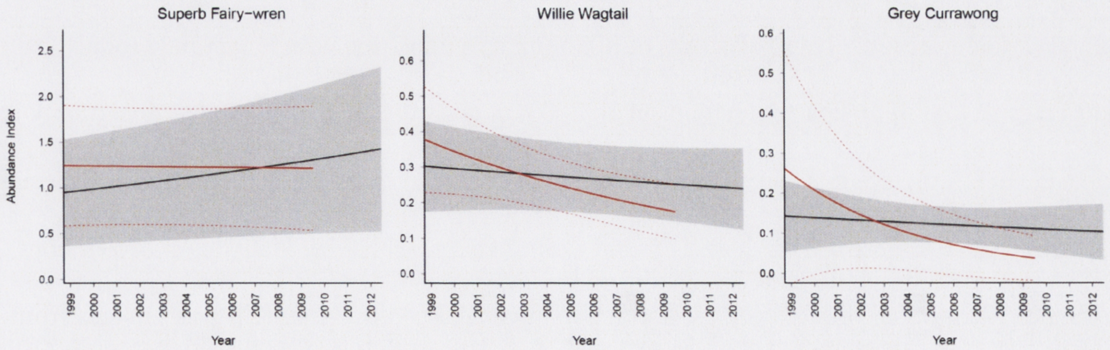

Figure 4. Plots illustrating the difference in trend lines calculated from the full time-series of survey data (black line, 95% confidence intervals shaded grey) and the model excluding post-drought survey data (red line, 95% confidence intervals dashed line).

Discussion

Deriving reliable trend indices is critical for the identification of species undergoing population declines and the development of effective conservation strategies to arrest those declines. In this study, we have explicitly demonstrated the importance of capturing climatic variation in population data used to diagnose declining species. By describing species-weather relationships, we have also provided a more comprehensive assessment of population variability in a nationally threatened assemblage of species, with valuable insights to their persistence in modified landscapes. Specifically, our study demonstrates that: (1) *The majority of bird species showed no significant change in population size over the study period (1999-2012)* and relatively few native species exhibited long-term declines. (2) *Effects of the ENSO explained more variability in the long-term trends of bird species than local-scale weather features*, and improved the accuracy of trend indices for 21 species. And (3) *Trend indices derived during drought varied substantially from those that incorporated post-drought data* for 14 species, with most of these species showing a positive trend change following the drought-breaking rains of 2010.

Long-term trends in abundance

If the conservation literature is searched for empirical evidence of Australian temperate woodland bird decline, we are faced with pervasive uncertainty (Rayner et al. 2014a). Much of this uncertainty results from a shortage of high-quality population data to facilitate robust estimates of long-term change (Jenkins et al. 2003; Szabo et al. 2010). However, uncertainty is also due to strong regional variation in the number, composition and functional traits of species identified to be in decline (Lindenmayer and Cunningham 2011; Mac Nally et al. 2009). For example, the number of bird species reported to have declined in the last 50 years ranges from 4–57 (median = 18) based on 20 studies from southern Australia (Appendix D). Given this range of estimates, the identification of only five native declining species in our study (Table 2) presents a positive, yet potentially conservative, result.

Our result may be conservative for two reasons. First, of the 122 woodland species observed during surveys, only 57 were detected regularly enough to assess long-term trends. This left 61 uncommon or "rare" species whose trends could not be reliably estimated. While many of these species were vagrants or historically uncommon in the study region, populations of other species such as the Jacky Winter, Diamond Firetail and Hooded Robin were once large but are now thought to be in decline (Barrett et al. 1994; Ford et al. 2009; Paton et al. 2004; Reid 1999; Reid and Cunningham 2008). Given such infrequent detection, these populations must be assumed to be vulnerable and targeted research is urgently needed to evaluate their extinction risk. Second, the longitudinal dataset used in this study is relatively short in terms of historical (e.g. extinction debt, Tilman et al. 1994) and climatic (e.g. multiple drought cycles) inference. In particular, many species may have undergone substantial declines prior to the commencement of our surveys, meaning our trend estimates reflect a much reduced baseline of abundance for some species (Pauly 1995). Thus, we acknowledge that our study may have overlooked important losses to the regional avifauna that may have occurred prior to 1999.

Irrespective of these caveats, our trend indices for species that *did* meet the required data criteria were inferentially rigorous. By capturing considerable variation in regional conditions (e.g. climate and land-use), they provide powerful insights to inter-annual population dynamics. Thus, we believe that the relatively small number of native declining species observed (< 10% of species) from the group of species analysed is a robust assessment for this system. Also robust is the lack of evidence for pervasive declines in species of broader conservation concern, such as the Brown Treecreeper and Speckled Warbler (Barrett et al. 1994; Ford et al. 2009; Paton et al. 2004; Reid 1999). Furthermore, while the majority of increasing species listed here were large-bodied generalists that have shown similar population growth elsewhere (e.g. Ellis and Taylor 2013; Szabo et al. 2011), an important exception was the Superb Fairy-wren (also previously noted for declines, Szabo et al. 2011); a small-bodied species (ca. 10g) that exhibited a positive linear trend in our study.

The five native birds exhibiting declines in our study area were the Grey Shrike-thrush, Striated Thornbill, Mistletoebird, Tree Martin, and Scarlet Robin. Rigorous trend assessments from two woodland studies conducted over a similar time period within 160 km of our study area (South-west slopes: Lindenmayer and Cunningham 2011; Cowra: Reid and Cunningham 2008) did not identify any of these species as declining. Further abroad, temporal population trends for the Grey Shrike-thrush, Striated Thornbill and Mistletoebird are markedly inconsistent (e.g. Cunningham and Olsen 2009; Szabo et al. 2011) suggesting that conservation gains for these species may best be achieved through regional-scale management. More concerning, however, are trends for the Tree Martin and Scarlet Robin. We identified these species to be declining in our study area and similar declines have been reported throughout their range (Barrett et al. 2003; Barrett et al. 1994; Paton et al. 2004; Szabo et al. 2011). Hence, these species appear to be in need of immediate conservation action.

Effects of the ENSO and drought

Our results showed that, while species abundance was often correlated with local weather, effects of the ENSO explained more variation in long-term abundances than any single weather parameter. The strength of climate indices for describing population dynamics has been demonstrated in various parts of the world for mammals (Dickman et al. 2001; Lima et al. 2002; Stapp et al. 2004), birds (Forchhammer et al. 1998; Grant et al. 2000; Manning et al. 2007), amphibians (Forchhammer et al. 1998), arthropods (Polis et al. 1998) and marine biota (Defeo et al. 2013; Drinkwater et al. 2003). Stenseth et al. (2003) and Hallett et al. (2004) suggest that these relationships occur because broad-scale climate indices offer a more holistic examination of meteorological conditions (operating through local, interacting weather parameters) that drive ecological processes affecting species populations. Thus, the strength of ENSO as a predictor of species abundance in our study is likely to have emerged as a result of its strong influence over local temperature and rainfall extremes (McAlpine et al. 2007; Nicholls et al. 1997), particularly rainfall deficits recorded during drought (van Dijk et al. 2013).

Effects of ENSO in this study manifested as a positive relationship between species abundances and SOI in most cases. That is, abundances were typically suppressed during the El Niño cycle (onset: 2002), and boosted during La Niña cycles (onset: 1998 and 2010). Recently, the positive influence of La Niña on faunal abundances is documented for other Australian bird assemblages (Pavey and Nano 2013; Tischler et al. 2013) as well as for small mammals (Greenville et al. 2013; Kelly et al. 2013; Pavey and Nano 2013). However, it is critical to note that the El Niño cycle did not significantly suppress abundances of all species in our study (e.g. Striated Thornbill) and we found no evidence to indicate that El Niño was responsible for long-term declines. Thus, our results offer additional support for studies that link declines in bird abundance to below-average rainfall years (e.g. Mac Nally et al. 2009; Reid and Cunningham 2008; Stevens and Watson 2013), but we emphasise that this relationship will not be consistent across species, and does not (of itself) appear to present a significant threat to species persistence.

Climate change

It is becoming increasingly important to evaluate the impacts of climate change on species persistence. It is highly likely that the behaviour of the ENSO will continue to change with global warming, leading to increased drying in Australia during future El Niño cycles (Power et al. 2013). The frequency of El Niño in Australia has increased in recent years (Steffen et al. 2009). This is consistent with computer projections by Cai et al. (2014) that the frequency of El Niños is likely to increase under greenhouse warming. Moreover, temperatures have been disproportionately increasing, and rainfall decreasing, for a given value of SOI since the 1970's (Nicholls 2003). Taken with the patterns observed for species in this study, droughts are likely to become increasingly arduous for some woodland birds (Recher et al. 2010). However, the lack of consistency among species' responses to climatic variability observed here suggests that species, rather than communities, will need to be the unit of measure for assessing the range of future climate impacts on birds in this ecosystem (Midgley et al. 2003; Peterson 2003). For this task, our study provides a valuable baseline for future research.

Conclusion

Identification of significant trend patterns in woodland bird species can be strongly influenced by the length of, and climatic conditions associated with, the sample period. For example, trend indices derived from population data that culminate in periods of drought have the potential to bias estimates toward decline for many species that may in fact recover their abundances post-drought. We have shown that broad-scale weather plays an important role in regulating species abundances. Therefore, assessments of population change should seek to reflect the temporal scale at which these broad climatic processes operate. Doing so will refine our predictions of species population growth and persistence, but relies heavily on systematic field-based monitoring and access to high accuracy climate and weather measurements.

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Appendix A

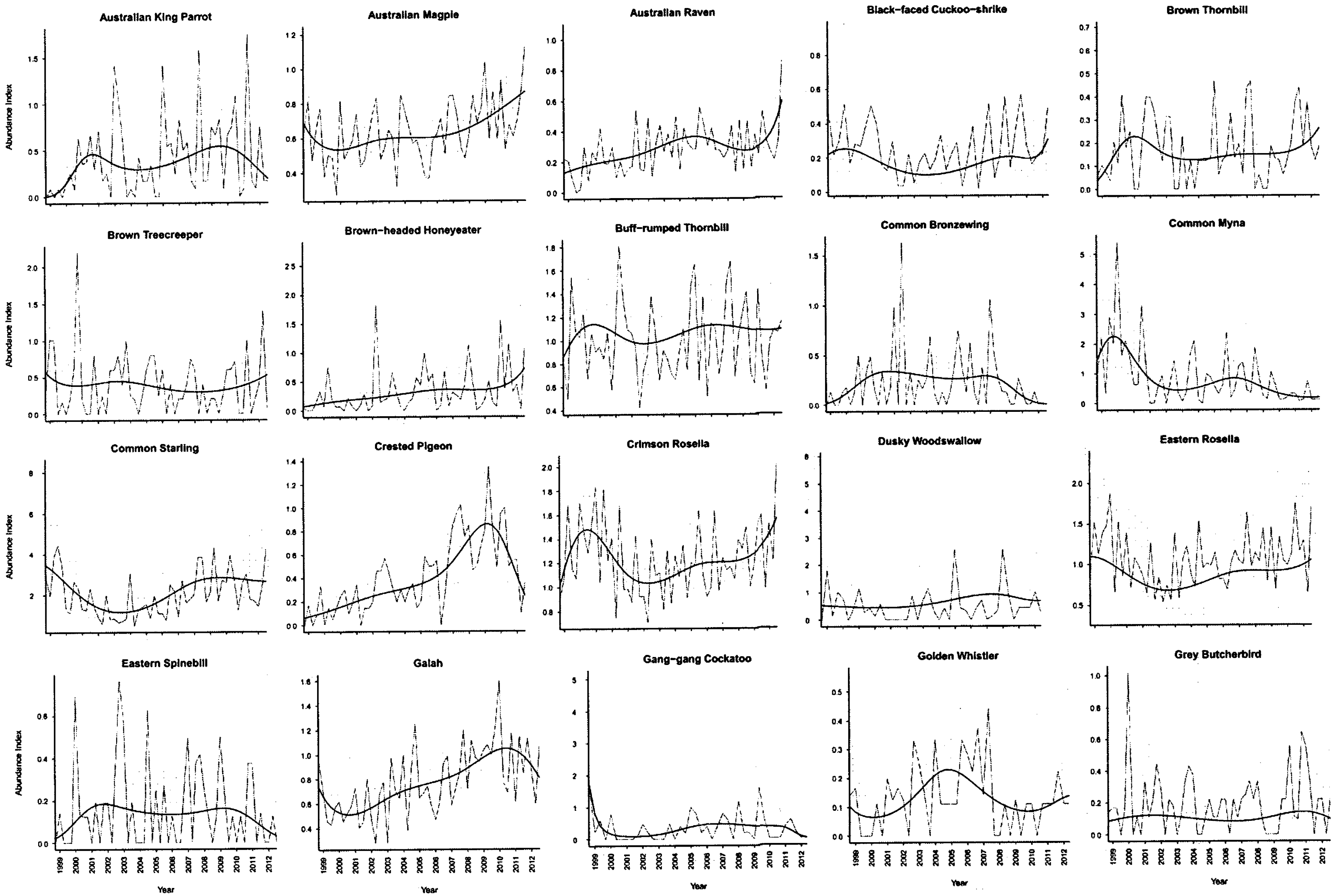
Table A1. Fifty-seven species analysed for long-term trends in abundance. For each species we report the number of: surveys present, individuals observed over the 14-year period, sites included in trend analysis (sites with > 3 observations of the species). We also report the effect of season on long-term abundances (P-value) and seasons excluded from trend analysis due to < 5% of a species total abundance. Nomenclature is taken from Christidis & Boles 2008. Migratory species are indicated by an aterisk (*) after Taylor and COG 1992.

Common name	Scientific name	Survey present (n)	Indiv. obs. (n)	Sites obs. (n)	Season effect (p)	Seasons excluded	Linear trend (p)	Slope ± SE
Australian King-Parrot	*Alisterus scapularis*	133	350	12	< 0.001	None	No change (0.072)	0.014 ± 0.0078
Australian Magpie	***Gymnorhina tibicen***	**1494**	**3047**	**91**	**< 0.001**	None	**Increase (< 0.001)**	**0.0067 ± 0.0021**
Australian Raven	***Corvus coronoides***	**507**	**903**	**50**	**< 0.001**	None	**Increase (< 0.001)**	**0.015 ± 0.0043**
Black-faced Cuckoo-shrike *	*Coracina novaehollandiae*	493	742	60	< 0.001	W	No change (0.970)	0.000 ± 0.0063
Brown-headed Honeyeater	***Melithreptus brevirostris***	**169**	**459**	**15**	**< 0.001**	None	**Increase (0.002)**	**0.027 ± 0.0085**
Brown Thornbill	*Acanthiza pusilla*	168	277	16	< 0.001	None	No change (0.497)	0.004 ± 0.0059
Brown Treecreeper	*Climacteris picumnus*	72	129	5	0.010	None	No change (0.628)	-0.0037 ± 0.0077
Buff-rumped Thornbill	*Acanthiza reguloides*	904	3203	62	0.062	None	No change (0.589)	0.00136 ± 0.0025
Common Bronzewing *	*Phaps chalcoptera*	113	156	8	0.004	None	No change (0.484)	-0.007 ± 0.0104
Common Myna	***Acridotheres tristis***	**237**	**736**	**15**	**< 0.001**	None	**Decrease (< 0.001)**	**-0.0377 ± 0.0067**
Common Starling	***Sturnus vulgaris***	**706**	**3408**	**34**	**0.189**	None	**Increase (0.028)**	**0.0090 ± 0.0041**
Crested Pigeon	***Ocyphaps lophotes***	**275**	**534**	**19**	**< 0.001**	None	**Increase (< 0.001)**	**0.035 ± 0.0054**
Crimson Rosella	*Platycercus elegans*	2072	5866	92	< 0.001	None	No change (0.836)	0.0003 ± 0.00162
Dusky Woodswallow*	*Artamus cyanopterus*	83	238	7	0.046	W	No change (0.163)	0.0186 ± 0.0134
Eastern Rosella	*Platycercus eximius*	1341	3923	69	< 0.001	None	No change (0.393)	0.0017 ± 0.0020
Eastern Spinebill *	*Acanthorhynchus tenuirostris*	92	111	8	< 0.001	None	No change (0.850)	-0.002 ± 0.0097
Galah	***Cacatua roseicapilla***	**1142**	**2958**	**67**	**< 0.001**	None	**Increase (< 0.001)**	**0.0127 ± 0.0024**

Gang-gang Cockatoo *	*Callocephalon fimbriatum*	57	133	5	0.032	W	No change (0.725)	-0.0049 ± 0.0139
Golden Whistler*	*Pachycephala pectoralis*	139	159	8	< 0.001	S	No change (0.853)	0.002 ± 0.0109
Grey Butcherbird	*Cracticus torquatus*	142	164	9	< 0.001	None	No change (0.667)	0.003 ± 0.0066
Grey Currawong	*Strepera versicolor*	84	107	6	< 0.001	None	No change (0.546)	-0.006 ± 0.0097
Grey Fantail *	*Rhipidura fuliginosa*	1182	2013	76	< 0.001	None	No change (0.734)	0.0009 ± 0.0028
Grey Shrike-thrush	***Colluricincla harmonica***	**155**	**172**	**12**	**< 0.001**	None	**Decrease (0.002)**	**-1.138 ± 0.3064**
Laughing Kookaburra	*Dacelo novaeguineae*	224	348	20	< 0.001	None	No change (0.445)	0.005 ± 0.0061
Leaden Flycatcher *	*Myiagra rubecula*	123	179	11	< 0.001	W	No change (0.379)	-0.009 ± 0.0098
Magpie-lark	***Grallina cyanoleuca***	**310**	**579**	**28**	**< 0.001**	None	**Increase (0.036)**	**0.009 ± 0.0043**
Mistletoebird *	***Dicaeum hirundinaceum***	**296**	**369**	**24**	**< 0.001**	W	**Decrease (0.008)**	**-0.0203 ± 0.0077**
Noisy Friarbird *	*Philemon corniculatus*	491	826	57	< 0.001	W	No change (0.578)	-0.0049 ± 0.0088
Noisy Miner	***Manorina melanocephala***	**894**	**3008**	**36**	**0.314**	None	**Increase (< 0.001)**	**0.0114 ± 0.0028**
Olive-backed Oriole *	*Oriolus sagittatus*	116	136	8	< 0.001	W	No change (0.878)	-0.002 ± 0.0132
Pied Currawong *	*Strepera graculina*	541	1089	39	< 0.001	None	No change (0.642)	0.0021 ± 0.0045
Red-rumped Parrot	*Psephotus haematonotus*	256	935	18	0.615	None	No change (0.254)	-0.0056 ± 0.0049
Red Wattlebird *	*Anthochaera carunculata*	567	1186	55	< 0.001	None	No change (0.406)	0.0049 ± 0.0059
Rufous Whistler *	*Pachycephala rufiventris*	598	784	53	< 0.001	W	No change (0.122)	-0.0063 ± 0.0041
Sacred Kingfisher *	*Todiramphus sanctus*	56	74	5	< 0.001	W,A	No change (0.083)	0.051 ± 0.0294
Scarlet Robin	***Petroica multicolor***	**277**	**404**	**31**	**< 0.001**	None	**Decrease (0.012)**	**-0.013 ± 0.0051**
Silvereye *	*Zosterops lateralis*	145	481	10	< 0.001	None	No change (0.884)	0.0014 ± 0.0095
Speckled Warbler	*Chthonicola sagittata*	215	401	20	0.014	None	No change (0.078)	0.012 ± 0.0071
Spotted Pardalote	*Pardalotus punctatus*	719	1426	74	< 0.001	None	No change (0.114)	0.0085 ± 0.0054
Striated Pardalote *	*Pardalotus striatus*	1620	3409	88	< 0.001	None	No change (0.166)	0.0047 ± 0.0034
Striated Thornbill	***Acanthiza lineata***	**519**	**1820**	**45**	**0.034**	None	**Decrease (0.011)**	**-0.0096 ± 0.0038**
Sulphur-crested Cockatoo *	***Cacatua galerita***	**753**	**1817**	**60**	**< 0.001**	None	**Increase (< 0.001)**	**0.016 ± 0.0031**
Superb Fairy-wren	***Malurus cyaneus***	**739**	**2740**	**43**	**0.639**	None	**Increase (0.010)**	**0.00740 ± 0.0029**
Tree Martin *	***Hirundo nigricans***	**154**	**616**	**10**	**< 0.001**	W,A	**Decrease (< 0.001)**	**-0.0678 ± 0.0120**
Varied Sitella	*Daphoenositta chrysoptera*	76	278	2	0.008	None	No change (0.322)	0.015 ± 0.0152
Weebill	***Smicornis brevirostris***	**1603**	**3971**	**85**	**< 0.001**	None	**Increase (0.008)**	**0.0067 ± 0.0025**
Welcome Swallow *	*Hirundo neoxena*	59	115	4	0.03	None	No change (0.054)	-0.0204 ± 0.0106

Western Gerygone *	*Gerygone fusca*	184	234	18	< 0.001	W	No change (0.225)	-0.010 ± 0.0081
White-eared Honeyeater	***Lichenostomus leucotis***	**198**	**231**	**19**	**< 0.001**	**S**	**Increase (< 0.001)**	**0.031 ± 0.0083**
White-plumed Honeyeater	*Lichenostomus pencillatus*	389	1032	18	0.346	None	No change (0.229)	-0.0057 ± 0.0048
White-throated Gerygone *	*Gerygone olivacea*	301	392	30	< 0.001	W	No change (0.207)	-0.0082 ± 0.0065
White-throated Treecreeper	*Cormobates leucophaeus*	489	574	41	< 0.001	None	No change (0.218)	-0.004 ± 0.0031
White-winged Chough	*Corcorax melanorhamphos*	265	1386	29	0.01	None	No change (0.062)	0.0122 ± 0.0065
White-winged Triller	*Lalage tricolor*	50	72	2	0.011	W,A	No change (0.246)	-0.0406 ± 0.0350
Willie Wagtail	*Rhipidura leucophrys*	194	255	15	< 0.001	None	No change (0.391)	-0.004 ± 0.0050
Yellow-faced Honeyeater *	*Lichenostomus chrysops*	459	2243	47	< 0.001	None	No change (0.427)	-0.007 ± 0.0085
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*	455	1669	45	0.139	None	No change (0.878)	-0.0005 ± 0.0034

S = Summer, A = Autumn, W = Winter, Sp = Spring; * = migratory


Australian King Parrot
Australian Magpie
Australian Raven
Black-faced Cuckoo-shrike
Brown Thornbill
Brown Treecreeper
Brown-headed Honeyeater
Buff-rumped Thornbill
Common Bronzewing
Common Myna
Common Starling
Crested Pigeon
Crimson Rosella
Dusky Woodswallow
Eastern Rosella
Eastern Spinebill
Galah
Gang-gang Cockatoo
Golden Whistler
Grey Butcherbird
Abundance Index
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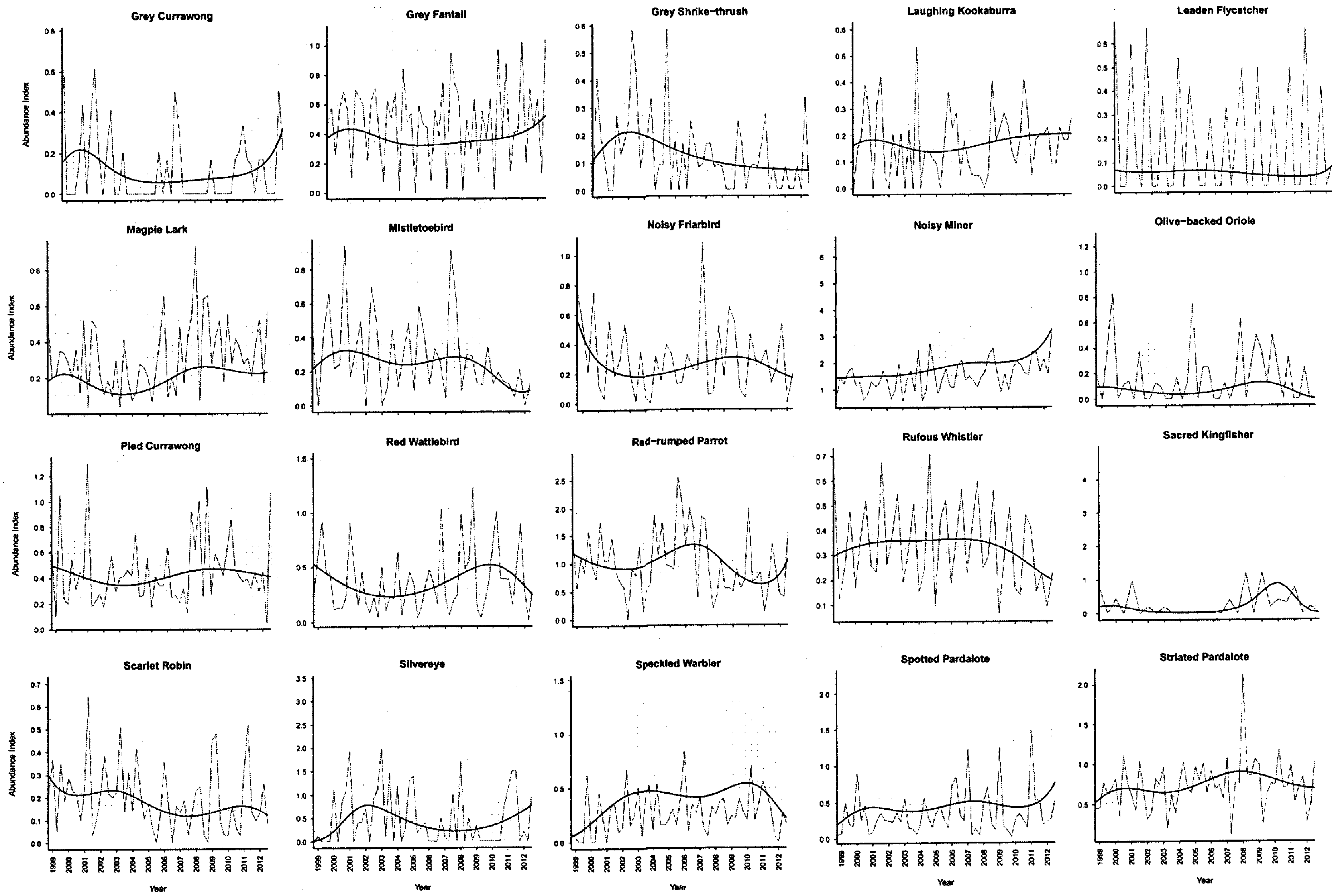
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Grey Fantail
Grey Shrike-thrush
Laughing Kookaburra
Leaden Flycatcher
Magpie Lark
Mistletoebird
Noisy Friarbird
Noisy Miner
Olive-backed Oriole
Pied Currawong
Red Wattlebird
Red-rumped Parrot
Rufous Whistler
Sacred Kingfisher
Scarlet Robin
Silvereye
Speckled Warbler
Spotted Pardalote
Striated Pardalote
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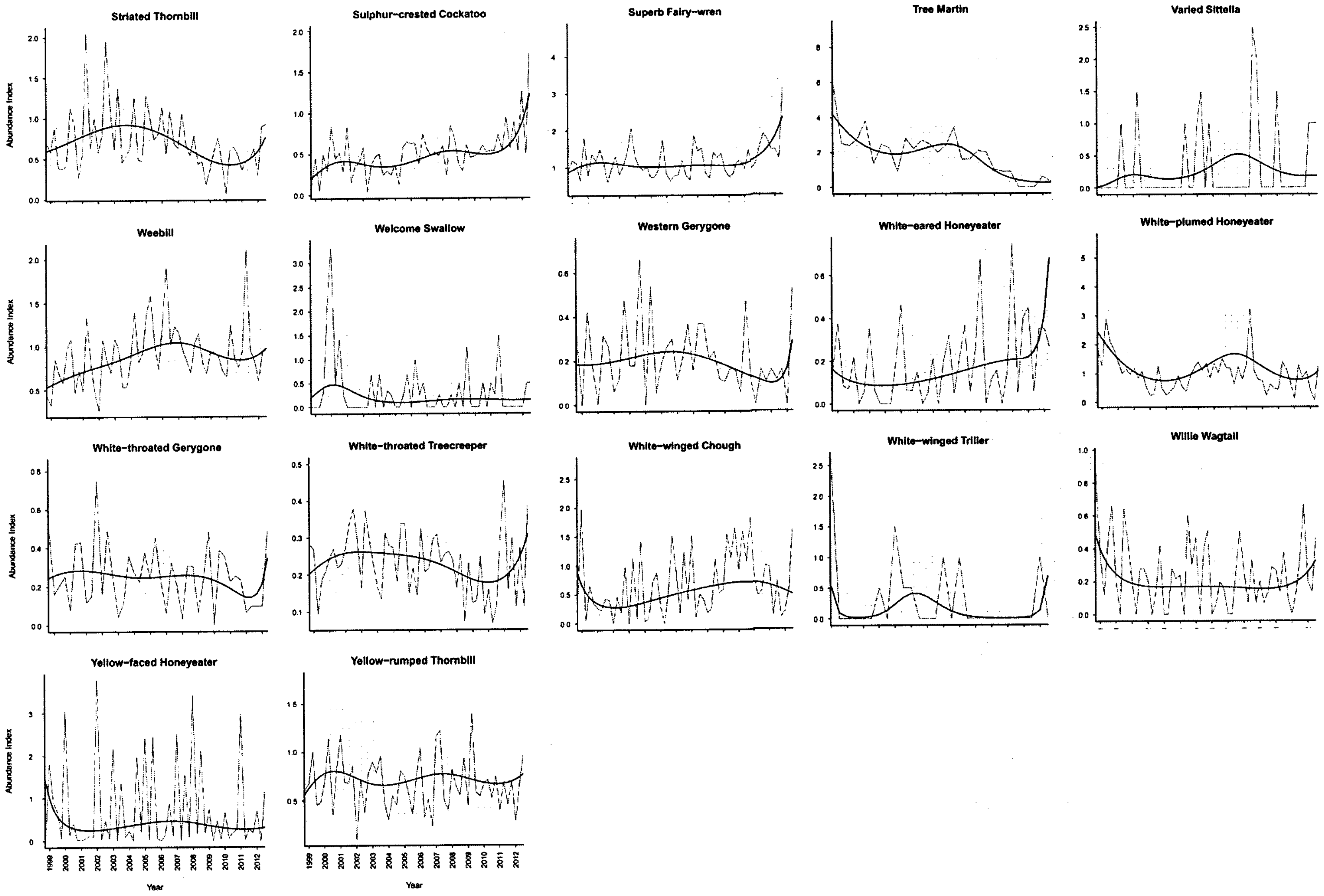
Striated Thornbill
Sulphur-crested Cockatoo
Superb Fairy-wren
Tree Martin
Varied Sittella
Weebill
Welcome Swallow
Western Gerygone
White-eared Honeyeater
White-plumed Honeyeater
White-throated Gerygone
White-throated Treecreeper
White-winged Chough
White-winged Triller
Willie Wagtail
Yellow-faced Honeyeater
Yellow-rumped Thornbill
Abundance Index
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Appendix B

Table B1. Significant weather correlates of species abundance (correlation analysis) and predictors of longitudinal trends in abundance (HGLM). Correlation analyses were only performed to reduce the number of weather parameters; therefore correlation statistics are not reported for climate indices. Blank cells indicate no significant weather or climate predictor. Lag time is reported in months (3, 6, 9, 12, 24) and is zero unless specified in parentheses after each predictor variable. Seasonal effect was non-significant and therefore removed from analysis for species marked with an asterisk (*).

Common name	Predictor (lag)	Correlation		HGLM			
		R	*P*	Est.	SE	Wald	*P*
Australian King-Parrot	Maximum spring temperature	-5.94	0.025	0.44	0.019	5.51	0.019
	ENSO annual (3)	0.30	0.022	-0.026	0.044	0.36	0.547
	Square root seasonal rainfall (9)	0.330	0.014	-0.011	0.046	0.06	0.809
Australian Magpie	Mean Annual ENSO (24)	-	-	0.035	0.020	2.87	0.090
Australian Raven	Mean autumn moisture	0.612	0.020	-0.426	0.300	2.01	0.156
Black-faced Cuckoo-shrike	ENSO (6)	-	-	0.221	0.065	11.46	< 0.001
	Mean spring temperature	-0.734	0.003	-0.011	0.017	0.41	0.522
Brown-headed Honeyeater	Mean Annual ENSO (24)	-	-	-0.191	0.083	5.37	0.020
	Mean annual growth (3)	0.619	0.018	-0.345	1.153	0.09	0.765
Brown Thornbill	Mean seasonal growth (6)	0.290	0.028	1.120	0.615	3.31	0.069
	ENSO (12)	-	-	0.068	0.061	1.24	0.266
	Minimum seasonal temperature (3)	-0.280	0.040	0.051	0.060	0.73	0.394
	ENSO (6)	0.420	0.001	-0.022	0.080	0.074	0.785
Brown Treecreeper	Square root seasonal rainfall (9)	0.320	0.015	0.137	0.047	8.459	0.004
	Mean annual nENSO (12)	-	-	-0.191	0.082	5.379	0.020
	Mean winter temperature	0.624	0.017	-0.133	0.066	4.091	0.043
	Minimum annual temperature	0.840	< 0.001	0.155	0.219	0.498	0.480
	Mean seasonal temperature (12)	-0.320	0.015	0.073	0.158	0.213	0.644
Buff-rumped Thornbill *	Mean autumn temperature	0.559	0.038	0.050	0.011	21.61	< 0.001
	Mean spring temperature	0.651	0.012	-0.039	0.011	12.11	< 0.001
	Maximum seasonal temperature (12)	0.390	0.003	-0.011	0.005	4.37	0.037

	Mean annual ENSO (12)	-	-	0.066	0.044	2.26	0.133
	Mean winter growth	0.886	< 0.001	4.165	2.711	2.36	0.124
Common Bronzewing	Mean annual temperature	0.583	0.029	0.187	0.057	10.69	0.001
	ENSO (6)	-	-	-0.218	0.097	9.50	0.025
	Maximum seasonal temperature (12)	0.280	0.036	0.141	0.099	2.04	0.154
Common Myna	Mean annual ENSO	0.605	0.029	0.429	0.142	9.16	0.002
	Mean annual moisture	0.784	0.001	-0.901	0.834	1.17	0.280
	Mean annual temperature	-0.820	< 0.001	0.046	0.038	1.42	0.234
	Mean winter temperature	-0.576	0.031	0.032	0.142	0.61	0.433
	Total autumn rainfall	0.600	0.023	-0.001	0.002	0.46	0.498
Common Starling *	Mean annual ENSO	-0.290	0.032	0.215	0.063	11.66	< 0.001
Crested Pigeon	Mean annual ENSO	0.638	0.019	0.128	0.077	2.79	0.095
	Total autumn rainfall	0.649	0.012	0.002	0.002	0.95	0.329
	Total seasonal rainfall (6)	0.360	0.007	<0.001	0.001	0.05	0.827
Crimson Rosella	Mean seasonal temperature (9)	-0.300	0.025	-0.016	0.008	3.95	0.047
	ENSO (3)			0.032	0.017	3.95	0.059
	Sqaure root seasonal rainfall (12)	0.310	0.021	0.008	0.009	0.72	0.395
Dusky Woodswallow	nENSO (3)	-0.310	0.043	-0.081	0.049	2.76	0.097
	Maximum winter temperature	-0.564	0.036	0.021	0.040	0.27	0.601
	Mean seasonal growth (6)	-0.470	0.002	-0.646	1.445	0.20	0.655
Eastern Rosella	ENSO (9)	-	-	0.072	0.018	15.72	< 0.001
	Minimum seasonal temperature (3)	-0.270	0.044	< 0.001	0.019	< 0.001	0.980
Eastern Spinebill	Mean annual ENSO (24)			-0.259	0.186	1.931	0.165
	Maximum seasonal temperature (6)	0.320	0.015	< 0.001	0.034	< 0.001	0.990
Galah	Maximum seasonal temperature (6)	0.380	0.004	0.010	0.007	2.12	0.145
	ENSO (3)	-0.272	0.043	-0.027	0.025	1.24	0.266
Gang-gang Cockatoo	Maximum seasonal temperature (9)	0.460	0.002	0.379	0.139	7.41	0.006
	Mean annual ENSO (24)	-	-	-0.419	0.211	3.95	0.047
	Minimum annual temperature	0.867	<0.001	0.307	0.165	3.46	0.063
	Mean spring temperature	-0.649	0.012	0.075	0.098	0.58	0.446
Golden Whistler	Mean annual ENSO (12)	-	-	-0.362	0.137	6.96	0.008
	Mean seasonal moisture	-0.310	0.042	-1.086	0.563	3.72	0.054
	Mean spring temperature	0.536	0.048	-0.032	0.036	0.77	0.381
	Minimum seasonal temperature (6)	0.390	0.010	0.104	0.080	1.70	0.193

	Mean winter growth	0.569	0.034	-2.988	9.616	0.10	0.756
	Sqaure root seasonal rainfall (12)	-0.360	0.018	0.006	0.044	0.02	0.889
Grey Butcherbird	Mean annual ENSO	-	-	0.166	0.102	2.63	0.105
	Mean summer moisture	0.597	0.024	0.448	0.549	0.67	0.414
Grey Currawong	Mean annual ENSO (24)	-	-	0.517	0.180	8.28	0.004
	Mean annual temperature	0.576	0.031	-0.044	0.045	0.93	0.335
Grey Fantail	ENSO (9)	-	-	0.081	0.028	8.24	0.004
	Minimum autumn temperature	-0.657	0.011	0.023	0.030	0.83	0.361
Grey Shrike-thrush *	Maximum autumn temperature	-0.621	0.018	-0.044	0.007	35.54	< 0.001
	ENSO	-	-	-0.275	0.093	8.69	0.003
	Maximum seasonal temperature (12)	0.330	0.014	0.099	0.053	3.47	0.062
Laughing Kookaburra	nENSO	-	-	0.065	0.053	1.51	0.219
	Maximum seasonal temperature (12)	-0.300	0.022	-0.006	0.025	0.06	0.800
	Total seasonal rainfall	-0.400	0.002	0.001	0.002	0.10	0.747
Leaden Flycatcher	Mean seasonal growth (9)	-0.310	0.044	-1.971	1.273	2.40	0.122
	ENSO (6)	-	-	0.075	0.134	0.31	0.576
Magpie-lark	Mean annual ENSO	-	-	0.144	0.069	4.44	0.035
	Mean autumn growth	-0.599	0.024	-1.076	0.639	2.84	0.092
	Minimum summer temperature	0.536	0.048	0.003	0.017	0.03	0.875
	Mean seasonal moisture	-0.410	0.002	-0.072	0.381	0.04	0.849
Mistletoebird	nENSO (6)	0.690	0.009	-0.067	0.043	2.50	0.114
	Mean annual growth	0.537	0.048	1.802	1.148	2.46	0.117
Noisy Friarbird	ENSO (9)	-	-	0.131	0.062	4.39	0.036
	Total seasonal rainfall (12)	-0.320	0.037	-0.001	0.002	0.29	0.593
Noisy Miner *	Mean annual ENSO (12)	0.732	0.005	0.052	0.027	3.64	0.057
	Maximum seasonal temperature (12)	-0.290	0.032	0.006	0.005	1.22	0.269
	Mean annual growth	0.580	0.030	-0.080	0.426	0.04	0.850
Olive-backed Oriole	Minimum summer temperature	-0.666	0.009	0.110	0.052	4.43	0.035
	Mean annual ENSO (12)	-	-	0.340	0.170	4.00	0.046
	Mean summer temperature (9)	-0.537	0.048	-0.036	0.148	0.06	0.806
Pied Currawong	Mean annual ENSO	-	-	0.112	0.071	2.46	0.117
Red-rumped Parrot *	ENSO annual (12)	-0.288	0.031	-0.124	0.049	6.44	0.011
	Maximum autumn temperature	0.559	0.038	0.004	0.006	0.39	0.533
	Square root spring rainfall	-0.742	0.002	-0.005	0.015	0.13	0.716

	Minimum seasonal temperature (3)	0.290	0.033	0.005	0.017	0.09	0.767
Red Wattlebird	Maximum winter temperature	-0.798	0.001	-0.041	0.011	14.07	< 0.001
	Square root annual rainfall	0.676	0.008	0.014	0.005	9.02	0.003
	nENSO	-	-	0.065	0.037	3.14	0.076
Rufous Whistler	Mean annual ENSO (24)	-	-	-0.092	0.054	2.87	0.090
	Total seasonal rainfall (12)	0.390	0.011	-0.0001	0.001	0.11	0.741
	Minimum seasonal temperature (9)	-0.340	0.026	0.008	0.028	0.07	0.786
Sacred Kingfisher	Mean annual ENSO (12)	-0.529	0.063	0.919	0.287	10.24	0.001
	Maximum seasonal temperature (12)	0.390	0.038	0.545	0.179	9.32	0.002
Scarlet Robin	ENSO (9)	-	-	0.117	0.055	4.46	0.035
	Total winter rainfall	0.712	0.004	-0.001	0.001	1.20	0.273
	Total spring rainfall	0.651	0.012	-0.001	0.001	0.34	0.561
Silvereye	Mean seasonal growth (6)	0.500	<0.001	2.578	0.957	7.26	0.007
	ENSO	0.326	0.014	-0.162	0.105	2.38	0.123
	Minimum seasonal temperature (3)	-0.370	0.006	0.088	0.105	0.70	0.405
Speckled Warbler	Mean seasonal temperature	-0.350	0.009	0.097	0.036	7.07	0.008
	ENSO (3)	0.270	0.043	-0.084	0.070	1.45	0.228
	Square root seasonal rainfall (6)	0.270	0.041	0.026	0.036	0.51	0.475
Spotted Pardalote	ENSO (12)	0.545	0.054	0.107	0.057	3.47	0.062
	Mean annual growth	0.781	< 0.001	0.385	0.793	0.23	0.628
	Minimum seasonal temperature (3)	0.310	0.019	0.020	0.069	0.08	0.773
Striated Pardalote	Minimum seasonal temperature (3)	0.340	0.011	0.057	0.038	2.24	0.134
	ENSO (12)	-	-	0.044	0.035	1.55	0.213
	Maximum seasonal temperature (9)	0.380	0.004	0.001	0.012	0.01	0.928
Striated Thornbill	Mean seasonal moisture	-0.360	0.007	-0.980	0.235	17.41	< 0.001
	ENSO (12)	-	-	-0.095	0.034	7.68	0.006
	Total summer rainfall	0.566	0.035	0.001	0.001	0.73	0.394
	Mean seasonal temperature (12)	-0.270	0.042	< 0.006	0.029	0.05	0.823
Sulphur-crested Cockatoo	Mean annual ENSO (12)	-	-	0.064	0.050	1.65	0.199
Superb Fairy-wren *	Mean annual ENSO (12)	-	-	0.069	0.046	2.28	0.131
Tree Martin	Mean annual ENSO (24)	0.600	0.030	-0.291	0.106	7.53	0.006
	Mean autumn moisture	0.545	0.044	-0.890	0.486	3.36	0.067
	Total summer rainfall	0.703	0.005	0.002	0.001	1.58	0.209
	Total seasonal rainfall (6)	0.440	0.019	0.001	0.002	0.37	0.543

Varied Sitella	Mean winter temperature	0.555	0.040	0.290	0.129	5.08	0.024
	Mean annual nENSO	-	-	-0.355	0.175	4.13	0.042
	Maximum spring temperature	0.728	0.003	-0.023	0.069	0.11	0.740
Weebill	Mean annual ENSO (24)	-	-	-0.142	0.040	12.34	< 0.001
	Mean seasonal moisture (6)	0.260	0.049	0.061	0.173	0.12	0.724
Welcome Swallow *	Mean seasonal temperature (3)	-0.360	0.006	-0.106	0.031	11.66	< 0.001
	Total annual rainfall	0.594	0.025	0.001	0.001	5.14	0.023
	ENSO (6)	-	-	-0.172	0.118	2.11	0.146
	Mean winter temperature	-0.559	0.038	0.006	0.110	< 0.001	0.957
Western Gerygone	ENSO	-	-	-0.132	0.056	5.58	0.018
	Mean seasonal growth (3)	-0.390	0.101	0.736	0.750	0.96	0.326
	Maximum seasonal temperature (3)	0.390	0.010	-0.005	0.021	0.06	0.805
White-eared Honeyeater	Mean annual ENSO	-	-	0.213	0.093	5.27	0.022
White-plumed Honeyeater *	Mean annual ENSO	-	-	0.189	0.072	6.99	0.008
White-throated Gerygone	Mean annual ENSO	-	-	-0.145	0.077	3.58	0.059
	Maximum seasonal temperature (9)	-0.400	0.009	-0.022	0.013	2.64	0.104
	Mean seasonal growth (12)	0.310	0.049	-0.539	0.504	1.14	0.285
	Minimum seasonal temperature (9)	-0.360	0.020	0.048	0.074	0.43	0.513
	Mean autumn growth	0.589	0.027	0.182	0.636	0.08	0.775
White-throated Treecreeper	ENSO (12)	-	-	-0.030	0.031	0.91	0.339
	Total seasonal rainfall (3)	0.360	0.007	-0.001	0.001	0.20	0.653
	Maximum seasonal temperature	-0.270	0.046	-0.002	0.009	0.05	0.820
White-winged Chough	ENSO (12)	0.560	0.047	-0.102	0.070	2.10	0.147
	Minimum annual temperature	0.552	0.041	0.059	0.059	1.01	0.314
	Square root seasonal rainfall (3)	-0.270	0.042	-0.006	0.031	0.04	0.840
White_winged_Triller	ENSO (12)	-	-	-0.128	0.114	1.27	0.260
	Minimum winter temperature	0.582	0.029	0.695	0.539	1.67	0.197
	Mean seasonal growth (12)	-0.390	0.039	0.696	1.767	0.16	0.694
	Maximum seasonal temperature (9)	0.53	0.004	0.034	0.182	0.04	0.851
Willie Wagtail	Mean winter growth	0.588	0.027	-14.975	5.269	8.08	0.004
	Mean annual ENSO	-	-	0.150	0.072	4.28	0.039
	Minimum autumn temperature	0.565	0.035	-0.047	0.063	0.56	0.454
Yellow-faced Honeyeater	ENSO (3)	-	-	0.102	0.081	1.56	0.211
	Total seasonal rainfall (12)	0.350	0.008	0.001	0.002	0.42	0.517

Yellow-rumped Thornbill *	Mean winter moisture	-0.621	0.018	0.505	0.235	4.62	0.032
	Square root annual rainfall	-0.550	0.042	-0.008	0.004	4.34	0.037
	Mean annual ENSO (12)	-	-	0.054	0.057	0.90	0.343

Appendix C

Table C1. Comparison of trend indices derived with and without the effects of weather included. Blank cells indicate no change between models.

Species	Non-climate Model			Climate Model			Δ slope	Δ error	Slope changed?	Precision improved?
	Trend (*P*)	Slope	SE	Trend (*P*)	Slope	SE				
Australian King-parrot	No change (0.072)	0.0140	0.0078	Increase (0.017)	0.0190	0.0079	-0.0050	-0.0001	N	N
Australian Magpie	Increase (< 0.001)	0.0067	0.0021							
Australian Raven	Increase (< 0.001)	0.0150	0.0043							
Black-faced Cuckoo-shrike	No change (0.970)	0.0000	0.0063	No change (0.779)	-0.0020	0.0058	0.0020	0.0005	N	Y
Brown-headed Honeyeater	Increase (0.002)	0.0270	0.0085	Increase (< 0.001)	0.0300	0.0084	-0.0030	0.0001	N	Y
Brown Thornbill	No change (0.497)	0.0040	0.0059							
Brown Treecreeper	No change (0.628)	-0.0037	0.0077	No change (0.983)	-0.0002	0.0079	-0.0035	-0.0002	N	N
Buff-rumped Thornbill	No change (0.589)	0.0014	0.0025	No change (0.276)	0.0024	0.0022	-0.0011	0.000269	N	Y
Common Bronzewing	No change (0.484)	-0.0070	0.0104	No change (0.392)	0.0090	0.0105	-0.0160	-0.0001	Y	N
Common Myna	Decrease (< 0.001)	-0.0377	0.0067	Decrease (< 0.001)	-0.0399	0.0067	0.0022	0	N	N
Common Starling	Increase (0.028)	0.0090	0.0041	No change (0.06)	0.0071	0.0038	0.0019	0.00031	N	Y
Crested Pigeon	Increase (< 0.001)	0.0350	0.0054							
Crimson Rosella	No change (0.836)	0.0003	0.0016	No change (0.632)	-0.0008	0.0016	0.0011	0	N	N
Dusky Woodswallow	No change (0.163)	0.0186	0.0134							
Eastern Rosella	No change (0.393)	0.0017	0.002	No change (0.809)	0.0004	0.0018	0.0013	0.0002	N	Y
Eastern Spinebill	No change (0.850)	-0.0020	0.0097							
Galah	Increase (< 0.001)	0.0127	0.0024							
Gang-gang Cockatoo	No change (0.725)	-0.0049	0.0139	No change (0.978)	0.0000	0.0140	-0.0049	-0.0001	N	N
Golden Whistler	No change (0.853)	0.0020	0.0109	No change (0.240)	0.0150	0.0124	-0.0130	-0.0015	Y	N

Grey Butcherbird	No change (0.667)	0.0030	0.0066							
Grey Currawong	No change (0.546)	-0.0060	0.0097	No change (0.241)	-0.0110	0.0096	0.0050	0.0001	N	Y
Grey Fantail	No change (0.734)	0.0009	0.0028	No change (0.736)	-0.0009	0.0027	0.0018	0.0001	N	Y
Grey Shrike-thrush	Decrease (0.002)	-1.1380	0.3064	Decrease (< 0.001)	-0.0380	0.0058	-1.1000	0.30065	Y	Y
Laughing Kookaburra	No change (0.445)	0.0050	0.0061							
Leaden Flycatcher	No change (0.379)	-0.0090	0.0098							
Magpie lark	Increase (0.036)	0.0090	0.0043	No change (0.127)	0.0070	0.0044	0.0020	-0.0001	N	N
Mistletoebird	Decrease (0.008)	-0.0203	0.0077							
Noisy Friarbird	No change (0.578)	-0.0049	0.0088	No change (0.376)	-0.0077	0.0087	0.0028	0.0001	N	Y
Noisy Miner	Increase (< 0.001)	0.0114	0.0028							
Olive-backed Oriole	No change (0.878)	-0.0020	0.0132	No change (0.943)	-0.0010	0.0137	-0.0010	-0.0005	N	N
Pied Currawong	No change (0.642)	0.0021	0.0045							
Red-rumped Parrot	No change (0.254)	-0.0056	0.0049	No change (0.481)	-0.0026	0.0036	-0.0030	0.00127	N	Y
Red Wattlebird	No change (0.406)	0.0049	0.0059	No change (0.312)	0.0061	0.0060	-0.0012	-0.0001	N	N
Rufous Whistler	No change (0.122)	-0.0063	0.0041							
Sacred Kingfisher	No change (0.083)	0.0510	0.0294	No change (0.482)	-0.0210	0.0300	0.0720	-0.0006	Y	N
Scarlet Robin	Decrease (0.012)	-0.0130	0.0051	Decrease (0.002)	-0.0154	0.0050	0.0024	0.0001	N	Y
Silvereye	No change (0.884)	0.0014	0.0095	No change (0.997)	0.0000	0.0098	0.0014	-0.0003	N	N
Speckled Warbler	No change (0.078)	0.0120	0.0071	Increase (0.011)	0.0180	0.0070	-0.0060	0.0001	N	Y
Spotted Pardalote	No change (0.114)	0.0085	0.0054							
Striated Pardalote	No change (0.166)	0.0047	0.0034							
Striated Thornbill	Decrease (0.011)	-0.0096	0.0038	Decrease (< 0.001)	-0.0119	0.0035	0.0023	0.0003	N	Y
Sulphur-crested Cockatoo	Increase (< 0.001)	0.0160	0.0031							
Superb Fairy-wren	Increase (0.010)	0.0074	0.0029							
Tree Martin	Decrease (< 0.001)	-0.0678	0.012	Decrease (< 0.001)	-0.0678	0.0120	0.0000	0	N	N

Varied Sittella	No change (0.322)	0.0150	0.0152	*No change (0.058)*	0.0420	0.0223	-0.0270	-0.0071	Y	N
Weebill	Increase (0.008)	0.0067	0.0025	Increase (< 0.001)	0.0077	0.0023	-0.0010	0.00022	N	Y
Welcome Swallow	No change (0.054)	-0.0204	0.0106	Decrease (0.006)	-0.0255	0.0093	0.0051	0.0013	N	Y
Western Gerygone	No change (0.225)	-0.0100	0.0081	No change (0.323)	-0.0076	0.0077	-0.0024	0.0004	N	Y
White-eared Honeyeater	Increase (< 0.001)	0.0310	0.0083	Increase (0.002)	0.0250	0.0080	0.0060	0.0003	N	Y
White-plumed Honeyeater	No change (0.229)	-0.0057	0.0048	No change (0.116)	-0.0068	0.0043	0.0011	0.00049	N	Y
White-throated Gerygone	No change (0.207)	-0.0082	0.0065							
White-throated Treecreeper	No change (0.218)	-0.0040	0.0031							
White-winged Chough	No change (0.062)	0.0122	0.0065							
White-winged Triller	No change (0.246)	-0.0406	0.035	Increase (0.023)	0.0158	0.0069	-0.0564	0.0281	Y	Y
Willie Wagtail	No change (0.391)	-0.0040	0.005	*No change (0.070)*	-0.0080	0.0044	0.0040	0.0006	N	Y
Yellow-faced Honeyeater	No change (0.427)	-0.0070	0.0085							
Yellow-rumped Thornbill	No change (0.878)	-0.0005	0.0034	No change (0.689)	-0.0013	0.00334	0.0008	0.0001	N	Y

Appendix D

Table D1. Studies that provide lists of declining species, their locations and the number of species listed as declining. “NSW” is New South Wales, “ACT” is Australian Capital Territory, “VIC” is Victoria, “SA” is South Australia, and “WA” is Western Australia.

Citation	Region, State	Species (n)
Barrett, G.W., Ford, H.A., Recher, H.F., 1994. Conservation of woodland birds in a fragmented rural landscape. Pac. Conserv. Biol. 1, 245-256.	New England, NSW	18
Barrett, G.W., Silcocks, A.F., Cunningham, R., Oliver, D.L., Weston, M.A., Baker, J., 2007. Comparison of atlas data to determine the conservation status of bird species in New South Wales, with an emphasis on woodland-dependent species. Aust. Zool. 34, 37-77.	All regions, NSW	32
Bounds, J., Taws, N., Cunningham, R., 2010. A statistical analysis of trends in occupancy rates of woodland birds in the ACT, December 1998 to December 2008: the ten year data analysis. Canberra Bird Notes. 35, 158-192.	Canberra, ACT	14
Catterall, C. P., Woinarski, J. C. Z., 2003. Birds of Coomooboolaroo, central Queensland, from 1873 to 1999. Sunbird.	Coomooboolaroo, QLD	68
Chapman, A., Kealley, I., 2001. The birds of Kurrawang Nature Reserve - observations of avifaunal change in the eastern goldfields of Western Australia. CALMScience.	Eastern goldfields, WA	7
Conole, L.E., 2002. Local extinction and decline of birds in a woodland remnant at Inverleigh, Victoria. Corella. 26, 41-46.	Inverleigh, VIC	22
Cunningham, R., Olsen, P., 2009. A statistical methodology for tracking long-term change in reporting rates of birds from volunteer-collected presence-absence data. Biodiv. Conserv. 18, 1305-1327.	Temperate east, NSW*	8
Egan, K.H., Farrell, J.R., Pepper-Edwards, D.L., 1997. Historical and seasonal changes in the community of forest birds at Longneck Lagoon Nature Reserve, Scheyville, New South Wales. Corella. 21, 1-16.	Scheyville, NSW	4
Kennedy, S.J., 2003. A four-year study of a bird community in a woodland remnant near Moyston, western Victoria. Corella. 27, 33-44.	Moyston, VIC	5
Lindenmayer, D.B., Cunningham, R.B., 2011. Longitudinal patterns in bird reporting rates in a threatened ecosystem: Is change regionally consistent? Biol. Conserv. 144, 430-440.	Jugiong, NSW	4
Loyn, R.H., Menkhorst, P.W., 2011. The bird fauna of Melbourne: changes over a century of urban growth and climate change, using a benchmark from Keartland (1900). Vic. Nat. 128, 210-232.	Melbourne, VIC	33

Paton, D. C., Rogers, D. J. and Harris, W. 2004. Birdscaping the environment: restoring the woodland systems of the Mt Lofty region, South Australia. In Lunney, D. (ed.) *Conservation of Australia's Forest Fauna* (second edition). Royal Zoological Society of New South Wales.	Mount Lofty, SA	27
Possingham, M. L., Possingham, H. P., 1997. Habitat use and abundance of dryland birds in heritage areas in the upper south east of South Australia. S. Aust. Ornit. 32, 145-160.	Bordertown, VIC	7
Recher, H. F., Serventy, D. L., 1991. Long term changes in the relative abundances of birds in King's Park, Perth, Western Australia. Conserv. Biol. 5, 90-102.	Perth, WA	23
Reid, J. R. W., 1999. *Threatened and declining birds in the New South Wales Sheep-Wheat Belt: Part I. Diagnosis. characteristics and management. Consultancy report to NSW National Parks and Wildlife Service.* CSIRO Wildlife and Ecology, Canberra.	Wheat belt, NSW	20
Reid, J.R.W., Cunningham, R.B., 2008. *Statistical analysis of the Cowra Woodland Birds Program's Bird Database... A report to Birds Australia and the Lachlan CMA.* Fenner School (ANU) and CSIRO Sustainable Ecosystems, Canberra.	Cowra, NSW	11
Robinson, D., 1993. Vale Toolern Vale: the loss of our woodland birds. Wingspan. 9, 1-3, 20-21.	Not specified, NSW	15
	Not specified, SA	21
	Not specified, VIC	57
	Not specified, WA	21
Saunders, D. A., 1989. Changes in the avifauna of a region, district and remnant as a result of fragmentation of native vegetation: the wheatbelt of western Australia. A case study. Biol. Conserv. 50, 99-135.	Wheat belt, WA	41
Szabo, J.K., Vesk, P.A., Baxter, P.W.J., Possingham, H.P., 2011. Paying the extinction debt: woodland birds in the Mount Lofty Ranges, South Australia. Emu. 111, 59-70.	Mount Lofty, SA	15
Traill, B. J., Collins, E., Peake, P., Jessup, S., 1996. Current and past status of the birds of Chiltern – a box-ironbark forest in north-eastern Victoria. Aust. Bird Watcher. 16, 309-326.	Chiltern, VIC	18

* study contains samples of Victoria and Queensland

III. Are protected areas maintaining bird diversity?

Whether originally located on species-rich sites, or actively managed to prevent habitat degradation, protected areas are expected to foster positive ecological effects on biodiversity. Studies that use long-term monitoring records to assess protected-area effectiveness are scarce, meaning that the capacity for protected areas to ensure the persistence of species populations is poorly understood. In this paper, I evaluate the ecological effectiveness of reserves for maintaining woodland bird diversity in an important woodland region of Australia.

Rayner L., Lindenmayer D.B., Wood J.T., Gibbons P. & Manning A.D. (2014) Are protected areas maintaining bird diversity? *Ecography*, 37, 43-53.

Abstract

Evaluating the effectiveness of protected areas for sustaining biodiversity is crucial to achieving conservation outcomes. While studies of effectiveness have improved our understanding of protected-area design and management, few investigations (< 5%) have quantified the ecological performance of reserves for conserving species. Here, we present an empirical evaluation of protected-area effectiveness using long-term measures of a vulnerable assemblage of species. We compare forest and woodland bird diversity in the Australian Capital Territory over 11 years on protected and unprotected areas located in temperate eucalypt woodland and matched by key habitat attributes. We examine separately the response of birds to protected areas established prior to 1995 and after 1995 when fundamental changes were made to regional conservation policy. Bird diversity was measured in richness, occurrence of vulnerable species, individual species trajectories and functional trait groups. We found that protected areas were effective in maintaining woody vegetation cover in the study region, but were ineffective in the protection of the target bird species assemblage. Protected areas were less species rich than unprotected areas, with significant declines in richness across sites protected prior to 1995. Small, specialised and vulnerable species showed stronger associations with unprotected areas than protected areas. Our findings indicate that recently established reserves (post-1995) are performing similarly to unprotected woodland areas in terms of maintaining woodland bird diversity, and that both of these areas are more effective in the conservation of woodland bird populations than reserves established prior to 1995. We demonstrate that the conservation value of protected areas is strongly influenced by the physical characteristics, as well as the landscape context, of a given reserve and can diminish with changes in surrounding land use over time. Both protected areas and off-reserve conservation schemes have important roles to play in securing species populations.

Introduction

Conserving biodiversity through protected areas has been at the core of global conservation strategies for more than a century (Pimm et al. 2001). Today, over 160,000 protected areas covering between 10.8% and 12.7% of the Earth's terrestrial surface comprise the global protected-area network (WDPA 2010; Bertzky et al. 2012). The primary objective of a protected area is "*to achieve the long-term conservation of nature with associated ecosystem services*", where 'conservation' refers to "*the in-situ maintenance of ecosystems... and of viable populations of species in their natural surroundings*" (Dudley 2008, pp. 8-9). Protected areas draw heavily on limited conservation resources in striving to achieve this objective (Brooks et al. 2004). Yet, the world continues to experience unprecedented levels of biodiversity loss (WWF 2012) and ongoing destruction of natural habitat (FAO 2011), sometimes *within* areas designated for biodiversity protection (e.g. DeFries et al. 2005).

Consequently, the capacity for protected areas to protect and maintain biological diversity is contested (Joppa et al. 2008), bringing their effectiveness as a global conservation tool into question. It is therefore essential to measure protected-area effectiveness as the first step towards improving biodiversity management efforts, and rectifying failures to achieve conservation goals.

To assess the effectiveness of protected areas, studies predominantly focus on one of three subjects: design, management processes, or ecological integrity (sensu Ervin 2003). We reviewed the empirical literature on protected-area effectiveness (539 studies) and found that studies of design, management and ecological integrity accounted for 39%, 44% and 17% of articles respectively (Rayner, unpublished data). Importantly, only a small subset of studies (< 5%) directly quantified the effectiveness of protection for sustaining biodiversity. This finding supports calls from the scientific community for greater research focus on the *ecological effectiveness* of protected areas to provide direct measures of conservation outcomes and enhance adaptive decision making (Gaston et al. 2008, Jones et al. 2011).

Here, we define 'ecological effectiveness' as *the ongoing maintenance or recovery of biodiversity within areas implicitly or explicitly established for its protection.* A comprehensive assessment of ecological effectiveness requires, at the least, comparative *and* temporal data. That is, the status of biodiversity in the presence and absence of protection should be compared through time. This is critical for determining whether ecosystems are showing direct and sustained benefits from protection. This approach is distinct from most available studies on protected-area design (e.g. location, coverage), management (e.g. funding, enforcement) and integrity (e.g. intactness, threats), which often evaluate effectiveness using proximal measures that are assumed to be reliable surrogates of biodiversity conservation, but are rarely tested (Brooks et al. 2004).

Important studies of ecological effectiveness exist, but few have measured the impact of protection on species populations; a core biodiversity indicator (Brooks et al. 2004, Gaston et al. 2006). For example, several studies examine the response of vegetative cover to protection over time using retrospectively collected, remotely-sensed, time-series data (e.g. Andam et al. 2008, Mas 2005). However, such methods cannot be used to track species populations, which rely on field-based monitoring records that are often difficult to obtain (Lindenmayer and Likens 2010). Consequently, studies that utilise long-term monitoring records to assess protected-area effectiveness are scarce (Gaston et al. 2006). As a result, the capacity for protected areas to ensure the persistence of species populations is poorly understood, and this has been identified as a significant knowledge gap in protected-area research (Gaston et al. 2008).

In this paper, we studied ecological effectiveness using a dataset for forest and woodland birds observed in temperate eucalypt woodland within and without protected areas spanning 11 years. We pose four primary questions: (1) Do protected areas support higher bird species richness than unprotected areas over time? (2) Do protected areas support more birds of conservation concern than unprotected areas over time? (3) Do protected areas support more species with stable or increasing trends than unprotected areas? (4) Do protected areas benefit birds with particular functional traits?

Where possible, we assessed separately, the response of birds to protected areas that were established pre- and post-1995, following a change in legislation that re-prioritised reserve selection criteria in the study region. This allowed us to account for developments in global reserve-selection standards. Further, to characterise protected-area conditions and explore potential environmental predictors of species-site occurrence, we investigated the physical characteristics (area and elevation), landscape context (relative topographic position and urban proximity) and environmental processes (woody vegetation cover and plant productivity) associated with our study sites. In doing so, our study demonstrates the strength of long-term ecological monitoring in evaluations of protected-area performance.

Methods

Study region and protected areas

Eucalypt woodland once covered over 1.5 million km^2 of the Australian continent (NLWRA 2001), this is the equivalent to the area of 19% of the lower 48 states of the USA. Since European settlement, almost 28% has been cleared, and less than 8% of the remainder is protected (NLWRA 2001). Consequently, these woodlands are an internationally-recognised endangered ecoregion (Hoekstra *et al.* 2005). We used a 20 km x 40 km area in the north-east region of the Australian Capital Territory (ACT) in south-eastern Australia (Fig. 1a) as an exemplar of this highly-modified, continent-scale ecosystem type. Prior to European settlement in 1824, this region was dominated by temperate eucalypt woodland (or temperate broad-leaf/mixed forest, sensu Jenkins and Joppa 2009). The type of temperate woodland found in this area (box-gum grassy woodland) is listed as critically endangered at the national level (ACT 2011). However, woodland remnants of the ACT are typically larger, more intact, and more adequately protected than woodlands found anywhere else in Australia (ACT 2004). These remnants make a significant contribution to the global protection of this biome (Jenkins and Joppa 2009).

For this study, sites in protected areas were located within the Canberra Nature Park, a series of protected areas within a matrix of urban and rural land uses (Fig. 1b). These protected areas contain the highest quality longitudinal records of birds and provide the best representation of protected temperate woodland for the region, including one woodland sanctuary (www.mfgowoodlandexperiment.org.au) and large areas of *Eucalyptus* *melliodora/Eucalyptus blakelyi* Grassy Woodland, an endangered ecological community in the ACT (ACT 2011).

Bird surveys and site selection

We sourced records of bird occurrence from a long-term woodland bird monitoring project undertaken by the Canberra Ornithologists Group (COG). The design and execution of this project was based on statistical principles ensuring a sound data collection framework (see Bounds et al. 2010 for further information). From this database, we selected 92 study sites nested within 10 broad locations for analysis (Fig. 1c). Sites were circular plots of 50 m radius. All sites were surveyed over an 11-year period between 2000 and 2010. Where possible, bird surveys were conducted seasonally, providing four surveys per year for each site. However, some variation in survey effort occurred in the dataset. Bird surveys were 10 minute point counts recording all bird species seen or heard within a 50 m radius of a permanent marker point (Bounds et al. 2010).

To compare bird responses, we located sites on both protected and unprotected land (hereafter "reserved sites" and "unreserved sites"). All reserved sites were managed strictly for biodiversity protection under IUCN protection class I-IV. Unreserved sites were of mixed land tenures and varied in the level of active biodiversity management, from very little (e.g. grazed leasehold land) to substantial (e.g. meeting statutory obligations on defence land). Reserved and unreserved sites were matched in three key characteristics: (1) all sites occurred in either temperate grassy woodland (86 sites) or dry forest contiguous with temperate grassy woodland (six sites), (2) all sites were dominated by eucalypt tree species with Eucalyptus blakelyi, Eucalyptus melliodora, Eucalyptus bridgesiana, Eucalyptus macroryncha and Eucalyptus polyanthemos being the most common over-storey trees, and (3) all sites were located within 25 km of the city of Canberra and were likely to have been subject to some level of modification over time as a result of fire, grazing and/or invasion from weeds and feral species. More remote woodland sites were not available due to limited habitat protection and a paucity of longitudinal bird data.

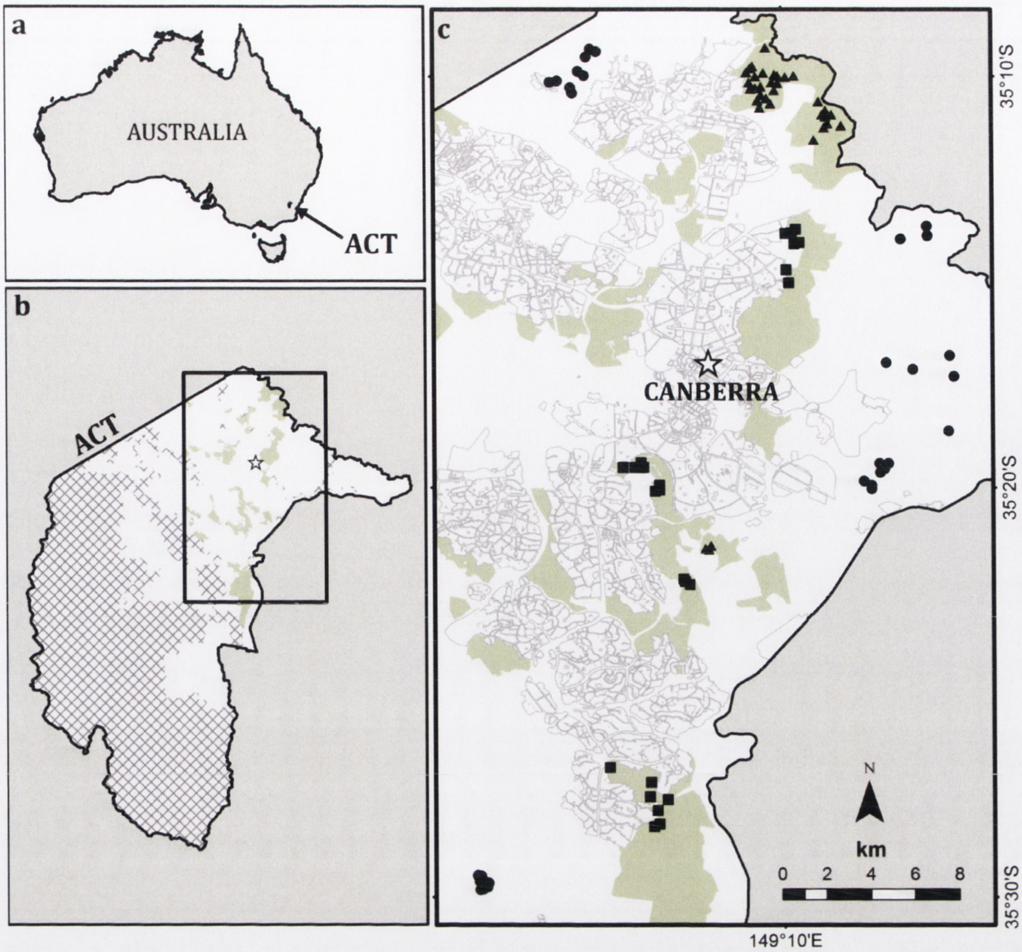

Figure 1. Map of Study Area. (a) Position of the Australian Capital Territory (ACT) within Australia. (b) Distribution of protected areas within the ACT, showing Canberra Nature Parks (shaded green) and all other protected areas (cross-hatched). (c) Location of sites in Pre-1995 reserves (squares), Post-1995 reserves (triangles) and unreserved land (circles). Distribution of Canberra Nature Parks (shaded green) and urban development (grey lines) within the study region. Location of Canberra, the capital city, is denoted by a star.

Reservation categories

The number of reserved and unreserved sites changed over time as 12 sites gained reservation status during the survey period (Table 1). This meant that, in any given year, data for 'reserved sites' included surveys from sites added recently to the reserve system where, one could argue, the effects of legal protection may not have had time to manifest. Despite this caveat, we argue that recently reserved sites make an important contribution to this study. Theoretically, the addition of reserved sites in a study where the total number of sites is fixed, should favour the long-term conservation performance of reserves **if** representativeness is the guiding principle behind land acquisition.

Within our sample of reserved sites, we examined separately, the response of birds to reserves established prior to 1995 and reserves established since 1995. The year 1995 coincides with a period of change in the motivation behind reserve establishment in the ACT, shifting reserve objectives from those of scenic value to conservation value (ACT 1994). Consequently, this provides a unique opportunity to examine the effect of changed global standards in reserve selection. Thus, three reservation categories were created for analysis: Pre-1995 reserved sites (n = 24), Post-1995 reserved sites (n = 34), and Unreserved sites (n = 34) (Table 1).

Table 1. The number of sites represented by the three reservation categories (Pre-1995 reserved sites, Post-1995 reserved sites and Unreserved sites) and their corresponding years of gazettal. Note that the total number of sites is fixed (n = 92). Twelve sites gained reservation status during the survey period (2000-2010). The total for unreserved sites is the number of sites that were unprotected for the duration of the survey period.

Year of establishment	Pre-1995 reserved sites	Post-1995 reserved sites	Unreserved sites
1975	14	0	78
1987	10	0	68
1995	0	22	46
2003	0	9	37
2004	0	3	34
Total	**24**	**34**	**34**

Species of conservation concern

We assigned conservation status to each bird species based on regionally-relevant current literature. Here, *species of conservation concern* included species that were declared as vulnerable at a regional level (ACTFFC 2011) or have exhibited a long-term declining trend in the region over the last decade (Bounds et al. 2010). We present the conservation status of each species in Appendix A in Supporting Information.

Species traits

Many authors encourage the use of functional trait analysis in ecological studies for a deeper understanding of community responses to environmental conditions (Devictor and Robert 2009). This is particularly relevant where changes to community composition might be missed by simple diversity measures such as richness (Filippi-Codaccioni et al. 2010). We therefore assigned each species to functional trait groups based on life-history attributes. These groups included habitat specialisation (woodland dependent, non-woodland dependent), bird mobility (resident and sedentary species versus migratory, part-migratory and dispersive species), body weight, nest type (e.g. hollow, cup, dome), nest location (e.g. arboreal, understorey, ground), main food type (e.g. invertebrates, seed, nectar), foraging substrate (e.g. aerial, arboreal, shrub) and whether the species feeds on the ground. A species could belong to multiple functional trait groups. We provide details of trait assignment for individual species and reference material in Appendix A.

Environmental descriptors

We examined four broad-scale environmental variables for their relationship with area protection and species functional traits. These were: woody vegetation cover, potential productivity, plant productivity, and proximity to the urban boundary. We chose these variables for two primary reasons: (1) their documented influence on woodland bird communities (e.g. Chace and Walsh 2006, Huth and Possingham 2011, Montague-Drake et al. 2011); and (2) their strength and increasing availability as data types to be used in protected-area design, management and performance assessments (e.g. Mas 2005, Radeloff et al. 2010). We also compared these variables, as well as reserve area, elevation and landscape position, across reservation categories. In doing so, we examined: (1) differences in physical reserve characteristics as an indicator of biases in reserve establishment, and (2) changes in ecological processes as an indicator of disturbance. We provide details on source and method of data collection for each environmental descriptor in Appendix B.

Data structure and statistical analyses

In total, we used 3768 bird surveys over 11 years in our analysis. Bird surveys were not available for one unreserved location, Majura Training Area (8 sites), between 2001 and 2003. All other sites were surveyed in all years. The spatio-temporal structure of the dataset is presented in Appendix C.

For our analyses, we examined all species detected in > 1% of surveys, excluding waterbirds (n = 60). These species are listed in Appendix A. We pooled bird surveys annually to give three measures per site: (1) Richness, the total number of species detected; (2) Proportion, the number of surveys in which a species was detected as a proportion of the total number of surveys conducted in that year; and (3) Presence, the species detected in at least one of the surveys conducted for each year. We derived all of these measures from presence/absence data. For all analyses, χ^2 test statistics quoted are derived for Wald statistics.

Trends in richness and species occurrence

We fitted Hierarchical Generalised Linear Models (HGLM, Lee et al. 2006) to determine whether bird responses differed across reservation categories over time. To do so, we calculated longitudinal trend patterns for: (1) species richness, (2) species of conservation concern, and (3) each species separately. The first two analyses assumed a Poisson distribution and we used the richness measure as the response, with survey effort included as a fixed effect. For individual species, we fitted quasi-binomial models with the proportion measure as the response, accounting for variability in survey effort directly. For both models, we included location and site as random effects to account for the influence of spatial autocorrelation that could result from the clustering of sites within locations. For 11 of the rarer species, there were insufficient data to estimate separate location and site components of variance. In these cases, we estimated the pooled variance of location and site combined. We fitted the HGLMs in *GenStat* statistical software package (14th Edition).

Functional trait analysis

We used RLQ analysis (Doledec et al. 1996) to relate environmental conditions and species functional traits to patterns in species-site occurrence (using the presence measure). RLQ analysis explains variation in species composition using scores derived from the ordinations of three separate matrices: (R) site by environmental descriptors, (L) site by species, and (Q) species by functional traits. We used reservation status as an environmental descriptor in the R matrix, to highlight the environmental conditions and species traits that are most strongly associated with reserved and unreserved sites.

A challenge with RLQ analysis is dealing with both spatial and temporal autocorrelation within the dataset. Including location and year as descriptors in the ordinations would mask the contribution of our environmental conditions of interest because: (1) location remains unchanged through time, and (2) surveys within years are likely to be more similar due to abiotic factors. RLQ analysis does not account for such random effects. To overcome this issue, we performed two separate analyses: one using data collected in 2000 and the second on data collected in 2010. This approach allowed us to maximise the covariance between site and species scores using only the environmental descriptors directly relevant to our aims. Furthermore, this approach allowed us to compare the relative influence of explanatory variables across two points in time (by standardising the RLQ eigenvectors for each year), while minimising the variance explained by location that would be inflated by pooling all survey years together. As we used only two years in this analysis (2000 and 2010), reservation categories were constrained to 'reserved' versus 'unreserved' categories.

We assessed the statistical strength of the analysis using a permutation test (1000 permutations) and by comparing variance explained by the RLQ analysis to separate R, L and Q ordinations. We conducted RLQ analysis in the *R* statistical program (R Development Core Team 2011), using the *ade4* software package.

Environmental differences among reservation categories

We used HGLMs to examine differences in environmental descriptors across reservation categories. We compared static environmental descriptors across reserves using Analysis of Variance (ANOVA) with location as a blocking variable. We calculated all static environmental descriptors as means at the reserve-level. Where environmental descriptors were derived from time-series data (temporal environmental descriptors), we used HGLMs to compare variation across reservation categories through time. These models included location as a random effect. We calculated all temporal environmental descriptors at the site-level. We performed both ANOVA and HGLMs in *GenStat* statistical software package (14th Edition).

Results

Species richness

We found a significant difference in species richness between reservation groups (χ^2_3 = 596, $p < 0.001$) with Unreserved sites supporting higher mean species richness for most years (Fig. 2). There also was a strong interaction between reservation category and time (χ^2_3 = 76, $p < 0.001$) with a decline in richness on Pre-1995 reserved sites and an increase in richness on Unreserved sites (Fig. 2; Appendix D). While these trends were highly significant, differences in expected (mean) richness among reservation categories were small for most years. There was no significant change in species richness on Post-1995 reserved sites during the survey period (Fig. 2; Appendix D).

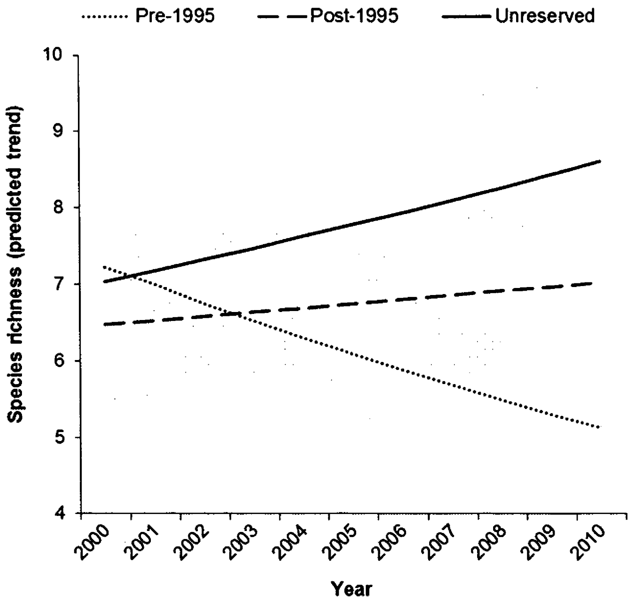

Figure 2. Trends in species richness on reserved and unreserved sites. Results of HGLM showing changes in mean species richness over time on sites reserved Pre-1995, sites reserved Post-1995 and Unreserved sites. Standard errors for the model predictions, which include the random effect of location, are shown in grey.

Number of species of conservation concern

The number of species of conservation concern was consistently lower on reserved sites, regardless of year or reservation category ($\chi^2_3 = 32$, $p < 0.001$) (Fig. 3). Like total species richness, there was a significant interaction between reserve category and time ($\chi^2_3 = 64$, $p < 0.001$), driven by a decline in the number of species of concern on Pre-1995 reserved sites (Fig. 3; Appendix D). In contrast, the number of species of conservation concern remained stable on Post-1995 reserved sites and Unreserved sites during the survey period (Fig. 3; Appendix D).

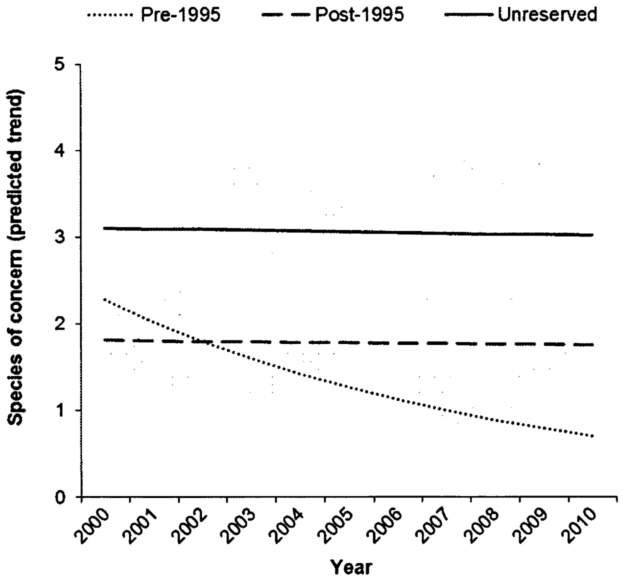

Figure 3. Trends in the number of species of conservation concern on reserved and unreserved sites. Results of HGLM showing changes in mean species richness for birds of conservation concern over time on sites reserved Pre-1995, sites reserved Post-1995 and unreserved sites. Standard errors for the model predictions, which include the random effect of location, are shown in grey.

Longitudinal trends

Of the 60 species detected in > 1% of surveys, 35 showed significant temporal trends in response to our reservation categories (Table 2; Appendix D). Temporal trends for a further six species were marginally significant ($p = 0.05$-0.1), leaving 18 species exhibiting no significant change in detection over time, for any reservation category. An examination of the long-term trends of individual species and their responses to reservation categories revealed three types of patterns: (1) *Increasers*, species for which a significant temporal trend was always positive, (2) *Decliners*, species for which a significant temporal trend was always negative, and (3) species that showed contrasting temporal trends dependent on reservation category (Table 2).

(1) *Increasers.* Twelve species were identified as increasers in this study (Table 2). Of these, four showed significant increasing trends across all reservation categories. These species were Australian King-Parrot (*Alisterus scapularis*), Australian Raven (*Corvus coronoides*), Crested Pigeon (*Ocyphaps lophotes*), and Noisy Miner (*Manorina melanocephala*). Of the 12 increasers, only three were defined as woodland-dependent:

Australian King-Parrot, Sacred Kingfisher (*Todiramphus sanctus*) and the White-eared Honeyeater (*Lichenostomus leucotis*) (Appendix A). All increasers were represented on Unreserved sites, while Pre- and Post-1995 reserved sites represented nine and six species respectively.

(2) *Decliners.* Twelve species were identified as decliners in this study (Table 2). Of these, two showed significant decreasing trends across all reservation categories. These species were the Striated Thornbill (*Acanthiza lineata*) and Superb Fairy-wren (*Malurus cyaneus*). Of the 12 decliners, 11 were defined as woodland-dependent species (Appendix A). The only decliner that was not dependent on woodland was the White-plumed Honeyeater (*Lichenostomus pencillatus*). Almost all decliners were represented on Pre-1995 reserves (except the Tree Martin *Hirundo nigricans*) while Post-1995 reserves and Unreserved sites supported seven and six species, respectively.

(3) *Contrasting trends.* Eleven species exhibited contrasting trends that were dependent on reservation category (Table 2). The most common pattern of contrasting trends was for a species to decline on Pre-1995 reserved sites, while increasing on Post-1995 reserved sites (n = 4) or Unreserved sites (n = 1) or both (n = 6) (Table 2). Such species included the Striated Pardalote (*Pardalotus striatus*) and Speckled Warbler (*Chthonicola sagittata*) (Table 2). Only one species, the Mistletoebird *(Dicaeum hirundinaceum),* showed a decreasing trend on both Pre-1995 reserved sites and Unreserved sites, while increasing on Post-1995 reserved sites (Table 2). Seven of the species listed here are dependent on woodland (Appendix A).

General trends across reservation category

Post-1995 reserved sites and Unreserved sites showed similar patterns in the number of species with increasing (n = 17 and 19, respectively) and decreasing (n = 7 for both) trends (Table 2). Pre-1995 reserved sites showed very different results with nine species exhibiting an increasing trend and 23 species exhibiting a decreasing trend (Table 2). Of these 23 decreasing species, 14 were unique to Pre-1995 reserved sites, showing stable or increasing trends across other reservation categories (Table 2). There were no declining species unique to Post-1995 reserved sites or Unreserved sites. That is, neither of these reservation categories supported species with decreasing trends that did not also show a decrease in another category.

Functional trait relationships

Both the 2000 and 2010 RLQ analyses performed best with a single common set of variables (permutation test $p < 0.001$; Table 3). These included two environmental descriptors: woody vegetation cover within 500 m of sites and distance from the urban boundary, and three species functional traits: habitat specialisation, body size and whether the species feeds on the ground (Fig. 4). The first axes of the 2000 and 2010 RLQ analyses explained 80% and 87% of total variance in environmental conditions and species functional traits across reservation, respectively. Thus, results here are presented along a single axis of eigenvalues standardised for separate years.

In both the 2000 and 2010 RLQ analyses, we observed clear differences in the functional groups and environmental conditions associated with reserved versus unreserved sites (Fig. 4). Reserved sites were more strongly associated with woody vegetation cover, and large, ground-feeding bird species that were not strictly dependent on woodland habitat. Unreserved sites were typically located further from the urban boundary and more strongly associated with smaller, non-ground-feeding birds that were woodland-dependent. While differing slightly in strength, the direction of these associations remained consistent across the two time periods analysed.

Table 2. Longitudinal trends of bird species across reservation categories. Results of HGLM showing individual species trends (Slope) including and standard errors (S.E.) on Pre- and Post-1995 reserved sites, and unreserved sites. Only species with significant trends ($p < 0.1$) are presented ($n = 42$). Significance is indicated by the Wald statistic ($\chi^2_{d.f.}$) and P-value as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Marginally significant trends ($p = 0.05$-0.10) are presented in italics and non-significant trends are presented in grey. Species are listed in order of detection frequency. Scientific names for species are provided in Appendix A.

Common name	**Surveys present (%)**	**Reservation x Year**	**Pre-1995 reserved trend**		**Post-1995 reserved trend**		**Unreserved trend**	
		χ^2_3	**Slope**	**S.E.**	**Slope**	**S.E.**	**Slope**	**S.E.**
Crimson Rosella	43.58	*6.50*	-0.011	0.023	-0.005	0.019	*0.050*	*0.020*
Striated Pardalote	35.75	41.08 ***	-0.133	0.027	0.078	0.020	0.019	0.020
Weebill	34.90	61.84 ***	-0.129	0.025	0.075	0.022	0.102	0.021
Australian Magpie	30.41	19.40 ***	0.046	0.023	0.036	0.022	0.084	0.021
Grey Fantail	24.04	41.31 ***	-0.198	0.033	-0.008	0.023	-0.049	0.021
Galah	23.67	50.21 ***	0.086	0.026	0.008	0.029	0.145	0.023
Buff-rumped Thornbill	18.90	21.96 ***	-0.161	0.037	0.020	0.023	0.038	0.027
Noisy Miner	18.37	67.34 ***	0.264	0.045	0.158	0.035	0.157	0.044
Common Starling	15.61	*7.67*	*-0.123*	*0.050*	*-0.053*	*0.044*	*0.014*	*0.027*
Superb Fairy-wren	15.10	43.82 ***	-0.228	0.035	-0.072	0.059	-0.025	0.024
Sulphur-crested Cockatoo	14.78	19.54 ***	0.108	0.031	0.010	0.027	0.079	0.030
Spotted Pardalote	14.68	13.22 **	-0.080	0.034	0.057	0.023	0.035	0.028
Rufous Whistler	13.16	14.11 **	-0.166	0.058	-0.008	0.025	-0.061	0.025
Red Wattlebird	11.65	16.31 ***	0.027	0.025	0.023	0.037	0.147	0.038
Pied Currawong	11.44	18.41 ***	0.038	0.025	-0.015	0.049	0.154	0.039
Striated Thornbill	11.12	18.86 ***	-0.165	0.064	-0.051	0.027	-0.089	0.030
Australian Raven	10.56	29.90 ***	0.035	0.033	0.041	0.038	0.152	0.029
White-throated Treecreeper	10.06	26.26 ***	-0.251	0.053	-0.051	0.028	-0.020	0.034
Yellow-rumped Thornbill	9.98	17.59 ***	-0.159	0.045	0.067	0.034	0.035	0.028
White-plumed Honeyeater	8.17	10.36 *	-0.326	0.212	-0.165	0.061	-0.023	0.030
Mistletoebird	6.61	23.77 ***	-0.229	0.062	0.077	0.036	-0.088	0.038
Magpie-lark	6.40	20.72 ***	-0.012	0.049	-0.005	0.043	0.188	0.042
White-throated Gerygone	6.24	17.53 ***	-0.423	0.117	-0.001	0.034	-0.076	0.036
White-winged Chough	5.79	24.93 ***	-0.080	0.057	0.101	0.034	0.196	0.052
Red-rumped Parrot	5.73	21.90 ***	-0.545	0.129	0.329	0.162	-0.005	0.031
Crested Pigeon	5.65	53.58 ***	0.230	0.047	0.271	0.068	0.170	0.046
Common Myna	5.39	68.24 ***	-0.319	0.045	0.162	0.119	0.201	0.049
Speckled Warbler	4.64	26.20 ***	-0.107	0.047	0.180	0.058	0.157	0.047
Willie Wagtail	3.90	*7.30*	*-0.408*	*0.156*	0.036	0.055	-0.002	0.038
White-eared Honeyeater	3.77	32.25 ***	-0.049	0.057	0.126	0.056	0.263	0.051
Brown-headed Honeyeater	3.69	8.79 *	-0.268	0.125	0.074	0.038	-0.030	0.055

continued

Grey Shrike-thrush	3.40	8.66 *	-0.266	0.103	-0.067	0.054	-0.025	0.040
Tree Martin	3.37	28.17 ***	0.017	3.000	-0.230	0.155	-0.182	0.036
Silvereye	3.24	20.21 ***	-0.249	0.056	0.010	0.057	-0.012	0.059
Brown Thornbill	3.13	*6.27*	*-0.162*	*0.072*	-0.049	0.064	-0.032	0.013
Australian King-Parrot	2.81	10.29 *	0.080	0.040	0.167	0.144	0.516	0.236
Golden Whistler	2.71	9.34 *	-0.207	0.069	0.003	0.053	-0.035	0.057
Leaden Flycatcher	2.42	10.53 *	-0.262	0.089	0.075	0.056	-0.023	0.069
Dusky Woodswallow	1.80	*7.44*	*-0.283*	*0.118*	*-0.151*	*0.117*	-0.003	0.051
Grey Currawong	1.65	*7.57*	*-0.194*	*0.079*	-0.099	0.823	0.010	0.081
Sacred Kingfisher	1.04	12.05 **	0.049	0.163	0.163	0.077	0.302	0.110

Table 3. Results of RLQ analysis. Eingenvalues for the first two axes of: (a) individual ordinations of the R (environmental variables of each site), L (species detection at sites) and Q (bird species traits) matrices, and (b) RLQ analysis, including covariance and correspondence with the L matrix, and projected variance of the R and Q matrices. Percent variance explained by each analysis component is shown in parentheses.

	2000 **Simulated p-value: < 0.001**		**2010** **Simulated p-value: < 0.001**	
	Axis 1 (%)	**Axis 2 (%)**	**Axis 1 (%)**	**Axis 2 (%)**
a. Individual ordinations:				
R (Hill-Smith PCA)	1.83 (60.87)	0.78 (25.85)	1.81 (60.24)	0.69 (23.09)
L (CA)	0.28 (8.93)	0.20 (6.39)	0.34 (11.75)	0.18 (6.09)
Q (Hill-Smith PCA)	1.88 (46.89)	1.02 (25.44)	1.82 (45.45)	1.03 (25.78)
b. RLQ analysis:				
RLQ axis eigenvalues	0.06 (79.58)	0.01(20.38)	0.07 (86.60)	0.01 (13.02)
Covariance	0.24	0.12	0.26	0.10
Correlation: L	0.15 (28.41)	0.12 (25.77)	0.16 (27.79)	0.12 (27.41)
Projected variance: R	1.42 (77.59)	2.55 (98.14)	1.63 (89.96)	2.36 (94.27)
Projected variance: Q	1.77 (94.14)	2.72 (94.17)	1.55 (85.19)	2.57 (90.37)

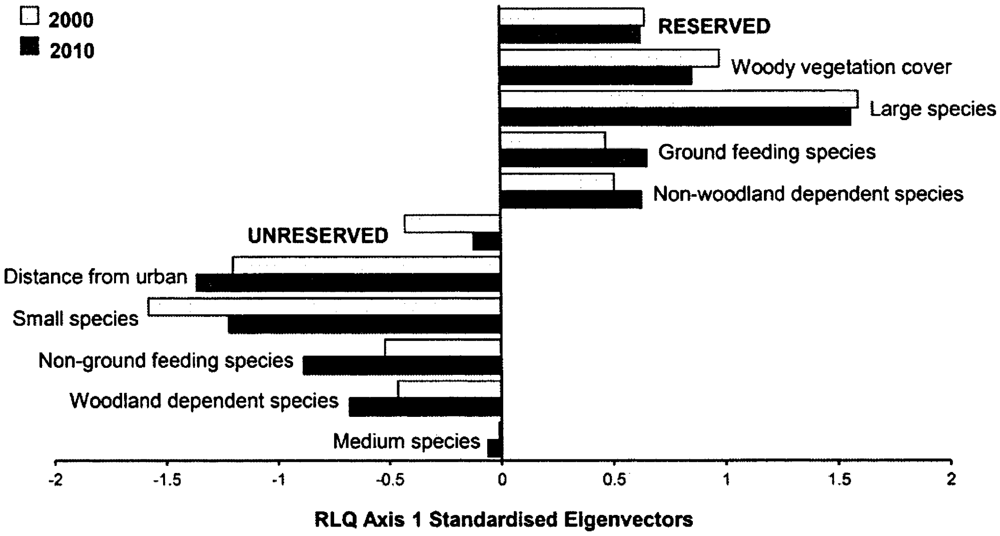

Figure 4. Associations among reservation, broad-scale environmental measures and species traits. Standardised eigenvectors for axis 1 of RLQ analyses relating bird species occurrence to environmental variables and species traits for the years 2000 and 2010. Variables with positive standardised eigenvectors are more strongly associated with reserved sites. Variables with negative standardised eigenvectors are more strongly associated with unreserved sites. Increasing difference from zero indicates increasing contribution to the inertia explained by the analysis.

Environmental descriptors across reservation categories

Static differences in environmental descriptors at the reserve-level

We found that Pre-1995 reserves were significantly higher in elevation and relative topographic position than Post-1995 reserves (Table 4). Compared to Pre-1995 reserves, Post-1995 reserves were generally larger with lower levels of woody vegetation cover based on the calculated reserve means. However, these results were not statistically significant (Table 4).

Static differences in environmental descriptors at the site-level

Potential productivity was significantly higher on Unreserved sites when compared to reserved sites (Table 4). This trend was reversed for measured plant productivity. Mean cover of woody vegetation at the site-level was significantly higher on reserved sites than unreserved sites. There also was a significant difference in urban proximity across reservation categories, with Pre-1995 reserves situated nearest to the urban boundary, followed by Post-1995 reserves, and Unreserved sites situated the furthest from the urban boundary.

Temporal change in environmental descriptors at the site-level

While potential productivity increased across all reservation categories over time, measured plant productivity decreased. Cover of woody vegetation decreased consistently over time and across all reservation categories. The urban boundary encroached on all sites, but this trend was only significant and particularly strong for Post-1995 reserved sites (Table 4).

Table 4. Comparison of environmental conditions across reservation categories. Differences in the physical characteristics of reserves (Pre- and Post-1995 reserved sites) are expressed using means with standard errors (S.E.). Differences and trends in environmental conditions across reservation categories (Pre- and Post-1995 reserved sites and unreserved sites) are expressed using the estimate (Est.) and slope respectively, including standard errors (S.E.). Significance is indicated using the Wald statistic ($\chi^2_{d.f.}$) and P-value as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Non-significant relationships are presented in grey. Details on source and method of data collection for each environmental covariate are provided in Appendix B.

		Pre-1995 reserved sites		**Post-1995 reserved sites**		**Unreserved sites**	
Static data	**$F_{1,5}$**	**Mean**	**S.E.**	**Mean**	**S.E.**	-	-
Reserve area (ha)	0.93	378.30	114.40	546.70	132.10	-	-
Reserve elevation (m)	7.06*	705.04	12.08	656.01	13.95	-	-
Reserve landscape position	26.14**	-1.19	0.16	0.06	0.18	-	-
Site woody cover	2.75	0.38	0.10	0.12	0.12	-	-
Pooled temporal data	**χ^2_3**	**Est.**	**S.E.**	**Est.**	**S.E.**	**Est.**	**S.E.**
Potential productivity	2226***	1.772	0.054	1.730	0.058	1.849	0.060
Plant productivity	2796***	1.530	0.039	1.494	0.040	1.481	0.045
Woody cover (within 500m)	107***	3.525	0.407	2.852	0.413	2.386	0.483
Distance to urban boundary	867***	6.679	0.328	7.022	0.321	7.759	0.393
Temporal data	**χ^2_3**	**Slope**	**S.E.**	**Slope**	**S.E.**	**Slope**	**S.E.**
Potential productivity	23***	0.010	0.005	0.015	0.004	0.008	0.004
Plant productivity	244***	-0.019	0.002	-0.020	0.002	-0.012	0.002
Woody cover (within 500m)	176***	-0.059	0.008	-0.091	0.009	-0.060	0.014
Distance to urban boundary	418***	-0.009	0.012	-0.087	0.004	-0.007	0.004

Discussion

Whether originally located on species-rich sites, or actively managed to prevent habitat degradation, protected areas are expected to foster positive relationships with biodiversity (Jackson et al. 2009). In this study, we assessed the ecological effectiveness of protected areas for conserving bird diversity by examining the long-term response of species to the presence and absence of protection. We posed four key questions to empirically test the long-term effect of protected areas on: (1) species richness, (2) species of conservation concern, (3) species persistence and (4) species functional groups.

We found that, compared to unprotected areas, protected areas collectively supported: lower species richness, fewer species of conservation concern, more species with declining trends, and larger-bodied, generalist species. By these measures, we can conclude that unprotected areas sampled in this study are more effective in conserving woodland bird diversity than protected areas within our study region. This is a striking and counter-intuitive result which we explore within the physical and ecological context of protected areas below.

Specifically, we draw attention to three key findings:

(1) *Reserve placement influenced ecological effectiveness over time.* Our results indicated that the long-term response of birds to protected areas was strongly influenced by the period of protected-area establishment. Long-established protected areas may be limited in their capacity to meet conservation objectives due to reserve design that was not ecologically-driven. For example, creating reserves to protect scenic values (Margules and Pressey 2000) and establishing reserves on less productive land (Joppa and Pfaff 2009). Indeed, we found that reserves established before 1995 in this study were significantly higher in elevation, higher in topographic position, had lower potential productivity and, on average, were smaller in size than Post-1995 reserves (although this last finding was not statistically significant).

In 1994, an amendment to the Nature Conservation Act 1980 in the ACT (ACT 1994) introduced a statutory requirement to conserve endangered ecological communities. Since that time, the characteristics of newer reserves have changed (Table

4) and our analyses indicated that their ecological effectiveness has improved. This was exemplified by increasing species richness, stabilisation of species populations of conservation concern and fewer individual species declines, particularly of less common specialist species on Post-1995 reserves when compared to Pre-1995 reserves. Hence, this study demonstrated that overcoming traditional biases in reserve placement and re-prioritising designation objectives **can** enhance the ecological effectiveness of protected areas.

(2) *Reserves protect habitat and ecological processes.* Despite an overall decline in woody vegetation cover across study sites (Table 4), our reserved sites supported significantly higher vegetative cover and productivity than unreserved sites (Fig. 3, Table 4). Other studies have found protected areas to be effective in representing and maintaining vegetation cover (e.g. Andam et al. 2008) and plant productivity (e.g. Tang et al. 2011). Such outcomes demonstrate that, where enforcement is adequate, protected areas **can** play a critical role in preserving habitat and maintaining ecological processes through legislative controls of destructive processes, such as land clearing, and can therefore be associated with enhanced protected-area performance (Stoll-Kleemann and Job 2008).

However, this may not strictly be the case for all woodland birds. For example, some argue that vegetation thickening favours the more specialised woodland bird species (e.g. Kutt and Martin 2010), but Montague-Drake et al. (2011) found that overstorey cover and productivity were positively related to the abundance of hyper-aggressor *Manorina melanocephala*; a species linked to declines in avian diversity and abundance (e.g. MacDonald and Kirkpatrick 2003). In our study, *Manorina melanocephala* exhibited highest detection and strongest increasing trends within reserves (Appendix D) and could be driving localised species declines. This example demonstrates that while the maintenance of vegetation characteristics within protected areas may provide broader landscape functions for biota (e.g. connectivity), additional on-site management actions (e.g. population control of interspecific competitors) may be required to secure vulnerable species populations.

(3) *Urban encroachment threatens ecological effectiveness.* In this study, smaller woodland-dependent species were associated with unprotected sites situated furthest from urban boundaries (Fig. 4; Table 4). While studies have shown positive relationships between human population density and avian richness (due to a mutually positive response to primary productivity, Luck 2010), such relationships are highly scale-dependent, with more localised effects tending to be negative (Pautasso 2007). Indeed, the direct effects of urban encroachment on protected areas and their associated biodiversity are often negative (Radeloff et al. 2010). The mechanisms which underpin the negative relationship between small, woodland-dependent species and urban proximity identified in this study are unclear, but may be associated with habitat or species composition changes within reserves close to the urban fringe (Ikin et al. 2012). This is of particular concern as urban encroachment is advancing rapidly toward the best-performing reserves in our study region (Table 4). Here, buffering protected areas from the impacts of urban development will become increasingly important as urban areas expand and opportunities for establishing future reserve sites contract (Ewers and Rodrigues 2008).

Together, our findings demonstrate that protected areas are dynamic systems, exhibiting their own temporal and spatial response to environmental gradients. We have shown that the conservation performance of protected areas can diminish over time with changes in landscape context. It is also likely that protected area effectiveness will be influenced by increasing environmental pressures associated with climate change (e.g. Hole et al. 2009; Araujo et al. 2011; Bagchi et al. 2013). For example, survey data for this study were collected during a period of severe drought in Australia (2001-2009) and one could suggest that reserve performance may improve during years of higher rainfall. However, projected climate changes include increased frequency and severity of drought for our study region, indicating that the results presented here may provide a good indication of future trends. Further research is needed to quantify the effect of weather on bird distributions in this region, and to determine whether protected areas are likely to facilitate (e.g. Thomas et al. 2012) or inhibit (e.g. Araujo et al. 2011) species' range expansions.

Given the above examples of measured and predicted fluctuations in protected area performance, studies of ecological effectiveness that incorporate comparative and temporal data are better equipped to track changes in protected systems relative to un-protected systems, identify the processes threatening protected-area performance, and assess the success (or otherwise) of management interventions addressing those processes. Moreover, representativeness and persistence are the primary indicators of protected-area performance (Margules and Pressey 2000) and should be addressed wherever possible in assessments of ecological effectiveness. Our results illustrate how studies that lack comparative data fail to examine the direct effect of protection on biodiversity and, therefore, are limited in their assessments of species *representativeness*. Similarly, studies that lack temporal data fail to examine the sustained effect of protection on biodiversity and therefore, will be limited in their assessments of species *persistence*.

Conservation implications

Our study joins a substantial body of work acknowledging the benefits and importance of protected areas, while also identifying significant shortfalls in their conservation performance (e.g. Fandohan et al. 2011, Vellak et al. 2009). We believe our study has taken a first step in addressing these shortfalls by quantifying the outcomes of past conservation efforts and establishing a contemporary ecological context to inform future systematic planning (sensu Hockings et al. 2004). The similar, and sometimes superior, performance of unprotected areas in comparison to protected areas was unexpected, but not unique to this study region (e.g. China, Liu et al. 2001; Canada, Kharouba & Kerr 2010; Europe, Araujo et al. 2011). Such findings suggest that the protection of modified habitats situated more favourably in the landscape (in terms of surrounding land-use threats and changing climate space) could maximise conservation benefits to a region, particularly where active restoration is feasible. Perhaps more importantly, it highlights that options for conservation are not limited to protected areas, and that there is great potential for biodiversity gains through investments in off-reserve conservation schemes (Lindenmayer and Franklin 2002; Cox and Underwood 2011).

The protected-area portfolio in the ACT has 99% of all ecosystems represented to the minimum global conservation target of 10% (Taylor et al. 2011). But does this mean that it is ecologically effective for conserving biodiversity? Our study showed that the protection of ecosystems has been effective in the maintenance of some ecological patterns and processes (i.e. vegetative cover and productivity), but has not been effective in ensuring the persistence of a vulnerable assemblage of species (i.e. woodland birds). Thus, a key lesson from this study is that the use of performance measures that are not necessarily proxies for ecological effectiveness (e.g. habitat classes, Brooks et al. 2004; or areal coverage, Gaston et al. 2008) can severely limit our capacity to understand and describe the actual performance of protected areas for biodiversity, particularly at the resolution needed for the on-ground adaptive management of species populations. This is not to say that direct biodiversity data should replace generalised environmental variables in all evaluations of protected area effectiveness. Indeed, monitoring a potentially unrepresentative assemblage of species will not, in itself, provide a comprehensive assessment of performance. Rather, we argue that species-specific data are needed to complement broader environmental data and that, where biodiversity data are lacking, assumptions of species persistence within protected areas should be made with great caution until such data are gathered.

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Appendix A

Table A1. List of species with assigned functional traits. Nomenclature taken from Christidis and Boles (2008). Habitat guilds taken from Reid and Cunningham (2008). Mobility derived from Reid (1999) and Lindenmayer and Cunningham (2011). Body size, nesting, and foraging traits derived from Ikin et al. (2012) and Lindenmayer and Cunningham (2011). Ground feeder identification taken from Silcocks et al. (2005). Conservation status derived from ACT Flora and Fauna Committee (2011) and Bounds et al. (2010). References are provided in full below.

Common name	Scientific name	Habitat	Mobility	Size	Nest type	Nesting	Main food	Foraging substrate	Ground feeder	Cons. Concern
Australian King-Parrot	*Alisterus scapularis*	WD	ResSed	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Australian Magpie	*Gymnorhina tibicen*	NWD	ResSed	LRG	Bowl	Arb	Invertebrates	Grnd	Y	N
Australian Raven	*Corvus coronoides*	NWD	ResSed	LRG	Bowl	Arb	Omnivorous	Grnd	Y	N
Australian Wood Duck	*Chenonetta jubata*	NWD	PMigMig	LRG	Hollow	Hol	Seeds, Grain, Plants	Aqu	Y	N
Black-faced Cuckoo-shrike	*Coracina novaehollandiae*	NWD	PMigMig	LRG	Cup	Arb	Invertebrates	Arb	N	Y
Brown Thornbill	*Acanthiza pusilla*	WD	ResSed	SML	Dome	Usty	Invertebrates	Shb	N	N
Brown Treecreeper	*Climacteris picumnus*	WD	ResSed	SML	Hollow	Hol	Invertebrates	Arb	Y	Y*
Brown-headed Homeyeater	*Melithreptus brevirostris*	WD	ResSed	SML	Purse	Arb	NPPI	NF	N	N
Buff-rumped Thornbill	*Acanthiza reguloides*	WD	ResSed	SML	Dome	Opp	Invertebrates	Shb	Y	N
Common Bronzewing	*Phaps chalcoptera*	WD	PMigMig	LRG	Platform	Opp	NPPI	Gran	Y	N
Common Myna	*Acridotheres tristis*	NWD	ResSed	LRG	Hollow	Hol	Omnivorous	Grnd	Y	N
Common Starling	*Sturnus vulgaris*	NWD	ResSed	INT	Cup	Opp	Omnivorous	Grnd	Y	N
Crested Pigeon	*Ocyphaps lophotes*	NWD	ResSed	LRG	Platform	Opp	Seeds, Grain, Plants	Gran	Y	N
Crimson Rosella	*Platycercus elegans*	WD	ResSed	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Dusky Woodswallow	*Artamus cyanopterus*	WD	PMigMig	SML	Bowl	Opp	Invertebrates	Air	N	Y
Eastern Rosella	*Platycercus eximius*	NWD	ResSed	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Eastern Spinebill	*Acanthorhynchus tenuirostris*	WD	PMigMig	SML	Cup	Arb	NPPI	NF	N	N
Galah	*Cacatua roseicapilla*	NWD	ResSed	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Gang-gang Cockatoo	*Callocephalon fimbriatum*	WD	PMigMig	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Golden Whistler	*Pachycephala pectoralis*	WD	PMigMig	SML	Cup	Usty	Invertebrates	Arb	N	N

Grey Butcherbird	*Cracticus torquatus*	WD	ResSed	INT	Bowl	Opp	Invertebrates	Grnd	Y	N
Grey Currawong	*Strepera versicolor*	WD	ResSed	LRG	Bowl	Arb	Invertebrates	Arb	Y	Y
Grey Fantail	*Rhipidura fuliginosa*	WD	PMigMig	SML	Cup	Arb	Invertebrates	Arb	N	Y
Grey Shrike-thrush	*Colluricincla harmonica*	WD	ResSed	INT	Cup	Opp	Invertebrates	Arb	Y	Y
Laughing Kookaburra	*Dacelo novaeguineae*	WD	ResSed	LRG	Hollow	Hol	Vertebrates	Carn	Y	N
Leaden Flycatcher	*Myiagra rubecula*	WD	PMigMig	SML	Cup	Arb	Invertebrates	Arb	N	N
Magpie-lark	*Grallina cyanoleuca*	NWD	ResSed	INT	Bowl	Arb	Invertebrates	Grnd	Y	N
Mistletoebird	*Dicaeum hirundinaceum*	NWD	PMigMig	SML	Purse	Arb	Fruits	NF	N	N
Nankeen Kestrel	*Falco cenchroides*	NWD	PMigMig	LRG	Various	Opp	Vertebrates	Carn	Y	N
Noisy Friarbird	*Philemon corniculatus*	WD	PMigMig	LRG	Purse	Arb	NPPI	NF	N	N
Noisy Miner	*Manorina melanocephala*	NWD	ResSed	INT	Cup	Opp	Omnivorous	Arb	N	N
Olive-backed Oriole	*Oriolus sagittatus*	WD	PMigMig	INT	Purse	Arb	NPPI	NF	N	N
Pacific Black Duck	*Anas superciliosa*	NWD	PMigMig	LRG	Hollow	Opp	Seeds, Grain, Plants	Aqu	Y	N
Pied Currawong	*Strepera graculina*	NWD	PMigMig	LRG	Bowl	Arb	Omnivorous	Arb	Y	N
Red Wattlebird	*Anthochaera carunculata*	NWD	PMigMig	LRG	Cup	Arb	NPPI	NF	N	N
Red-rumped Parrot	*Psephotus haematonotus*	NWD	ResSed	INT	Hollow	Hol	Seeds, Grain or Plants	Gran	Y	Y
Rufous Whistler	*Pachycephala rufiventris*	WD	PMigMig	SML	Cup	Arb	Invertebrates	Arb	N	N
Sacred Kingfisher	*Todiramphus sanctus*	WD	PMigMig	SML	Hollow	Hol	Invertebrates	Grnd	Y	N
Scarlet Robin	*Petroica multicolor*	WD	ResSed	SML	Cup	Arb	Invertebrates	Grnd	Y	Y
Silvereye	*Zosterops lateralis*	WD	PMigMig	SML	Purse	Arb	Omnivorous	Shb	N	Y
Speckled Warbler	*Chthonicola sagittata*	WD	ResSed	SML	Dome	Grnd	Invertebrates	Grnd	Y	N
Spotted Pardalote	*Pardalotus punctatus*	WD	ResSed	SML	Hollow	Hol	Invertebrates	Arb	N	N
Striated Pardalote	*Pardalotus striatus*	NWD	PMigMig	SML	Hollow	Hol	Invertebrates	Arb	N	N
Striated Thornbill	*Acanthiza lineata*	WD	ResSed	SML	Dome	Arb	Invertebrates	Arb	N	N
Sulphur-crested Cockatoo	*Cacatua galerita*	NWD	PMigMig	LRG	Hollow	Hol	Seeds, Grain, Plants	Gran	Y	N
Superb Fairy-wren	*Malurus cyaneus*	WD	ResSed	SML	Dome	Usty	Invertebrates	Shb	Y	Y
Tree Martin	*Hirundo nigricans*	WD	PMigMig	SML	Hollow	Hol	Invertebrates	Air	N	Y
Varied Sitella	*Daphoenositta chrysoptera*	WD	ResSed	SML	Cup	Arb	Invertebrates	Arb	Y	Y*
Weebill	*Smicornis brevirostris*	WD	ResSed	SML	Purse	Arb	Invertebrates	Arb	N	N
Welcome Swallow	*Hirundo neoxena*	NWD	PMigMig	SML	Bowl	Opp	Invertebrates	Air	N	N
Western Gerygone	*Gerygone fusca*	WD	PMigMig	SML	Purse	Arb	Invertebrates	Arb	N	N
White-eared Honeyeater	*Lichenostomus leucotis*	WD	ResSed	SML	Cup	Usty	Invertebrates	Arb	N	N
White-naped Honeyeater	*Melithreptus lunatus*	WD	PMigMig	SML	Purse	Arb	NPPI	Arb	N	N
White-plumed Honeyeater	*Lichenostomus pencillatus*	NWD	ResSed	SML	Cup	Arb	NPPI	NF	N	Y

White-throated Gerygone	*Gerygone olivacea*	WD	PMigMig	SML	Purse	Arb	Invertebrates	Arb	N	N
White-throated Treecreeper	*Cormobates leucophaeus*	WD	ResSed	SML	Hollow	Hol	Invertebrates	Arb	N	N
White-winged Chough	*Corcorax melanorhamphos*	WD	ResSed	LRG	Bowl	Arb	Invertebrates	Grnd	N	N
Willie Wagtail	*Rhipidura leucophrys*	NWD	ResSed	SML	Cup	Arb	Invertebrates	Arb	Y	Y
Yellow-faced Honeyeater	*Lichenostomus chrysops*	WD	PMigMig	SML	Cup	Usty	Omnivorous	NF	N	N
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*	NWD	ResSed	SML	Dome	Arb	Invertebrates	Grnd	N	N

Habitat abbreviations: NWD = non-woodland dependent, WD = woodland dependent; Mobility abbreviations: ResSed = resident or sedentary, PMigMig = part migratory or migratory; Size abbreviations: SML = small, INT = intermediate, LRG = large; Nesting abbreviations: Hol = hollow, Arb = arboreal, Usty = understorey, Opp = opportunistic, Grnd = ground; Main Food: NPPI = Nectar, Pollen, Plants and Invertebrates; Foraging substrate abbreviations: Gran = granivore, Grnd = ground insectivore, Aqu = aquatic, Arb = arboreal insectivore, Shb = shrub insectivore, NF = nectar and fruit, Air = aerial insectivore, Carn = carnivore; Y = Yes; N = No; *Listed as vulnerable by ACT Flora and Fauna Committee.

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Appendix B

Table A2. Static and long-term environmental descriptors used in analyses. Variables were compared across reservation categories to examine the differences in physical characteristics, and temporal change in ecological processes, associated with protected areas through time. Selected variables were also investigated for their relationship with bird occurrence using RLQ analysis. All variables were either collected as, or transformed to, annual measures. Measures at the Site and Local scale were calculated within a 50 and 500 metre radius of sites respectively. Longitudinal estimates were calculated for each site/reserve using remotely-sensed time-series data. Further information on data is available via the references provided below.

Environmental descriptor	Data source	Data description	Scale	Data type (period)
Reserve area	ACT Environment and Sustainable Development Directorate	The total area of each reserve measured in hectares.	Reserve	Static value (2010)
Elevation	Australian Capital Territory, Parks, Conservation and Lands	The mean elevation of each reserve calculated in ArcGIS using spatial data provided by Australian Capital Territory, Parks, Conservation and Lands.	Reserve	Static mean (2010)
Landscape position (twi)	Fenner School of Environment and Society, The Australian National University	The mean topographic wetness index (twi) is derived by dividing contributing catchment by slope. It is a continuous terrain-based measure of position in the landscape, ranging from negative values on ridges (with no contributing catchment) and upper slopes (small contributing catchment/steep slope) to increasingly higher positive values through lower slopes, valley flats and eventually drainage lines.	Reserve	Static mean (2010)
Potential productivity (fpi)	National Carbon Accounting Service. Also see Landsberg & Kesteven (2001) and Kesteven et al. (2004) below.	Monthly values of environmental constraints on productivity indices were averaged to provide annual estimates for each site. Productivity indices (here named "potential productivity") are expressed by modifiers calculated from abiotic measures. These measures included temperature, vapour pressure deficit (*VPD*) of the atmosphere, soil water deficit and number of frost days.	On-site	Temporal (Jan. 2000 – Dec. 2010)
Plant productivity (fPAR)	Mackey, B. and colleagues. Also see Berry et al. 2007 and Mackey et al. (2008) below.	Monthly measures of normalized difference vegetation index (NDVI) are treated to extract the fraction of photosynthetically active radiation absorbed by vegetation (fPAR, here named "plant productivity", but also referred to as a measure of "greenness" or a"greenness index"). Monthly calculations were summed to provide annual totals. This provides a relative measure of plant production per year. Unavailable months of data (Jan, Feb, March 2000 and Sep, Oct, Nov, Dec 2010) were imputed using generalised linear models.	On-site	Temporal (Apr. 2000 – Aug. 2010)

Woody vegetation cover	National Carbon Accounting Service. Also see Furby & CSIRO (2002).	Landsat satellite imagery is used to discriminate between forest and non-forest cover. Forest cover (here named "woody vegetation cover") is defined as vegetation with a minimum 20 per cent canopy cover, potentially reaching 2 metres high and a minimum area of 0.2 hectares. NB: this product does not adequately represent sparse open woodland or scattered trees. Mean values of woody cover were used in analyses.	Reserve and Local	Temporal (Jan. 2000 – Dec. 2010)
Urban proximity	ACT Environment and Sustainable Development Directorate	The proximity of sites to the urban boundary was calculated using the near function in ArcGIS with spatial data provided by ACT Environment and Sustainable Development Directorate. Estimates of distance for each year were cross-checked using aerial imagery of the Canberra region provided by Australian Capital Territory, Parks, Conservation and Lands.	Regional	Temporal (Jan. 2000 – Dec. 2010)

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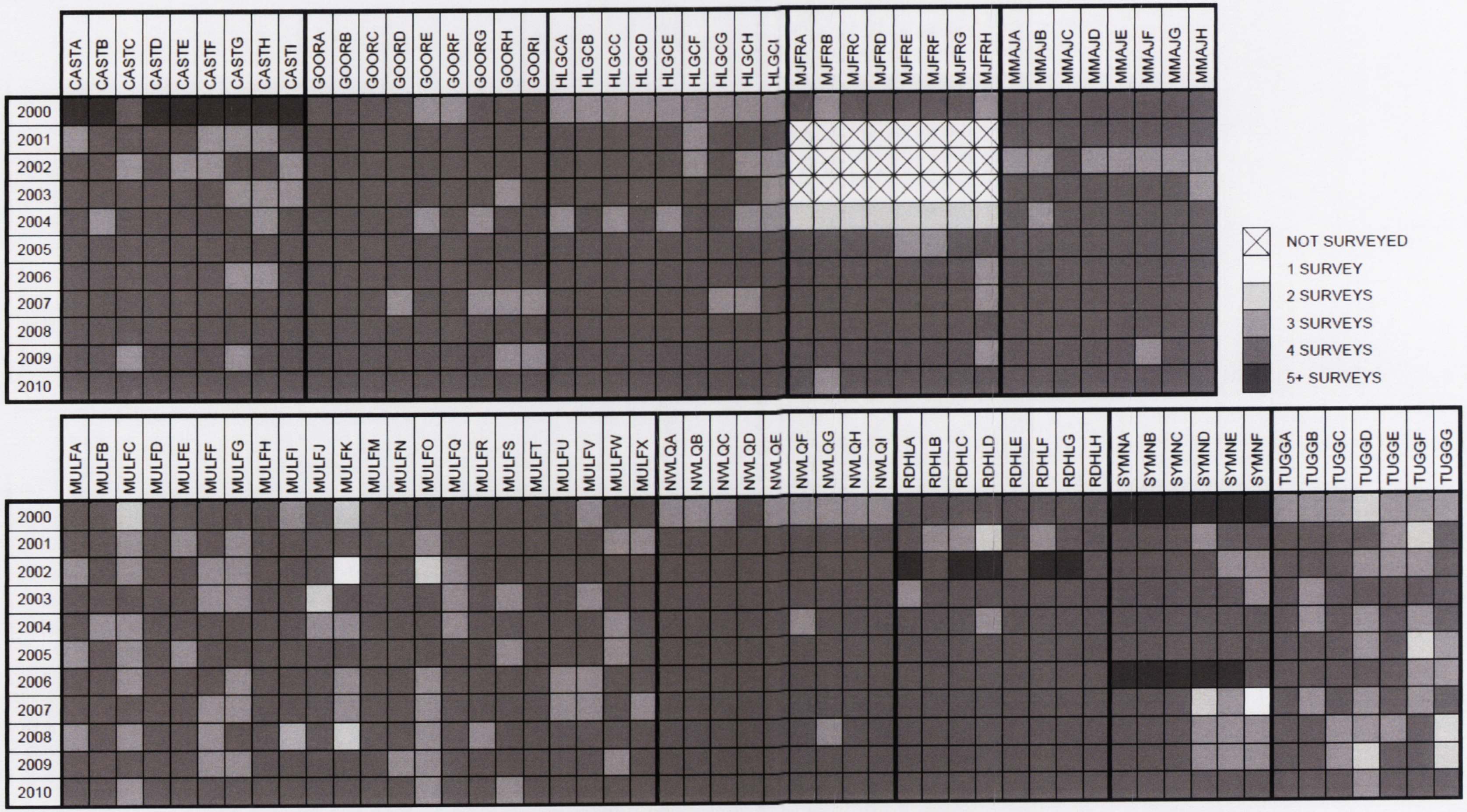
Appendix C

Figure A3. Temporal structure of the dataset. Column labels are sites, grouped by location (bold border) and row labels are years. Shading in boxes reflect survey effort – the darker the shading the more surveys were conducted. Crosses indicate no survey.



Appendix D

Table A4. Differences and long-term trends in species richness and individual species across reservation categories. Analyses of richness include survey effort as a fixed effect, which was highly significant for species richness ($p < 0.001$) and marginally significant for the number of species of conservation concern ($p = 0.065$). Location explained a significant amount of variation in both models of richness, and for 40 individual species. Site explained a significant amount of variation in both models of richness, and for 45 individual species. Random effects of location and site were pooled, and explained a significant amount of variance, for 11 of the more spatially restricted species (denoted by *). All species occurred in > 1% of surveys and listed in order of detection rate. Scientific names are provided in Appendix A.

Response measure	Surveys present (%)	Sites pres. (n)	Total obs. (n)	Reservation category		Pre-1995 reserved		Post-1995 reserved		Unreserved		Reservation x Year		Pre-1995 reserved trend		Post-1995 reserved trend		Unreserved trend	
				χ^2_3	P	Est.	S.E.	Est.	S.E.	Est.	S.E.	χ^2_3	P	Slope	S.E.	Slope	S.E.	Slope	S.E.
Richness	100.00	92	13507	596.7	< 0.001	1.567	0.090	1.670	0.099	1.813	0.089	76.1	< 0.001	-0.034	0.005	0.008	0.004	0.020	0.004
Species of concern richness	59.87	91	3355	32.05	< 0.001	0.101	0.192	0.444	0.205	0.985	0.183	63.91	< 0.001	-0.118	0.015	-0.003	0.011	-0.003	0.009
Crimson Rosella	43.58	92	1642	0.41	0.938	-0.150	0.373	-0.137	0.388	-0.217	0.430	6.50	0.090	-0.011	0.023	-0.005	0.019	0.050	0.020
Striated Pardalote	35.75	92	1347	23.40	< 0.001	-1.653	0.340	-0.124	0.366	-0.331	0.341	41.08	< 0.001	-0.133	0.027	0.078	0.020	0.019	0.020
Weebill	34.90	88	1315	14.63	0.002	-0.819	0.309	-0.834	0.323	-0.461	0.282	61.84	< 0.001	-0.129	0.025	0.075	0.022	0.102	0.021
Australian Magpie	30.41	92	1146	36.32	< 0.001	-0.547	0.239	-1.116	0.259	-0.899	0.225	19.40	< 0.001	0.046	0.023	0.006	0.022	0.084	0.021
Eastern Rosella	28.48	89	1073	12.68	0.005	-1.355	0.480	-0.922	0.566	-1.016	0.497	6.08	0.108	-0.020	0.025	0.030	0.025	0.044	0.022
Grey Fantail	24.04	86	906	148.28	< 0.001	-2.062	0.240	-1.416	0.193	-0.914	0.189	41.31	< 0.001	-0.198	0.033	-0.008	0.023	-0.049	0.021
Galah	23.67	83	892	47.31	< 0.001	-1.166	0.378	-1.997	0.401	-1.222	0.339	50.21	< 0.001	0.086	0.026	0.008	0.029	0.145	0.023
Buff-rumped Thornbill	18.90	75	712	32.78	< 0.001	-2.261	0.521	-1.759	0.576	-2.019	0.585	21.96	< 0.001	-0.161	0.037	0.020	0.023	0.038	0.027
Noisy Miner	18.37	56	692	19.65	< 0.001	-2.968	1.067	-2.526	1.016	-3.300	1.112	67.34	< 0.001	0.264	0.045	0.158	0.035	0.157	0.044
Common Starling	15.61	47	588	38.03	< 0.001	-4.487	0.840	-3.054	0.949	-1.911	0.877	7.67	0.053	-0.123	0.050	-0.053	0.044	0.014	0.027
Superb Fairy-wren	15.10	55	569	36.00	< 0.001	-2.696	0.719	-3.973	0.795	-1.575	0.703	43.82	< 0.001	-0.228	0.035	-0.072	0.059	-0.025	0.024
Sulphur-crested Cockatoo	14.78	78	557	64.25	< 0.001	-2.143	0.427	-1.812	0.454	-2.229	0.415	19.54	< 0.001	0.108	0.031	0.010	0.027	0.079	0.030

Spotted Pardalote	14.68	89	553	330.40	< 0.001	-2.043	0.184	-1.631	0.183	-1.952	0.164	13.22	0.004	-0.080	0.034	0.057	0.023	0.035	0.028
Rufous Whistler *	13.16	76	496	373.00	< 0.001	-3.667	0.287	-1.805	0.176	-1.762	0.178	14.11	0.003	-0.166	0.058	-0.008	0.025	-0.061	0.025
Red Wattlebird	11.65	82	439	206.70	< 0.001	-1.191	0.241	-2.973	0.307	-2.684	0.261	16.31	< 0.001	0.027	0.025	0.023	0.037	0.147	0.038
Pied Currawong	11.44	72	431	28.86	< 0.001	-2.064	0.659	-2.119	0.732	-2.807	0.651	18.41	< 0.001	0.038	0.025	-0.015	0.049	0.154	0.039
Striated Thornbill	11.12	71	419	38.39	< 0.001	-2.989	0.665	-3.275	0.793	-2.441	0.723	18.86	< 0.001	-0.165	0.064	-0.051	0.027	-0.089	0.030
Australian Raven	10.56	85	398	128.27	< 0.001	-2.268	0.307	-2.577	0.346	-1.967	0.315	29.90	< 0.001	0.035	0.033	0.041	0.038	0.152	0.029
Noisy Friarbird	10.16	89	383	195.24	< 0.001	-2.308	0.264	-1.959	0.287	-2.650	0.269	3.08	0.379	-0.007	0.034	0.023	0.028	0.057	0.037
White-throated Treecreeper	10.06	62	379	52.71	< 0.001	-3.314	0.630	-3.074	0.728	-3.072	0.701	26.26	< 0.001	-0.251	0.053	-0.051	0.028	-0.020	0.034
Yellow-rumped Thornbill	9.98	70	376	131.81	<0.001	-2.972	0.389	-2.762	0.410	-2.160	0.351	17.59	< 0.001	-0.159	0.045	0.067	0.034	0.035	0.028
Black-faced Cuckoo-shrike	9.82	87	370	285.5	< 0.001	-2.615	0.237	-2.184	0.247	-2.252	0.217	6.09	0.107	-0.096	0.039	-0.002	0.032	0.002	0.031
Yellow-faced Honeyeater	9.16	83	345	223.70	< 0.001	-2.072	0.260	-3.222	0.308	-2.072	0.256	2.37	0.499	-0.033	0.035	0.006	0.042	0.034	0.028
White-plumed Honeyeater	8.17	41	308	77.65	< 0.001	-6.529	1.015	-3.789	0.791	-2.630	0.711	10.36	0.016	-0.326	0.212	-0.165	0.061	-0.023	0.030
Mistletoebird	6.61	64	249	55.06	< 0.001	-3.238	0.655	-3.664	0.744	-2.833	0.638	23.77	< 0.001	-0.229	0.062	0.077	0.036	-0.088	0.038
Magpie-lark	6.40	54	241	148.93	< 0.001	-3.482	0.452	-3.431	0.499	-3.145	0.424	20.72	< 0.001	-0.042	0.049	-0.005	0.043	0.188	0.042
White-throated Gerygone	6.24	60	235	180.85	< 0.001	-5.368	0.654	-2.883	0.464	-2.841	0.396	17.53	< 0.001	-0.423	0.117	-0.001	0.034	-0.076	0.036
White-winged Chough	5.79	61	218	176.57	< 0.001	-3.624	0.423	-2.913	0.413	-3.436	0.381	24.93	< 0.001	-0.080	0.057	0.101	0.034	0.196	0.052
Red-rumped Parrot	5.73	21	216	111.69	< 0.001	-6.680	0.925	-6.813	1.065	-3.236	0.660	21.90	< 0.001	-0.545	0.129	0.329	0.162	-0.005	0.031
Crested Pigeon	5.65	49	213	90.87	< 0.001	-3.538	0.638	-4.240	0.698	-3.824	0.657	53.58	< 0.001	0.230	0.047	0.271	0.068	0.170	0.046
Scarlet Robin	5.47	60	206	155.11	< 0.001	-3.636	0.437	-3.091	0.463	-3.265	0.423	5.55	0.136	-0.032	0.071	-0.072	0.032	0.030	0.045
Common Myna	5.39	34	203	80.27	< 0.001	-3.770	0.733	-5.030	0.909	-4.195	0.784	68.24	< 0.001	-0.319	0.045	0.162	0.119	0.201	0.049
Australian Wood Duck	5.28	50	199	129.36	< 0.001	-4.462	0.567	-3.418	0.554	-3.150	0.473	1.84	0.607	0.001	0.066	0.023	0.042	0.052	0.042
Speckled Warbler	4.64	51	175	135.78	< 0.001	-3.170	0.497	-4.064	0.551	-3.473	0.477	26.20	< 0.001	-0.107	0.047	0.180	0.058	0.157	0.047
Laughing Kookaburra	4.25	61	160	242.90	< 0.001	-3.298	0.349	-3.989	0.420	-2.902	0.331	2.97	0.397	0.022	0.053	-0.073	0.063	0.046	0.039
Western Gerygone	3.93	50	148	112.37	< 0.001	-6.070	0.828	-3.030	0.560	-3.309	0.537	1.77	0.622	0.132	0.192	-0.027	0.040	-0.040	0.044
Willie Wagtail *	3.90	40	147	413.20	< 0.001	-5.981	0.700	-4.202	0.325	-3.197	0.270	7.30	0.063	-0.408	0.156	0.036	0.055	-0.002	0.038

White-eared Honeyeater	3.77	54	142	196.20	< 0.001	-3.395	0.396	-3.881	0.440	-3.400	0.398	32.25	< 0.001	-0.049	0.057	0.126	0.056	0.263	0.051
Brown-headed Honeyeater *	3.69	51	139	666.70	< 0.001	-5.013	0.474	-2.860	0.186	-3.640	0.225	8.79	0.032	-0.268	0.125	0.074	0.038	-0.030	0.055
Grey Shrike-thrush	3.40	56	128	458.80	< 0.001	-4.700	0.420	-3.493	0.292	-3.009	0.241	8.66	0.034	-0.266	0.103	-0.067	0.054	-0.025	0.040
Tree Martin *	3.37	27	127	273.80	< 0.001	-12.28	9.145	-5.870	0.587	-3.035	0.264	28.17	< 0.001	0.017	3.000	-0.230	0.155	-0.182	0.036
Silvereye	3.24	50	122	225.10	< 0.001	-3.750	0.439	-3.688	0.450	-3.782	0.391	20.21	< 0.001	-0.249	0.056	0.010	0.057	-0.012	0.059
Brown Thornbill	3.13	52	118	153.53	< 0.001	-4.113	0.526	-4.468	0.621	-3.117	0.448	6.27	0.099	-0.162	0.072	-0.049	0.064	-0.032	0.043
Grey Butcherbird	2.89	47	109	265.20	< 0.001	-3.898	0.391	-3.475	0.396	-3.681	0.358	3.24	0.355	0.107	0.070	0.001	0.050	0.054	0.058
Australian King-Parrot	2.81	29	106	45.29	< 0.001	-4.436	1.145	-4.667	1.169	-7.109	1.383	10.29	0.016	0.080	0.040	0.167	0.144	0.516	0.236
Golden Whistler *	2.71	54	102	911.20	< 0.001	-3.724	0.258	-3.557	0.189	-3.662	0.201	9.34	0.025	-0.207	0.069	0.003	0.053	-0.035	0.057
Common Bronzewing	2.47	40	93	74.92	< 0.001	-4.574	0.930	-5.085	0.969	-3.694	0.700	1.07	0.784	-0.005	0.052	0.018	0.083	0.059	0.058
Leaden Flycatcher *	2.42	45	91	716.20	< 0.001	-4.346	0.354	-3.736	0.226	-4.114	0.259	10.53	0.015	-0.262	0.089	0.075	0.056	-0.023	0.068
Olive-backed Oriole	2.28	44	86	424.00	< 0.001	-4.337	0.422	-3.758	0.398	-4.022	0.359	4.36	0.226	-0.068	0.077	0.034	0.058	0.121	0.067
Eastern Spinebill	2.04	26	77	115.96	< 0.001	-5.351	0.792	-4.310	0.728	-4.703	0.719	5.21	0.157	-0.280	0.149	-0.070	0.055	0.020	0.068
Dusky Woodswallow *	1.80	24	68	421.20	< 0.001	-5.065	0.505	-5.812	0.542	-3.881	0.296	7.44	0.059	-0.283	0.118	-0.151	0.117	-0.003	0.051
Pacific Black Duck	1.78	14	67	128.41	< 0.001	-7.058	1.115	-4.827	0.740	-5.618	0.735	5.93	0.115	0.186	0.240	-0.133	0.058	-0.001	0.106
Varied Sittella *	1.73	40	65	831.10	< 0.001	-4.548	0.355	-4.163	0.235	-3.909	0.217	4.76	0.190	-0.212	0.101	0.031	0.072	-0.027	0.064
Grey Currawong	1.65	33	62	117.71	< 0.001	-4.240	0.667	-5.345	0.799	-4.448	0.629	7.57	0.056	-0.194	0.079	-0.099	0.823	0.010	0.081
Brown Treecreeper *	1.62	14	61	265.50	< 0.001	-7.620	1.740	-41.63	70.48	-4.250	0.360	0.98	0.807	-0.380	0.450	7.730	14.310	0.005	0.050
Welcome Swallow *	1.27	22	48	412.90	< 0.001	-5.866	0.686	-5.879	0.585	-4.427	0.328	5.54	0.136	-0.213	0.187	-0.285	0.144	-0.035	0.065
White-naped Honeyeater	1.22	34	46	353.30	< 0.001	-4.809	0.469	-4.748	0.460	-4.078	0.356	3.49	0.322	-0.149	0.112	0.056	0.100	0.082	0.069
Gang-gang Cockatoo *	1.19	16	45	266.00	< 0.001	-3.371	0.248	-13.283	12.669	-6.481	0.727	2.89	0.408	0.091	0.054	0.020	4.156	0.055	0.234
Sacred Kingfisher	1.04	23	39	135.46	< 0.001	-6.065	0.748	-3.851	0.663	-5.123	0.676	12.05	0.007	0.049	0.163	0.163	0.077	0.302	0.110
Nankeen Kestrel	1.01	17	38	201.80	< 0.001	-5.343	0.594	-4.746	0.599	-4.956	0.517	4.46	0.216	-0.064	0.100	-0.198	0.099	0.023	0.102

IV. Avifauna and urban encroachment in time and space.

Urban expansion significantly and disproportionately alters fringe environments, and can compromise the conservation performance of peri-urban reserves. Factors that influence avian populations occupying urban fringe habitats are assumed to be temporally dynamic in type, extent, rate and intensity. However, this assumption is rarely tested with empirical field monitoring data. In this paper I investigate the effects of urban proximity, and rate of encroachment, on woodland birds occupying urban fringe habitats.

Rayner L., Evans, M. J., Gibbons P., Ikin K., Lindenmayer D.B. & Manning A.D. (2014) Avifauna and urban encroachment in time and space. *Diversity and Distributions*, 21, 428-440.

Abstract

Urban expansion significantly alters fringe environments often with undesirable impacts on biodiversity. Consequently, there is a need to define clear conservation objectives for areas subject to urban encroachment. Urban fringe development is a highly dynamic process, both spatially and temporally, but few studies are equipped to examine its temporal effects on biota. We aimed to explore the impacts of urban encroachment on avifauna through space and time. We used records from an extensive 14-year monitoring program undertaken in temperate woodland. We fitted hierarchical generalised linear models to assess individual species responses to the distance from monitoring sites to the urban boundary, and the temporal rate of change in this distance through time. We used factorial analysis on mixed data to examine trait group responses to these predictors.

Our results indicated that the occurrence of approximately half of the study region's avifauna is strongly linked to the proximity of their habitat to the urban fringe, but that the impact of urban fringe development on the occurrence of some species changed through time. We identified several species of conservation concern that respond negatively to large annual increases in urban fringe development, irrespective of its proximity to suitable habitat. Species responses to urban proximity were linked to life history traits, with small, migratory, woodland-dependent species that rely on mid- and upper-canopy structures, clearly disadvantaged by urban environments. Our findings demonstrate the breadth of species responses to urban encroachment over much larger distances than is typically investigated in urban ecological studies. We identify guilds vulnerable to the impacts of urban fringe development, and therefore in need of ecologically sensitive urban design. We argue that future urban expansion toward important fringe habitats will need to be planned strategically through space *and* time.

Introduction

Urban areas occupy a relatively small proportion of terrestrial land (Grimm *et al.*, 2008), but impact disproportionately on biologically productive landscapes (Luck, 2007). Consequently, highly populated environments and biodiversity hotspots show strong spatial congruence at broad scales (Güneralp & Seto, 2013). In these species-rich environments, human population growth exceeds that of global background levels (Cincotta *et al.*, 2000; Seto *et al.*, 2012). Urban expansion is spatially concentrated at the edge of major urban centres (Fisher, 2003; Robinson *et al.*, 2005), significantly and disproportionately altering fringe ecosystems (Radeloff *et al.*, 2005) often with undesirable impacts on biodiversity (Marzluff *et al.* 2001; Pautasso, 2007).

Urban fringe development threatens biodiversity through habitat loss (Foley *et al.*, 2005), fragmentation (Crossman *et al.*, 2007) and the introduction of invasive species (Marzluff & Ewing, 2001; Forys & Allen, 2005). If persistent, these threats can ultimately lead to biotic homogenization (McKinney, 2006) and species population declines (Aronson *et al.*, 2014) in affected environments. Urban encroachment into rural or wild lands also can undermine the effectiveness of nearby protected areas to abate such threats (Radeloff *et al.*, 2010) and to safeguard species populations in perpetuity (Rayner *et al.*, 2014). However, evidence also exists for species that are promoted by urbanisation (e.g. Wania *et al.*, 2006). This is particularly the case where important or rare habitats occur within urban landscapes (Sorace & Gustin, 2010).

Conflicting data on the impacts of urban fringe development on biodiversity means it is difficult to define clear conservation objectives for peri-urban environments (Turner *et al.*, 2004). This is pertinent to Australia, where over 50% of nationally-listed threatened species occur in vulnerable urban fringe habitats (Bekessy *et al.*, 2012). In response to this challenge, many researchers have examined the effects of urbanisation on neighbouring ecological communities, primarily using sites located along urban-rural gradients (reviewed in McKinney, 2002). However, few studies have explored the ecological effects of urbanisation through time (Chace & Walsh, 2006; Garden *et al.*, 2006; Chamberlain *et al.*, 2009; Luck & Smallbone, 2010).

Understanding the temporal patterns in responses of biota to urban fringe development is important because the process of land-use change is dynamic, both spatially and temporally (Figure 1), and because faunal communities are assumed to change with ongoing development (Scott, 1993). Therefore, an important consideration when evaluating the effects of urban fringe development on neighbouring species populations may not only be the **extent** and **proximity** of development, but the **rate** of land-use change.

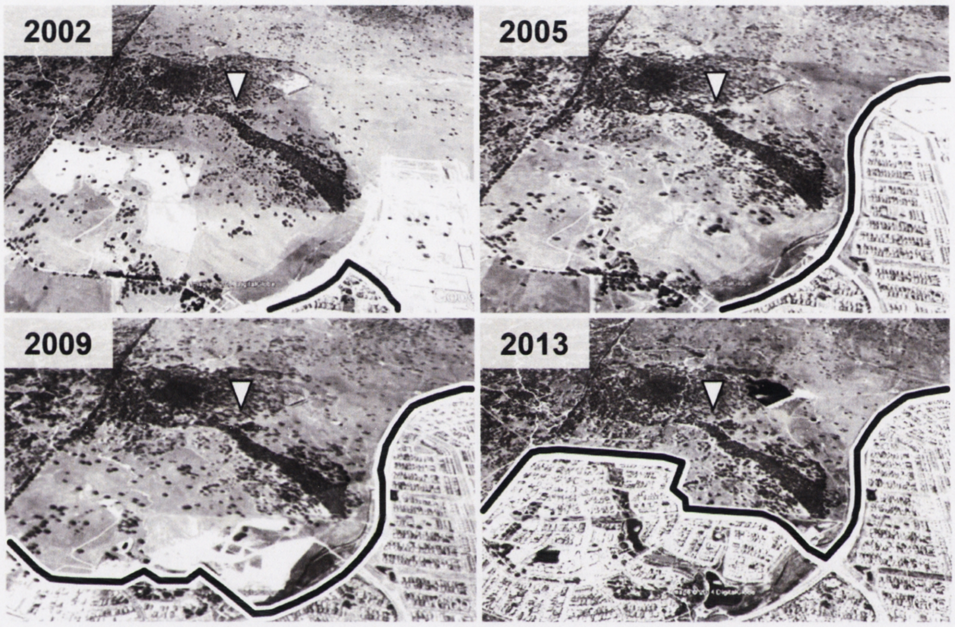


Figure 1. Example of the spatio-temporal change associated with urban fringe development in North Canberra, Australia. The urban boundary is indicated by the bold black line, with development encroaching into an endangered ecological community found in the study area (box-gum grassy woodland – arrow) over a period of 12 years. Image source: Google Earth.

In this study, we used records from a 14-year biodiversity monitoring program to explore the impacts of urban fringe development on a vulnerable assemblage of species: Australian temperate woodland birds. Our systematic survey design enabled us to examine the response of birds to both the spatial extent and temporal rate of urban fringe development (Figure 2) and test two key hypotheses:

Hypothesis 1: The proximity of urban development will influence observed patterns of bird occurrence in neighbouring woodland habitats. Many short-term studies have found distance to the urban boundary to be a driver of species abundance, occurrence and community structure (Brearley *et al.*, 2010; Dallimer *et al.*, 2012; Ikin *et al.*, 2013), and that the tolerance of species to urban development is often linked to life history traits and resource use (Sol *et al.*, 2014). For example, species requiring more complex environments (e.g. specialist species, small-bodied species) may be disadvantaged by the simplified structure of urban systems and may present as "urban avoiders" (*sensu* Blair, 1996). We postulated that the incidence and abundance of urban avoiders would increase with increasing distance from the urban fringe, and that the converse would be found for "urban exploiters" which favour urban zones (*sensu* Blair, 1996; Figure 2b).

Hypothesis 2: The negative impact of urbanisation on urban-sensitive species will be greater in areas of rapid encroachment than in areas of static or gradual change. Urban fringe development significantly modifies existing habitats (Grimm *et al.*, 2008) with considerable levels of disturbance during the construction of human infrastructure. Human-induced disturbance significantly reduces bird densities and adversely affects foraging and breeding behaviour (Burton *et al.*, 2002; Reijnen & Foppen, 2006). We assumed that the larger the annual change in urban extent, the more pronounced the effects of disturbance would be, because more of the existing habitat is altered with little time for species to adapt. Correspondingly, we postulated that the incidence of all species, but especially urban avoiders, would decrease with larger annual changes in urban proximity due to displacement effects (e.g. Pearce-Higgins *et al.*, 2012; Figure 2c). However, over longer periods, we expected urban exploiters to respond positively to large changes in urban extent because the process of urban encroachment creates favourable habitat (post-disturbance) that will continue to be inhospitable to urban avoiders.

Our aim in testing these two hypotheses was to determine whether the rate of urban change had a distinct and significant effect on species inhabiting urban fringe ecosystems above that of spatial proximity alone. To our collective knowledge, this effect has not been previously examined with empirical field data.

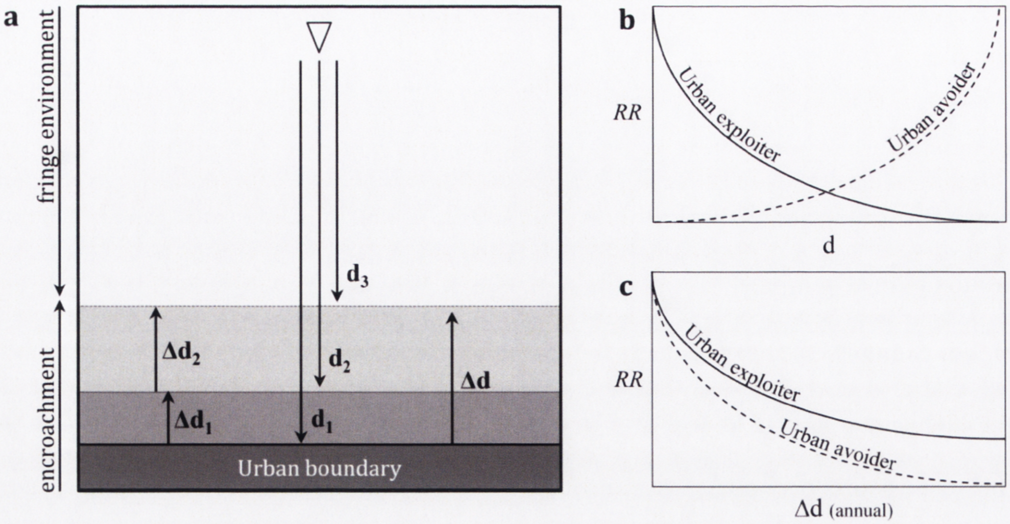


Figure 2. Conceptual model showing (a) the measures of urban encroachment used in this study, where: **d** is the distance from a permanent field monitoring site (arrow) to the urban boundary recorded at annual time steps (1,2,3); and **Δd** is the distance that the urban boundary has moved in time, recorded at annual time steps (1,2) and over the full period of observation (d_1 - d_n). The hypothesized relationships between species reporting rate 'RR' (the proportion of surveys in which a species was recorded out of the total number of surveys conducted at a site in a given year) and our measures of urban encroachment are shown in figure panels (b) and (c).

Methods

Study region

Our study area comprised a 20 x 40 km area (bounded by -35.1°, 149.3° and -35.6°, 148.9°) in the sub-humid region of the Australian Capital Territory, south-eastern Australia (see Appendix A). The city of Canberra covers ~800 km^2 and contains a population of ~380,000 people (ABS, 2013). Population density in 2013 was 162 people km^{-2}, but is variable across the Territory (ABS, 2013). Strongest population growth has occurred in the northern fringe suburbs of Canberra, shifting the centre of population north by 1.5 km over the last decade. In areas adjacent to our study sites, population density ranged from 0.44 – 14.54 residents per hectare of urban area (mean = 8.63, median = 10.28). Residential density in these areas ranged from 0.28 – 6.58 dwellings per hectare of urban area (mean = 3.48, median = 3.70). All new developments (areas measured as encroachment in this study) were uniformly higher in residential density, ranging from 3.89 – 6.58 dwellings per hectare of urban area (mean = 4.95, median = 4.64).

The dominant vegetation type in peri-urban zones of the study area was temperate eucalypt woodland. These woodlands once covered vast areas of the Australian continent, but have been heavily cleared since European settlement in the mid-1800s (Lindenmayer *et al.*, 2010). Some large intact remnants of critically endangered box-gum grassy woodland remain in the study area (ACT, 2011), but most have been perturbed by grazing, altered fire regimes, and invasion by weeds and feral animals. Urbanisation presents ongoing threats to woodland extent in the region and significant challenges for protecting the ecological integrity of remnants on the urban fringe (Ikin *et al.*, 2014; Rayner *et al.*, 2014).

Bird data

We sourced records of bird occurrence and abundance from a long-term woodland bird monitoring project undertaken by the Canberra Ornithologists Group. We used data from 92 permanent field sites nested within 10 broader survey locations (Figure 3). Sites were at least 100 m apart, ranging from a minimum of 105 m to a maximum of 2,473 m (mean = 357 m). All sites were located in temperate grassy woodland (n=86) or dry forest contiguous with temperate grassy woodland (n=6) for the duration of the study (i.e. no sites were consumed by urban development). Sites were surveyed every year for 14 years from 1999 to 2012. Surveys were 10-minute point-counts conducted seasonally (four surveys/site/year) with no changes to survey protocol and little appreciable variation in effort. During surveys, experienced observers counted all birds seen or heard within a 50m radius. Detailed site descriptions and further information on bird survey protocols can be found in Bounds *et al.* (2010). Only species occurring in >1% of surveys were included in formal analysis.

Urban data

Spatio-temporal data on the changing extent of urban Canberra were sourced from the Australian Capital Territory Government for the period 1999 to 2010. For our purposes, change in urban extent was recorded at the commencement of urban development. This included areas cleared of native vegetation for the construction of human infrastructure. From these data, we identified the location of the urban boundary at annual time steps. Geographic Information System (GIS) Software was used to calculate Euclidean distances from each of the 92 survey sites to the nearest point along the urban boundary corresponding with each year of bird survey data. Three metrics were calculated from these data for analysis (Figure 2a): *Urban Distance* (the distance from each site to the urban boundary for a given year), *Urban Annual Change* (the annual incremental change in Urban Distance through time, e.g. Urban Annual Change_{2005} = Urban Distance_{2005} – Urban Distance_{2004}), and *Urban Long-term Change* (the total change in Urban Distance over the period 1999-2010.

Statistical analysis

We fitted hierarchical generalised linear mixed models (HGLM) to examine the separate effects of our three urbanisation metrics on individual species reporting rates and abundances. Reporting rates are defined as the proportion of surveys in which a species was recorded out of the total number of surveys conducted at a site in a given year. This response variable provides a measure of change in species site occurrences, accounting for small variations in survey effort directly. For each year, we also pooled multiple visits to a given site to calculate annual abundances for each species. We assumed quasi-binomial distributions for models using reporting rate, and Poisson distributions for models using relative abundance. We standardised all predictor variables prior to modelling. We modelled the variables Urban Distance and Urban Annual Change together (i.e. in the same model) to examine the independent effects of these predictors. For our investigation of long-term change, we related reporting rates and relative abundances calculated for the last two years of the dataset (2011/2012) to the total change in the urban boundary recorded between 1999 and 2010. We also provide long-term trend estimates based on simple linear models of species abundances to assist ecological inference of long-term encroachment effects. For all models, we accounted for spatial and temporal dependence in the data that resulted from location-, site-and year-specific variations in occurrence and abundance by including these factors as random effects. We assumed a beta-distribution with a logit-link function for the random component in binomial models, and a gamma-distribution with a log-link function for the random component in Poisson models. We fitted HGLMs in GenStat 15th Edition statistical software package (VSN International Ltd).

We used Factorial Analysis on Mixed Data (FAMD) to examine the effect of Urban Distance and Urban Annual Change on functional trait groups. FAMD is a principal component method that explores similarities among trait groups in terms of their responses to environmental predictors. We included only those species that showed significant responses to either Urban Distance or Urban Annual Change in FAMD, analysing each predictor separately. Prior to analysis, we assigned each bird species to functional trait groups based on life-history attributes. These groups included habitat specialisation (woodland specialist, woodland generalist), mobility (sedentary, migratory, dispersive), body size (small, intermediate, large), and nesting substrate (hollow, understorey, arboreal, opportunistic). We provide details of trait assignment for individual species, including sources of information for classification in Appendix B. We applied FAMD in the R statistical program (R Development Core Team) using the FactoMineR software package (Husson *et al.*, 2014).

Results

A total of 4,750 surveys was undertaken at the 92 permanent field monitoring sites between 1999 and 2012. We analysed data for 59 species that occurred in >1% of surveys (Appendix B). We excluded waterbirds from our analysis because their primary habitat is underrepresented in the dataset. The distance from survey sites to the urban boundary ranged from 16 to 5,363 metres between 1999 and 2010. The distance of urban encroachment ranged from 0 to 1,052 metres annually, and from 0 to 2,330 metres between 1999 and 2010.

Hypothesis 1: Effects of urban proximity

Individual species responses

We identified 32 species whose reporting rates or abundances were significantly related to Urban Distance (Table 1). Responses were mixed with 15 species increasing (hereafter *urban exploiters*) and 17 species decreasing (hereafter *urban avoiders*) with urban proximity. The distance over which species were affected by urbanisation also varied (Figure 4a-d). For example, the Common Myna responded strongly within 1km of development (e.g. Common Myna, Figure 4a), while the Red Wattlebird showed an urban response that extended up to 5 km away (Figure 4b). Only two exotic bird species were recorded during surveys (the Common Myna and Common Starling) and both showed significantly higher reporting rates proximal to the urban boundary. We found no observable effects of Urban Distance on the reporting rates or abundances of the remaining 27 bird species.

Trait-based responses

Dimensions one and two of our FAMD explained 45% of variability in trait-based responses to Urban Distance. We found a clear pattern in the response of trait groups along an urban proximity gradient (Dimension 1, Figure 5). Sites located nearest to the urban boundary supported larger-bodied species not strictly dependent on woodland habitats and opportunistic in their nesting requirements. In contrast, sites located at increasing distances from the urban boundary supported more smaller-bodied, woodland-dependent birds that rely on mid- and upper-canopy structure for nesting. Hollow-dependent species (also known as 'cavity nesters') showed a stronger association with sites located near to the urban boundary, as did sedentary species. Migratory and dispersive species were more likely to be observed on sites at increasing distances from the urban fringe.

Table 1. Relationships between Urban Distance and species (a) reporting rates and (b) relative abundances. Positive estimates represent increasing reporting rate/abundance with increasing distance from the urban boundary. Only species showing a significant response to urban distance ($\alpha = 0.05$) are listed. Exotic species are denoted by an asterisk (*). Scientific names for species are provided in Appendix B.

Response	Species	(a) Reporting rate				(b) Relative abundance			
		Est.	SE	Wald	P	Est.	SE	Wald	P
Urban exploiters	Australian King-Parrot	-2.656	0.658	16.29	<0.001	-2.724	0.595	20.98	<0.001
	Brown Treecreeper					-3.698	0.824	20.16	<0.001
	Common Myna*	-2.160	0.429	25.40	<0.001				
	Red-rumped Parrot	-1.565	0.444	12.42	<0.001	-4.006	0.738	29.46	<0.001
	Welcome Swallow	-1.248	0.205	37.03	<0.001				
	Common Starling*	-0.769	0.162	22.55	<0.001				
	Crested Pigeon	-0.686	0.249	7.62	0.006	-0.852	0.252	11.39	<0.001
	Striated Pardalote	-0.317	0.112	8.10	0.004	-0.256	0.086	8.82	0.003
	Eastern Rosella	-0.324	0.131	6.18	0.013	-0.281	0.097	8.35	0.004
	Crimson Rosella	-0.188	0.073	6.73	0.009				
	Grey Butcherbird	-0.443	0.142	9.74	0.002				
	Red Wattlebird	-0.286	0.132	4.70	0.030	-0.477	0.122	15.35	<0.001
	Silvereye	-0.392	0.182	4.66	0.031				
	Australian Raven	-0.289	0.142	4.15	0.042				
	Mistletoebird	-0.278	0.137	4.12	0.042				
Urban avoiders	Sacred Kingfisher	1.310	0.247	28.04	<0.001				
	Superb Fairy-wren	0.958	0.179	28.51	<0.001				
	Dusky Woodswallow	0.874	0.257	11.56	<0.001				
	White-plumed Honeyeater	0.757	0.218	12.02	<0.001	0.579	0.232	6.21	0.013
	Common Bronzewing	0.509	0.163	9.80	0.002				

Noisy Miner	0.498	0.171	8.45	0.004				
Western Gerygone	0.478	0.124	14.81	<0.001				
Willie Wagtail	0.476	0.165	8.34	0.004				
Scarlet Robin	0.412	0.123	11.25	<0.001	0.422	0.117	13.12	<0.001
Brown Treecreeper	0.371	0.071	27.47	<0.001				
Striated Thornbill	0.344	0.100	11.76	<0.001				
Tree Martin	0.317	0.064	24.43	<0.001				
Brown-headed Honeyeater					0.432	0.158	7.51	0.006
Rufous Whistler	0.239	0.104	5.29	0.022				
Golden Whistler	0.230	0.115	3.97	0.046				
Mistletoebird					0.197	0.084	5.46	0.019
Weebill					0.139	0.070	3.93	0.047

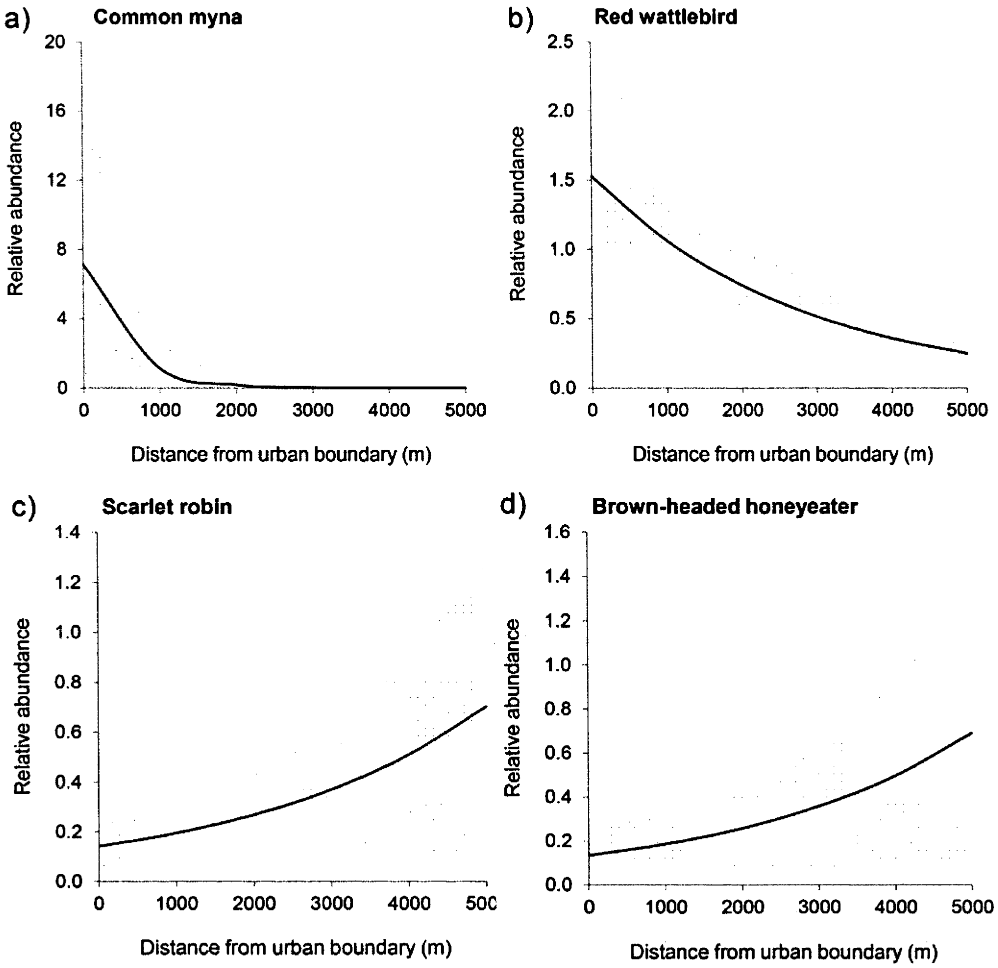


Figure 4. Examples of two species responding positively to urban proximity (a-b), and two species responding negatively to urban proximity (c-d). Plots show predicted trends (bold line) with 95% confidence intervals (shaded grey). All responses are significant at $\alpha = 0.05$. Note: Y axes are scaled to best visualise responses and vary between species.

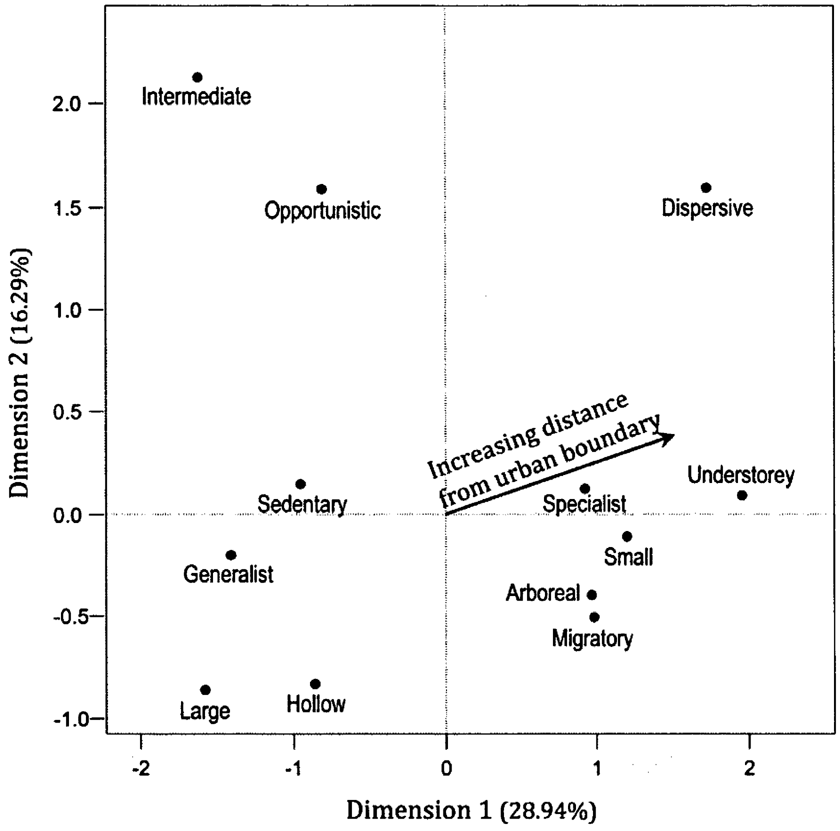


Figure 5. FAMD ordination indicating a clear shift in species trait groups along a gradient of urban proximity (Dimension 1). Traits included in the ordination were: habitat specialisation (Generalist, Specialist), body size (Small, Intermediate, Large), mobility (Sedentary, Migratory, Dispersive) and nesting substrate (Hollow, Arboreal, Understorey, Opportunistic).

Hypothesis 2: Effects of urban change

Individual species responses to annual change

We identified 15 species whose reporting rates or abundances were significantly related to Urban Annual Change (Table 2). Responses to annual change were primarily negative with reporting rates or abundances of 12 species decreasing as rate of change in urban proximity increased (hereafter *rapid change intolerant*, e.g Figure 6a, Brown Treecreeper). However, three species showed the opposite effect, responding positively to increasing annual changes in urban proximity (hereafter *rapid change tolerant*, e.g. Figure 6b, White-plumed Honeyeater). Most species that were influenced by annual change also exhibited a significant relationship with distance (9/15 species), but these associations were not always intuitive. For example, the White-plumed Honeyeater and Rufous Whistler both responded negatively to urban proximity, but positively to increasing annual change. Two species, the Grey Currawong and Varied Sittella, showed negative responses to annual change with no significant response to Urban Distance. Overall, we found no observable effects of annual change on the reporting rates or abundances of most species in the dataset (n = 44).

Trait-based responses to annual change

Dimensions one and two of our FAMD explained 56% of variability in trait-based responses to annual urban change. However, patterns in the response of trait groups were less clear for change than for distance (see Appendix C). This may be due to the small number of species included in the ordination (15 species listed in Table 2). There was no clear association between annual change and species body size. However, we found some evidence to suggest that sites experiencing lower rates of annual change support more generalist, sedentary and hollow-dependent species.

Table 2. Relationships between annual incremental change in urban proximity and species (a) reporting rates and (b) relative abundances. Positive estimates indicate higher reporting rates/abundances on sites where the annual rate of urban change is slower. Only species showing a significant response to urban annual change ($\alpha = 0.05$) are listed. Exotic species are denoted by an asterisk (*). Scientific names for species are provided in Appendix B.

Response	Species	(a) Reporting rate				(b) Relative abundance			
		Est.	**SE**	**Wald**	**P**	**Est.**	**SE**	**Wald**	**P**
Rapid change tolerant	Eastern Spinebill	-0.125	0.045	7.69	0.006				
	White-plumed Honeyeater	-0.207	0.087	5.67	0.017	-0.234	0.079	8.80	0.003
	Rufous Whistler	-0.087	0.044	3.99	0.046				
Rapid change intolerant	Brown Treecreeper	0.877	0.225	15.17	<0.001	1.299	0.218	35.40	<0.001
	Tree Martin	0.734	0.160	21.15	<0.001				
	Grey Currawong	0.313	0.109	8.26	0.004				
	Red-rumped Parrot					0.319	0.130	6.06	0.014
	Varied Sittella	0.338	0.116	8.50	0.004				
	White-naped Honeyeater					0.212	0.104	4.11	0.043
	Mistletoebird	0.156	0.057	7.45	0.006	0.119	0.053	5.04	0.025
	Brown-headed Honeyeater					0.170	0.065	6.92	0.009
	White-winged Chough					0.159	0.064	6.11	0.013
	Common Starling*	0.247	0.103	5.78	0.016				
	Golden Whistler	0.187	0.085	4.84	0.028	0.173	0.084	4.26	0.039
	Galah					0.128	0.059	4.75	0.029

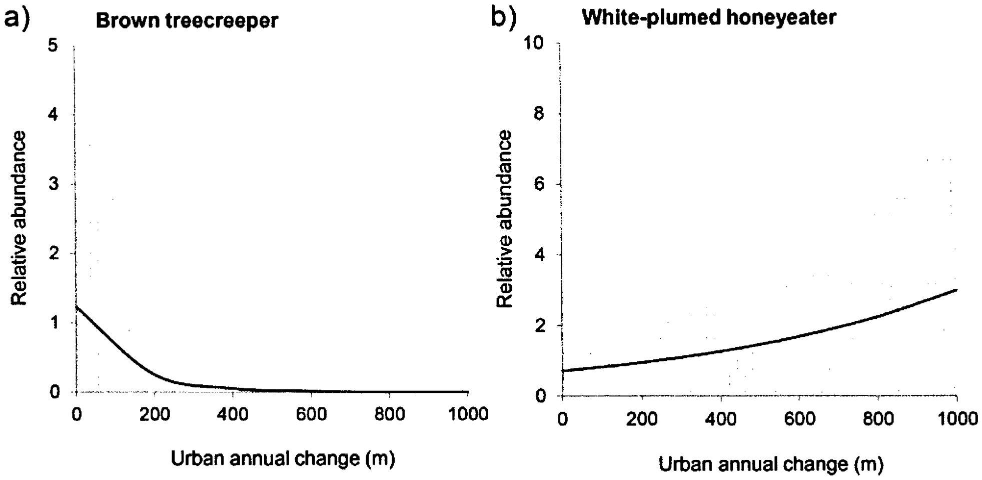


Figure 6. Examples of two species responding to increasing urban annual change: one positively (a) and one negatively (b). Plots show predicted trends (bold line) with 95% confidence intervals (shaded grey). All responses are significant at α = 0.05. Note: Y axes are scaled to best visualise responses and vary between species.

Individual species responses to long-term change

We identified 15 species whose reporting rates or abundances calculated in the final two years of surveys (2011/2012) were significantly related to Long-term Urban Change (Table 3). Species with positive associations tended to be urban exploiters (Table 3) that typically occupied sites located near to the urban boundary at the start of the observation period, where limited encroachment had taken place over the preceding 12 years. Species with negative associations tended to be urban avoiders (Table 3) that typically occupied sites further from the urban boundary at the start of the observation period, which were sites subjected to higher rates of encroachment over the the preceding 12 years.

We found no strong link between the population trends of species that exhibited positive associations with long-term urban change. These species showed a combination of increasing, stable and declining trends in our study area. However, species negatively associated with long-term urban change showed only stable or declining population trends in our study area. Three urban-avoiding species (the Scarlet Robin, Striated Thornbill and Rufous Whistler) showed both negative association with long-term urban change and a long-term declining population trend.

Table 3. Relationship between the total long-term change in urban proximity (1999-2010) and species (a) reporting rates and (b) relative abundances in the two years following (2011/2012), along with long-term species trends for the full study period (1999-2012). Positive estimates indicate higher reporting rates/abundances on sites where urban encroachment has been smallest (i.e. sites located near to the urban boundary at the start of the study period). Only species showing a significant response to long-term urban change are listed ($\alpha = 0.05$). Exotic species are denoted by an asterisk (*).

Response	**Species**	**Trend**	**Class**	**(a) Reporting rate**				**(b) Relative abundance**			
				Est.	**SE**	**Wald**	**P**	**Est.**	**SE**	**Wald**	**P**
More common on sites near to urban, with limited encroachment	Australian King-parrot	Increase	Urban exploiter					2.935	1.220	5.79	0.016
	Common Starling*	Decreaser	Urban exploiter					2.377	0.616	14.89	<0.001
	Pied Currawong	Increaser		1.114	0.407	7.50	0.006	1.135	0.422	7.22	0.007
	Superb Fairy-wren	Decreaser	Urban avoider	1.110	0.453	6.02	0.014	1.066	0.394	7.31	0.007
	Crested pigeon	Increase	Urban exploiter					0.774	0.393	3.88	0.049
	Red Wattlebird	No trend	Urban exploiter	0.939	0.453	4.31	0.038	0.735	0.358	4.21	0.040
	Galah	Increaser		0.658	0.234	7.91	0.005	0.661	0.185	12.81	<0.001
	Sulphur-crested Cockatoo	Increase						0.456	0.233	3.84	0.050
More common on sites far from urban, with greater encroachment	Scarlet Robin	Decreaser	Urban avoider					-0.460	0.161	8.15	0.004
	Buff-rumped Thornbill	No trend						-0.513	0.239	4.61	0.032
	Golden Whistler	No trend	Urban avoider					-0.625	0.203	9.52	0.002
	Brown Treecreeper	No trend	Urban avoider	-0.674	0.267	6.38	0.012				
	Striated Thornbill	Decreaser	Urban avoider	-0.702	0.324	4.71	0.030				
	Rufous Whistler	Decreaser	Urban avoider	-0.774	0.364	4.53	0.033				
	White-throated Treecreeper	No trend		-1.234	0.399	9.56	0.002	-0.972	0.384	6.42	0.011

Discussion

In this paper, we tested two hypotheses of how woodland bird occurrence might be directly influenced by urban fringe development: (1) via the spatial proximity of urban development and (2) via the rate of change in urban proximity. Based on data from a spatially replicated long-term monitoring project, our study shows that the occurrence of approximately half of the region's avifauna is strongly linked to the proximity of their habitat to urban fringe development, but that the impact of urban fringe development on the occurrence of some species is also temporally dependent. These findings, and their implications for conservation management, are discussed below.

Hypothesis 1: Proximity of urban fringe development

More than half of our study species showed a clear relationship to urban proximity and, within that group of species, positive and negative responses were almost evenly split. Most urban exploiters identified in this study were species that we would expect, and possessed traits that we would expect, based, on the literature (e.g. Luck & Smallbone, 2010). The tendency for urban exploiters to be woodland generalists is supported by Bonier *et al.* (2007) who demonstrated that, globally, urban birds have broad environmental tolerances (as indicated by their larger geographical ranges). There is also substantial support for urban exploiters being larger, exotic and sedentary (McKinney, 2002; Garden *et al.*, 2006; Kark *et al.*, 2007; Croci *et al.*, 2008; Luck & Smallbone, 2010), as found in this study.

Conversely, our finding that urban exploiters were more likely to be hollow-dependent is interesting, and both supported (Kluza *et al.*, 2000; Miller *et al.*, 2003; Chace & Walsh, 2006) and contradicted (Sandström *et al.*, 2006; Pidgeon *et al.*, 2007) by the literature. Within Australia, the relationship between hollow-nesters and urbanisation is suggested to be negative due to the mechanisms underlying hollow development and the removal of senescing trees from urban landscapes (Shanahan *et al.*, 2013; Le Roux *et al.* 2014). Indeed, within our study area, previous research indicates that hollow-nesters decline in occurrence from the suburb-reserve interface to the suburb core (Ikin *et al.*, 2014). However, our results suggest that this relationship is one of more complex urban adaptation (*sensu* Johnston, 2001), where hollow-nesters are attracted to novel resources within the urban boundary, but critically rely on natural resources (i.e. remnant trees) that are more abundant outside the urban boundary (McKinney, 2002; Blewett & Marzluff 2005). This would explain why hollow-nesters appear to favour urban fringe habitats in our study, declining as distances increase both into the suburbs and away from the urban fringe.

A key outcome of our study was the identification of urban avoiders, because these species may require greater conservation effort as urban centres continue to expand and opportunities for protection through new reserves become limited (Mcdonald *et al.*, 2009). Perhaps unsurprisingly, a number of urban avoiders identified in this study are woodland-dependent species that have shown declines in the study area (Table 3) or in various parts of south-eastern Australia over the last decade (e.g. Dusky Woodswallow, Sacred Kingfisher, Scarlet Robin, Striated Thornbill, Superb Fairy-wren, Tree Martin; Barrett *et al.*, 2007; Szabo *et al.*, 2011). Specialised habitat requirements, and a reliance on natural resources, are common traits among urban avoiding species (McKinney, 2002; Møller, 2009; Luck & Smallbone, 2010).

In addition to their habitat specialisation, urban avoiders were found in this study to be small-bodied, migratory or dispersive, and dependent on mid and upper canopy structures for nesting. This is consistent with the literature (Lim & Sodhi, 2004: Garden *et al.*, 2006; Kark *et al.*, 2007). It is documented that mid and upper canopy structures are reduced in urban environments (Chace & Walsh, 2006; Le Roux *et al.* 2014), but the avoidance of urban areas by migrants is also suggested to be linked to nesting requirements (Kark *et al.*, 2007). Specifically, sedentary species may occupy the limited number of nest sites during the absence of migratory species, thus gaining a competitive advantage in urban systems (Kark *et al.*, 2007). This also supports arguments that nesting requirements are a strong determinant of urban tolerance for birds (Lim & Sodhi, 2004; Marzluff & Neatherlin 2006).

Another important inter-specific interaction to consider involves the presence of the Noisy Miner (*Manorina melanocephala*). The Noisy Miner is an abundant species commonly found in urban areas, but was identified as an urban avoider because its reporting rate significantly increased with distance from the boundary. Given the documented impact of this hyper-aggressive species on woodland bird communities (Montague-Drake *et al.*, 2011) and its strong increasing trend in our study area (Rayner *et al.* unpublished data), additional work is needed to examine the relative effects of Noisy Miner occurrence and urban fringe development on sites where other avoider species co-occur. In the present study, the occurrence of the Noisy Miner is unlikely to have biased our definition of urban avoiders because this species shows strong site fidelity and was absent from, or rare in (present in <10 surveys over 12 years) the majority of our study sites (n=72/92).

Hypothesis 2: Change in urban fringe development

Species responses to urban fringe development are not driven by proximity alone. For some species, the rate of change in urban proximity also contributes to observed patterns of occurrence. For example, the Common Starling (exotic and declining; Barrett *et al.*, 2007; Rayner *et al.* unpublished data) and Mistletoebird (declining; Szabo *et al.*, 2011; Rayner *et al.* unpublished data) both responded positively to urban proximity, but were negatively impacted by increasing rates of urban change. That is, the greater the annual change in urban proximity, the less likely we were to observe these species on a site. Other species, such as the Grey Currawong and Varied Sittella did not exhibit significant relationships with urban distance at all, but also showed supressed reporting rates with rapid changes at the urban fringe. Both of these species are declining more broadly (Barrett *et al.*, 2007). Of greatest concern are species that exhibited both a negative response to urban proximity *and* change, such as the Brown Treecreeper (listed as near threatened; EPBC, 1999), Tree Martin (declining; Barrett *et al.*, 1994; Paton *et al.*, 2004; Szabo *et al.*, 2011) and Golden Whistler. These examples demonstrate that urban fringe development is having a detrimental impact on those bird species which are often of conservation concern, but in a way that is not captured by static distance metrics alone.

Common traits were generally lacking among species responding to urban change. However, our results indicate that generalist, sedentary and hollow-dependent species, which are typically favoured by urban environments (Figure 5), are negatively affected by large annual shifts in proximity. If the response of these trait groups to urban fringe development is driven primarily by resource availability (McKinney, 2002), it is possible that the human-subsidised resources favouring these species groups are not available in the initial phase of urban construction (i.e. within one year). This supports arguments that species responses to urban fringe development are likely to change through time (Scott, 1993) and that the age of a suburb is a strong determinant in how communities respond to urbanisation (Møller *et al.*, 2012). Indeed, we found little congruence between the responses of species to rapid, short-term changes in urban fringe development and the delayed, longer-term effects of an established urban suburb. Pearce-Higgins *et al.* (2012) found a similar pattern of response for birds inhabiting areas adjacent to wind farms in the United Kingdom, where population declines were linked to immediate construction disturbance rather than subsequent operation. Unfortunately, we found no comparative studies examining this effect in urban fringe environments elsewhere around the world.

When relating species population trends to the extent of urban change in the preceding 12 years, we found little support for a linear association. That is, species in areas subject to minimal urban encroachment showed variable long-term trend responses, including population increases and declines. However, areas of most extensive change in urban fringe development were more often associated with species exhibiting stable or declining trend patterns, and these species were more likely to be urban avoiders. This finding suggests that long-term changes in urban fringe development may be influencing woodland bird persistence, but that its effects could be spatially dependent on other landscape factors.

One such factor influencing species responses to urban fringe development may be the spatial distribution of protected areas. In our study system, protected areas have been established around most of the sites that were subject to the highest rate of urban change over the last decade (Rayner *et al.*, 2014). Direct conservation action within reserves that target the protection of woodland avifauna (such as predator removal and the addition of coarse woody debris; Manning *et al.*, 2011; Shorthouse *et al.*, 2012) may have influenced our results on long-term responses to urban change by reducing the detectable impact of rapid, large-scale urban encroachment. While this result has the potential to be an encouraging conservation outcome, the role of protected areas for abating the impacts of urban fringe development remain inconclusive without further replication of areas subject to high urban change in the absence of formal protection.

Management implications

Defining conservation objectives in urban fringe environments remains an important challenge for conservation biology (Miller & Hobbs, 2002; Battisti & Gippoliti, 2004). There is an urgent need for long-term monitoring data to assist the management of species-urban interactions (Chace & Walsh, 2006). Our study is one of the first to track species responses to urban fringe development through time using empirical data from permanent field monitoring sites. Temporal replication in our surveys lends additional rigour to our assessment of species urban tolerance as significant relationships are based on a consistent response to urban proximity through time.

However, this investigation shows that the examination of proximity alone will not reveal all that we need to know about the impact of urban fringe development on those species occupying fringe habitats. We have discovered that several species respond to the rate of change in development at the urban fringe. Given that these species are frequently of conservation concern regionally and nationally, we argue that testing the response of species to urban change provides critical insight to those taxa that are particularly vulnerable to urban-related disturbance. We provide examples of where our results might be regionally specific and encourage careful consideration of ecological context when examining the effects urban fringe development elsewhere (Luck & Smallbone, 2010).

The adverse effect of urban fringe development on the reporting rates and abundances of vulnerable species warrants careful attention in terms of conservation management and planning. At a minimum, our findings suggest that vegetation (specifically mid- and upper-canopy structures) should be retained wherever possible in urban environments, particularly during the construction phase of development. In addition, future urban expansion toward important fringe habitats (e.g. endangered ecological communities or areas supporting threatened species) will need to be planned strategically through space *and* time. Spatially, we detected urban proximity effects on species frequently beyond 3 km (and up to 5 km) from the urban boundary. Decision makers will need to consider this distance when acquiring land for future urban fringe development in areas of high conservation value. Planners will need to do their best to minimise construction-related disturbance, particularly on large development blocks. Ideally, the spatial scale of suburbs also would be considered prior to establishment. Avoiding blocks of development that result in large advances toward sensitive habitats would be preferable so that species sensitive to urban fringe development can benefit from smaller incremental changes in urban encroachment.

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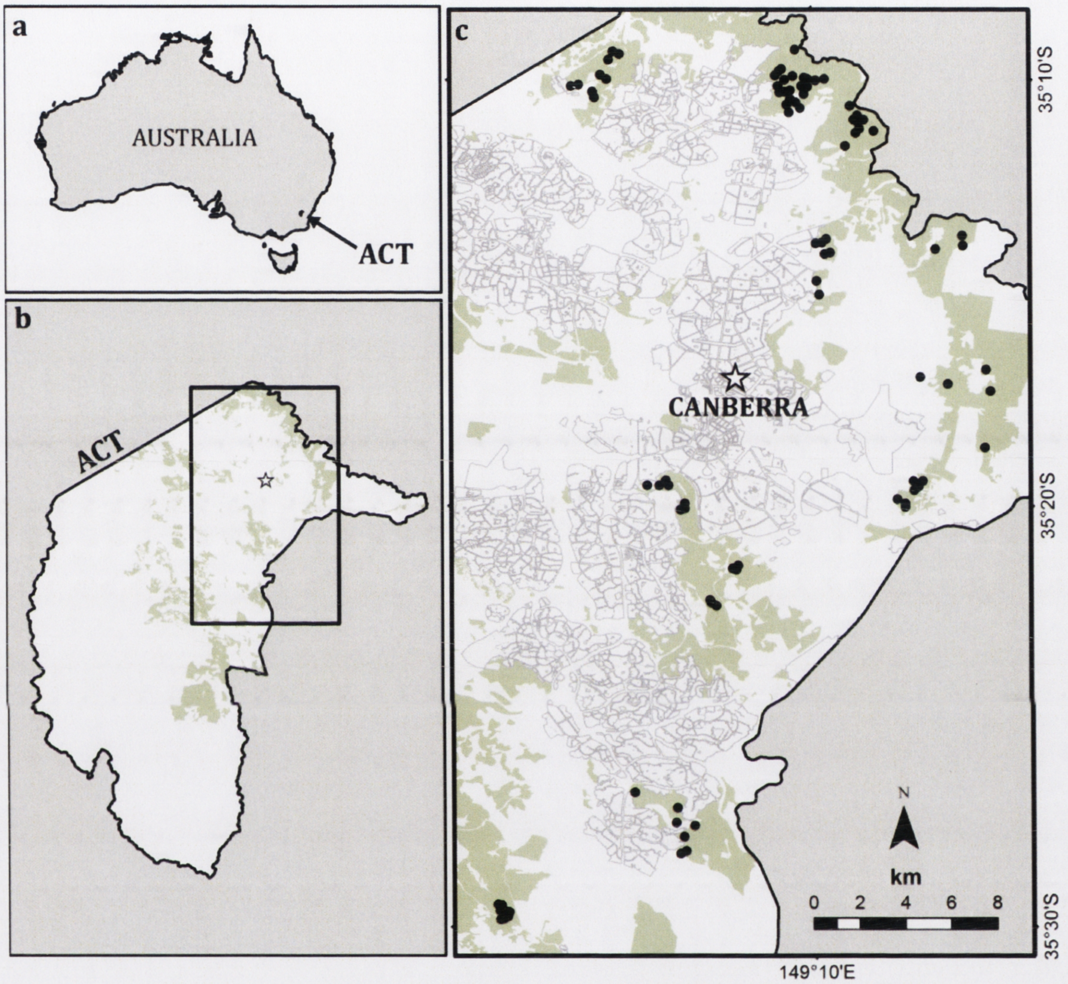
Appendix A

Figure A1. (a) Location of the Australian Capital Territory (ACT) within Australia, (b) distribution of woodland extent across the ACT (dark grey), and (c) the study area with location of sites (black circles) nested within 10 broader geographic locations situated in woodland remnants (dark grey) and the urban area (grey lines) including the location of the capital city, Canberra (star).



Appendix B

Table B1. List of species with assigned functional traits. Nomenclature for species names taken from Christidis & Boles 2008. Habitat guilds ("Hab.") taken from Reid & Cunningham 2008. Mobility derived from Reid 1999 and Lindenmayer et al. 2011. Body size and nesting traits derived from Ikin et al. 2012 and Lindenmayer et al. 2011. Full references are provided below.

Common name	Scientific name	Hab.	Mobility	Size	Nesting
Australian King-Parrot	*Alisterus scapularis*	WG	Sedentary	Large	Hollow
Australian Magpie	*Gymnorhina tibicen*	WG	Sedentary	Large	Arboreal
Australian Raven	*Corvus coronoides*	WG	Sedentary	Large	Arboreal
Black-faced Cuckoo-shrike	*Coracina novaeholandiae*	WS	Migratory	Large	Arboreal
Brown Thornbill	*Acanthiza pusilla*	WS	Sedentary	Small	Understy
Brown Treecreeper	*Climacteris picumnus*	WS	Sedentary	Small	Hollow
Brown-headed Homeyeater	*Melithreptus brevirostris*	WS	Sedentary	Small	Arboreal
Buff-rumped Thornbill	*Acanthiza reguloides*	WS	Sedentary	Small	Opportn
Common Bronzewing	*Phaps chalcoptera*	WS	Migratory	Large	Opportn
Common Myna	*Acridotheres tristis*	WG	Sedentary	Large	Hollow
Common Starling	*Sturnus vulgaris*	WG	Sedentary	Interm	Opportn
Crested Pigeon	*Ocyphaps lophotes*	WG	Sedentary	Large	Opportn
Crimson Rosella	*Platycercus elegans*	WG	Sedentary	Large	Hollow
Dusky Woodswallow	*Artamus cyanopterus*	WS	Dispersive	Small	Opportn
Eastern Rosella	*Platycercus eximius*	WS	Sedentary	Large	Hollow
Eastern Spinebill	*Acanthorhynchus tenuirostris*	WS	Migratory	Small	Arboreal
Galah	*Cacatua roseicapilla*	WG	Sedentary	Large	Hollow
Gang-gang Cockatoo	*Callocephalon fimbriatum*	WS	Migratory	Large	Hollow
Golden Whistler	*Pachycephala pectoralis*	WS	Migratory	Small	Understy
Grey Butcherbird	*Cracticus torquatus*	WS	Sedentary	Interm	Opportn
Grey Currawong	*Strepera versicolor*	WS	Sedentary	Large	Arboreal
Grey Fantail	*Rhipidura fuliginosa*	WS	Migratory	Small	Arboreal
Grey Shrike-thrush	*Colluricincla harmonica*	WS	Sedentary	Interm	Opportn
Laughing Kookaburra	*Dacelo novaeguineae*	WS	Sedentary	Large	Hollow
Leaden Flycatcher	*Myiagra rubecula*	WS	Migratory	Small	Arboreal
Magpie-lark	*Grallina cyanoleuca*	WG	Sedentary	Interm	Arboreal
Mistletoebird	*Dicaeum hirundinaceum*	WS	Dispersive	Small	Arboreal
Noisy Friarbird	*Philemon corniculatus*	WS	Migratory	Large	Arboreal
Noisy Miner	*Manorina melanocephala*	WG	Sedentary	Interm	Opportn
Olive-backed Oriole	*Oriolus sagittatus*	WS	Migratory	Interm	Arboreal
Pied Currawong	*Strepera graculina*	WG	Migratory	Large	Arboreal
Red Wattlebird	*Anthochaera carunculata*	WG	Migratory	Large	Arboreal
Red-rumped Parrot	*Psephotus haematonotus*	WS	Sedentary	Interm	Hollow
Rufous Whistler	*Pachycephala rufiventris*	WS	Migratory	Small	Arboreal
Sacred Kingfisher	*Todiramphus sanctus*	WS	Migratory	Small	Hollow
Scarlet Robin	*Petroica multicolor*	WS	Sedentary	Small	Arboreal
Silvereye	*Zosterops lateralis*	WS	Migratory	Small	Arboreal
Speckled Warbler	*Chthonicola sagittata*	WS	Sedentary	Small	Understy
Spotted Pardalote	*Pardalotus punctatus*	WS	Sedentary	Small	Hollow
Striated Pardalote	*Pardalotus striatus*	WS	Migratory	Small	Hollow
Striated Thornbill	*Acanthiza lineata*	WS	Sedentary	Small	Arboreal
Sulphur-crested Cockatoo	*Cacatua galerita*	WG	Migratory	Large	Hollow
Superb Fairy-wren	*Malurus cyaneus*	WS	Sedentary	Small	Understy
Tree Martin	*Hirundo nigricans*	WG	Migratory	Small	Hollow
Varied Sitella	*Daphoenositta chrysoptera*	WS	Sedentary	Small	Arboreal
Weebill	*Smicornis brevirostris*	WS	Sedentary	Small	Arboreal
Welcome Swallow	*Hirundo neoxena*	WG	Migratory	Small	Opportn

Western Gerygone	*Gerygone fusca*	WS	Migratory	Small	Arboreal
White-eared Honeyeater	*Lichenostomus leucotis*	WS	Sedentary	Small	Understy
White-naped Honeyeater	*Melithreptus lunatus*	WS	Migratory	Small	Arboreal
White-plumed Honeyeater	*Lichenostomus pencillatus*	WS	Sedentary	Small	Arboreal
White-throated Gerygone	*Gerygone olivacea*	WS	Migratory	Small	Arboreal
White-throated Treecreeper	*Cormobates leucophaeus*	WS	Sedentary	Small	Hollow
White-winged Chough	*Corcorax melanorhamphos*	WS	Sedentary	Large	Arboreal
Willie Wagtail	*Rhipidura leucophrys*	WG	Sedentary	Small	Arboreal
Yellow-faced Honeyeater	*Lichenostomus chrysops*	WS	Dispersive	Small	Understy
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*	WG	Sedentary	Small	Arboreal

Habitat abbreviations: WG = woodland generalist, WS = woodland specialist; Size abbreviations: Interm = intermediate; Nesting abbreviations: Understy = understorey, Opportn = opportunistic.

Christidis, L. & Boles, W. (2008) Systematics and taxonomy of Australian birds. Collingwood: CSIRO Publishing

Ikin, K., Knight, E., Lindenmayer, D. B., Fischer, J. & Manning, A. D. (2012) Linking bird species traits to vegetation characteristics in a future urban development zone: implications for urban planning. Urban Ecosystems, 15, 961-977.

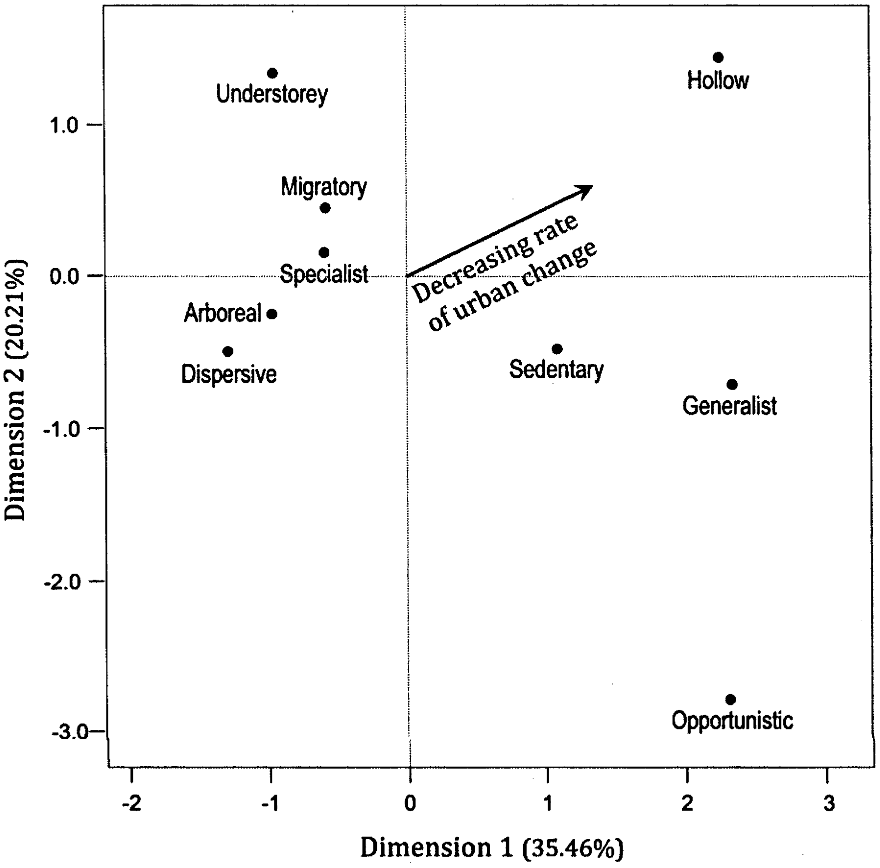
Lindenmayer, D.B. & Cunningham, R.B. (2011) Longitudinal patterns in bird reporting rates in a threatened ecosystem: Is change regionally consistent? Biological Conservation, 144, 430-440.

Reid, J. R. W. (1999) Threatened and declining birds in the New South Wales sheep-wheat belt: I. Diagnosis, characteristics and management. Canberra: CSIRO Wildlife and Ecology.

Reid, J. & Cunningham, R.B. (2008). Statistical Analysis of the First Six Years of Bird Surveys for the Cowra Woodland Birds Program: Trends and Implications for Woodland Bird Conservation in the Cowra Shire, NSW. Unpublished Report to Lachlan Catchment Management Authority, Birds Australia and the Fenner School of Environment and Society, ANU, Canberra.

Appendix C

Figure C1. FAMD ordination showing limited similarity among species trait groups in response to annual change in urban proximity. Traits included in the ordination were: habitat specialisation (Generalist, Specialist), mobility (Sedentary, Migratory, Dispersive) and nesting substrate (Hollow, Arboreal, Understorey, Opportunistic).



V. Conservation of temperate woodland birds: Lessons from long-term population monitoring and research.

In this paper, I draw together the key findings of my empirical research chapters, and disucss their implications for Australian temperate woodland bird conservation in context of the broader published literature. This concluding chapter is intended as a management report that can be used by practitioners to improve conservation outcomes for birds dependent on temperate woodland habitats. Accordingly, this paper has been submitted to the journal *Ecological Management and Restoration*, which addresses the specific task of communicating reliable, relevant scientific information to land managers and decision makers.

Rayner L., Gibbons P., Lindenmayer D.B. & Manning A.D. (2014) Conservation of temperate woodland birds: Lessons from long-term population monitoring and research.

Abstract

Managing for the long-term survival of species means learning from past drivers of population change to predict future threats to persistence. In the Australian Capital Territory, conservation researchers have engaged with a government agency and passionate citizen-scientists to identify new insights into the conservation of birds in Australian temperate woodlands. This article draws together existing knowledge from long-term monitoring and empirical research to discuss the role of three primary regulators (weather, reservation and urbanisation) in shaping the population trajectories of nationally threatened bird assemblages.

Introduction

Temperate woodland ecoregions are globally under threat due to high levels of land conversion and limited levels of formal protection (Hoekstra et al. 2005). This is certainly the case in Australia, where agricultural and urban development is spatially concentrated in temperate zones, resulting in the loss of almost 90% of woodland (Lambert et al. 2000). This loss has had detrimental effects on biota (Lindenmayer et al. 2010), including birds, which are reported to be in national decline (Ford 2011). However, despite widespread concern, conservation research has rarely used long-term monitoring data to examine factors affecting woodland bird persistence (Maron et al. 2005).

In a review of the conservation literature, Rayner et al. (2014a) found that over 50% of woodland bird studies (n = 251) discussed long-term population declines. However, only 7% of studies (n = 33) attempted to measure change using empirical data. Rayner et al. (2014a) further assessed the inferential rigour of trend estimates reported (Box 1) and concluded that evidence for decline in this nationally threatened assemblage was limited to only nine robust studies from over 50 years of research in Australia's temperate zone (~775,000 km^2; larger than France).

There are several critical knowledge gaps in the effective conservation of woodland birds that cannot be addressed with short-term studies (Maron et al. 2005). Inter-annual variation in woodland bird populations is high (Mac Nally 1996), making the extrapolation of short-term results to predict long-term persistence potentially misleading (Porszt et al. 2012). In contrast, systematic long-term monitoring data capture important information about population growth (trends) and fluctuation (variance). These data can assist conservation objectives by facilitating: (1) the calculation of long-term trend patterns to assess the likelihood of species persistence (Meir & Fagan 2000), (2) the identification of processes that pulse and stress species populations through time (Lindenmayer et al. 2012), and (3) the evaluation of management interventions aimed to maintain biodiversity assets in perpetuity (Gaston et al. 2002). Given the value of such outputs for evidence-based planning, further research on Australian temperate woodland birds using long-term population monitoring data is required (Ford 2011; Lindenmayer et al. 2014).

Box 1: Checklist for evaluating the inferential rigour of trend assessments

This checklist is aimed at improving the inferential status of population trend assessments (Rayner et al. 2014a). It can also be used as a guide for the minimum required outputs of population monitoring programs, and to inform the preparation of tenders for scientific work in this field. In presenting this list, we emphasise its generality, acknowledging that specific actions will be context-based and should always reflect the objectives of monitoring. For example, the number of sites required for monitoring should depend on the scale of study, the habitat under investigation, the land-use types sampled, and many other factors. However, as a generic guide, the following features of population datasets will enhance conservation products for evidence-based planning:

- **Primary data**, collected first-hand in the field by the investigators, is favourable for trend assessment as important information regarding data collection and format is easily accessed.
- **Quantitative data** improves population trend estimates, and predictions of species persistence, because the rate and magnitude of change can be quantified.
- **Defined target species or assemblage** should inform survey design (sampling in areas and seasons relevant to the species or group of interest), and will indicate the generality of analytical results when inferring conservation implications.
- **Multiple survey years** disentangle natural fluctuations from trends in species populations. It is not clear what the minimum length of biodiversity monitoring should be, but authors have suggested that 10-15 years of time series data are needed before error levels in trend estimates are acceptable (e.g. Field et al. 2007).
- **Replicate sites** reveal site-specific variation in population data.
- **Repeat visits** reveal time-specific variation in population data.
- **Consistent sampling protocol** is necessary for surveys to be comparable in time.
- **Consistent sampling effort** is favourable to avoid bias in trend estimation, both spatially and temporally.
- **Formal statistical analysis** is necessary to measure observation and process error, as well as spatial and temporal autocorrelaton in data structure.
- **Clear reporting** of the design features and outputs of monitoring (items listed above) is essential for sound ecological inference of population trend estimates.

In this article, we report new findings from a major collaboration, termed the ACT Woodland Birds Project (hereafter "ACTWBP"), that took place in the critically endangered box-gum woodlands of the Australian Capital Territory. The ACTWBP combined funding support from a government agency (Environment and Planning Directorate ACT Government), long-term monitoring records from a dedicated community group (Canberra Ornithologists Group), and science and funding support from The Australian National University. These features provided a unique opportunity to study the population dynamics of temperate woodland avifauna (Box 2).

Box 2: Examining drivers of population change in woodland birds

Long-term data gathered in the ACT enabled examination of the multi-scale factors influencing the occurrence and abundance of woodland birds through time. The study was characterised by several key features:

- The ACT contains some of the most extensive and intact remnants of temperate box-gum grassy woodland in Australia, including large samples of critically endangered Yellow Box - Blakely's Red Gum Grassy Woodland.
- The ACT supports a diverse avifauna, including species of conservation concern, such as the Hooded Robin, Brown Treecreeper and Superb Parrot.
- The ACT is the best protected state or territory in the National Reserve System, with 99% of ecosystems represented to the minimum global conservation target of 10%.
- The ACT region is experiencing rapid population growth, with remaining woodland remnants under significant threat from future fringe and exurban development.
- There is strong interest and active support from the ACT government to protect woodland communities and improve the conservation status of woodland birds.
- There is a highly experienced ornithologists group (COG) who monitor important woodland bird habitats in ACT.
- There is extensive, high-quality mapping data of vegetation and land management available from government databases and records.
- Bird and habitat data are available at spatial scales (local to landscape) suitable for assessing and informing conservation management.

The core focus of the ACTWBP was to describe the effects of three potentially important regulatory factors on woodland bird populations: (1) weather, (2) reservation, and (3) urbanisation. Below, we draw together existing long-term research, and present the key findings of our project, to discuss how these factors are likely to affect the long-term persistence of woodland birds more generally.

Factors regulating woodland bird populations

Weather

Weather regulates woodland bird occurrence and abundance through the availability of resources in time and space (Loyn & Menkhorst 2011). Naturally, discussion has emerged on the influence of weather on long-term species trajectories and, in particular, the effects of drought and climate change on species persistence (Recher et al. 2010; Ford 2011). There is evidence that the abundance of many species is suppressed during drought periods (e.g. Loyn & Menkhorst 2011; Stevens & Watson 2013; Ellis & Taylor 2014). Some authors infer that these species could be ill-equipped to recover their populations post-drought, particularly in degraded habitats (Mac Nally et al. 2009). This has led to concern that more frequent droughts of increasing severity (as expected with climate change, Power et al. 2013) could slowly erode woodland bird communities over time (Recher et al. 2010). However, until recently, there has been limited quantitative research to address these concerns (Rayner et al. 2014a).

South-eastern Australia experienced its worst drought on record from 2001-2009 (the "Millennium Drought", van Djik et al. 2013). The majority of long-term research conducted during this time indicated that the drought affected bird populations in the temperate zone. On average, evidence suggests about one quarter of a region's avifauna declined in occurrence or abundance during drought, though to varying degrees (Table 1). In most cases, rainfall is suggested as a key driver of observed population variability (Reid & Cunnigham 2008; Cunningham & Olsen 2009; Bounds et al. 2010; Stevens & Watson 2013). For example, Mac Nally et al. (2009) documented declines in ~70% of bird species in northern Victoria, primarily due to climatic effects. However, drought is not associated with decline in all studies.

Lindenmayer & Cunningham (2011) found declines in only ~5% of species in southern NSW during the Millennium Drought (~250 km away from Mac Nally et al. 2009), with little evidence of drought-related stress on avian populations.

Table 1. Population declines in temperate woodland avifauna during drought. "Species" is the total number of species assessed for long-term trend patterns in the study. "Decline" is the percent of species assessed that showed significant declining trends over the period of study.

Location	Study period	Species	Decline	Reference
Northern VIC	1995 – 2008	159	~70%	Mac Nally et al. 2009
Cowra, NSW	2002 – 2008	62	~30%	Reid & Cunningham 2008
Mount Lofty, SA	1999 – 2007	59	~30%	Szabo et al. 2011
Temperate NSW	1999 – 2007	31	~25%	Cunningham & Olsen 2009
Warrumbungle, NSW	1990 – 2010	25	~24%	Stevens & Watson 2013
Canberra, ACT	1998 – 2008	62	~20%	Bounds et al. 2010
Southern NSW	1998 – 2009	76	~5%	Lindenmayer & Cunningham 2011

In 2010, extreme rainfall events occurred throughout south-eastern Australia (Beard et al. 2011). These events led to important advances in our understanding of how temperate woodland birds respond to weather variability. Two important studies, one from central-west NSW (Ellis & Taylor 2014) and one from northern Victoria (Bennett et al. 2014), compare the reporting rates of birds in periods during and after drought. Both studies found evidence of population increases following the drought-breaking rains of 2010 (51% of species, Ellis & Taylor 2014; 29% of species, Bennett et al. 2014). However, both studies report few species recovering their populations to pre-drought levels within two years of the drought breaking. These studies also demonstrate that responses by avian fauna to weather cannot be generalised across guilds or functional groups, and are highly variable between regions. For example, following the 2010 rains, the reporting rate of Jacky Winter (*Microeca fascinans*) more than halved in central western NSW, but completely recovered (and surpassed pre-drought levels) in northern Victoria.

Relationships between bird observations and climatic data were not explicitly analysed in either of the above studies. The ACTWBP (Rayner et al. *in review*) was the first study to use a quantitative measure of drought (the Southern Oscillation Index, hereafter "SOI"), among other meteorological parameters, to examine multiple species responses to weather variability in temperate woodland. These authors found that, for species with reporting rates > 1% in the ACT region, short-term fluctuations in woodland bird populations were significantly related to SOI, and that SOI was often a better predictor of population change than local-scale weather parameters (e.g. rainfall or temperature). However, SOI did not explain long-term population declines. Time-series data were used in the ACTWBP (Rayner et al. *in review*) to investigate non-linear population growth, thereby removing any pre-determined bounds on exactly when drought effects begin and end (e.g. 'drought' vs. 'post-drought') and when populations may, or may not, respond. Using this method, Rayner et al. (*in review*) found relatively few native species exhibited significant long-term declines (n = 5/57 species; Table 2) and, more importantly, that most of these declining species showed a neutral or positive association with drought (Fig. 1; Table 2).

While generalisations can be made about how temperate avian communities will respond to drought (~25% of species may decline) and subsequent high rainfall events (~40% of species may increase), the effects of weather on long-term species persistence are not straight-forward (e.g. Loyn & Menkhorst 2011), highly variable across regions, and species-specific. There remains scant evidence that weather variability is a primary driver of decline (see also MacHunter et al. 2006), or that declining species will be ubiquitously disadvantaged by drought.

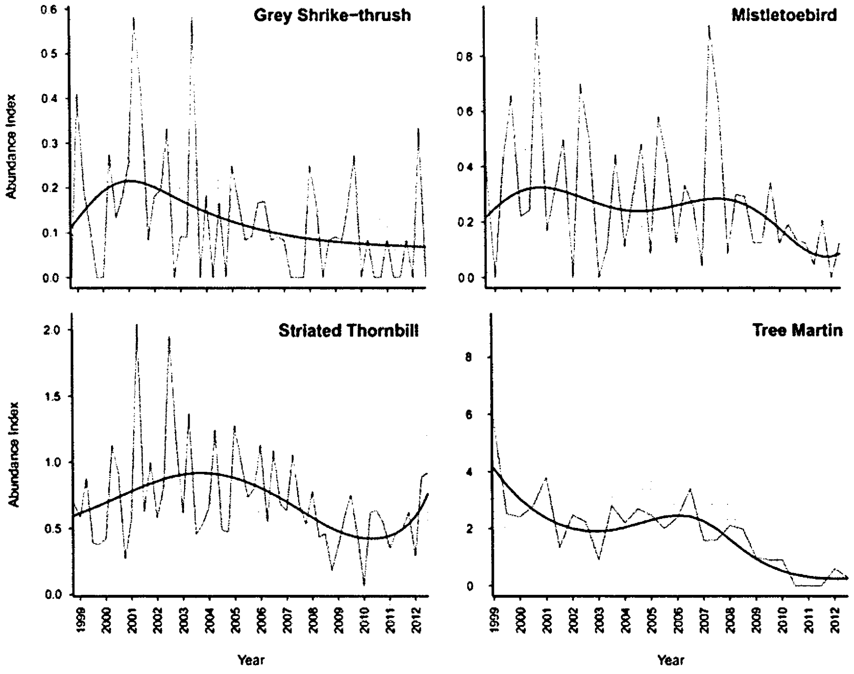


Figure 1. Species that showed significant declines in the Australian Capital Territory, and neutral (Mistletoebird) or positive (Grey-shrike Thrush, Striated Thornbill, Tree Martin) associations with the Southern Oscillation Index (a measure of the El Nino Southern Oscillation). Dotted lines show mean abundance across 92 woodland survey sites, bold lines indicate long-term trends (smoothed spline, adjusted for seasonality) with 95% confidence intervals shaded grey.

Table 2: Declining species observed in the Australian Capital Territory (1998-2013) and their association with the regulatory factors investigated in the ACTWBP. Drought is measured by Southern Oscillation Index (SOI). Response to reservation compares trends on best-performing reserves to trends off-reserve. Uncommon species (reporting rate < 1%) were excluded from analysis.

Declining native species	**Drought**	**Reserves**	**Urban proximity**	**Urban change**
Striated Thornbill (*Acanthiza lineata*)	Positive	Positive	Negative	Neutral
Mistletoebird (*Dicaeum hirundinaceum*)	Neutral	Positive	Positive	Negative
Scarlet Robin (*Petroica multicolor*)	Negative	Neutral	Negative	Neutral
Grey-shrike Thrush (*Colluricincla harmonica*)	Positive	Negative	Neutral	Neutral
Tree Martin (*Hirundo nigricans*)	Positive	Negative	Negative	Negative

Reservation

Protected area establishment is a conservation intervention frequently employed to address biodiversity loss (Joppa & Pfaff 2011). Effective reservation is defined not only by containing important biodiversity assets spatially (representativeness), but by maintaining those assets through time (persistence) (Margules & Pressey 2000). While there are detailed studies evaluating the effectiveness of Australian reserves for capturing important biodiversity values in space (e.g. Watson et al. 2011), few studies examine the effectiveness of reserves for *maintaining* those values (particularly species) through time (Gaston et al. 2008). Assessing the impact of reserves on species persistence is important because the factors that threaten species can be temporally dynamic in their extent and intensity (Gaston et al. 2002).

For temperate woodland birds, there are several long-term population studies that occur partially, or entirely, within protected areas. In most cases, these studies have reported bird declines *inside* reserves (e.g. Recher & Serventy 1991), leading to the conclusion that reserves are limited in their capacity to protect woodland birds in perpetuity (e.g. Mac Nally et al. 2009). However, while these studies highlight important short-comings of reservation, it remains unclear to what degree reserves assist species persistence. This is because, when evaluating protected area effectiveness, population trends observed within reserves have not been compared to trends from similar, but unreserved, areas in the same landscape. The ACTWBP (Rayner et al. 2014b) addressed this uncertainty by assessing the effectiveness of reservation for sustaining Australian woodland bird populations through time.

The ACTWBP compared population trends for birds between old reserves (established pre-1995), new reserves (established post-1995) and unreserved land located in temperate woodland remnants. We found that, in the ACT region, positive trends in woodland avifauna were most strongly associated with unprotected woodland remnants located on private land (Fig. 2; Rayner et al. 2014b). These areas also supported smaller-bodied, woodland-dependent species that forage on the ground (Rayner et al. 2014b), and that are of greater conservation concern broadly (Ford 2011). These findings support arguments for the critical importance of off-reserve conservation in maintaining bird populations (Bennett et al. 1997). However, we also found that new reserves maintained species richness and vulnerable species through time (Fig. 2), and contained fewer declining species than older reserves that were smaller on average, and established primarily for their scenic value (Rayner et al. 2014b). There also was a significant positive relationship between reserves and two declining species observed in the study area, the Striated Thornbill and Mistletoebird (Table 2). Differences in the performance of new and old reserves were attributed to reserve placement, in particular, their topographic position and proximity to urban development (see below). New reserves were located lower in the landscape, further from urban development, and tended to be larger with lower levels of woody vegetation cover (i.e. more productive box-gum woodland) (Rayner et al. 2014b).

Thus, it is likely that reserves have assisted the conservation of woodland birds in the ACT, despite containing species that exhibited long-term declines. Furthermore, the newer reserves in our study system performed similarly to unreserved areas, which were located further from urban disturbance in more productive landscapes. It is clear from the ACTWBP and the available long-term research, that protected areas are not immune to the processes that threaten woodland bird persistence (Laurance et al. 2012). However, reserves can contribute to important conservation objectives (e.g. maintaining species richness and vulnerable species) where reserve placement is carefully planned.

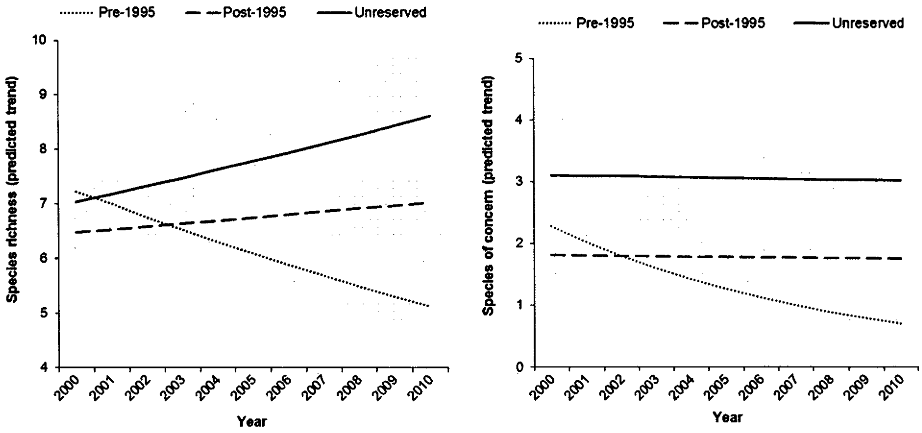


Figure 2. Trends in mean species richness, species richness for birds of conservation concern, over time on sites reserved Pre-1995, Post-1995 and unreserved sites. Standard errors for the model predictions, which include the random effect of location, are shown in grey.

Urbanisation

The expansion of urban areas can modify and degrade habitats for many native bird species (Marzluff 2001; Ikin et al. 2014b; Le Roux et al. 2014), and occurs predominantly at the fringe of major urban centres (Fisher 2003). In Australia, urban development is spatially concentrated in temperate regions where six out of eight capital cities are located (Newton et al. 2001). The impact of urbanisation on temperate woodland birds has been examined spatially in numerous short-term studies (e.g. Ikin et al. 2014b) which reveal important compositional differences in avian communities along urban ecological gradients. However, long-term research on the effects of urban expansion is rare in the conservation literature (Garden et al. 2006), apart from a few studies examining historical changes in Perth, WA (e.g. Recher & Serventy 1991; Smith 2002) and Adelaide, SA (Tait et al. 2005).

These long-term studies demonstrate that urban areas benefit some bird species while disadvantaging others (Recher & Serventy 1991; Smith 2002; Tait et al. 2005), as is frequently detected in short-term research (e.g. Blair 1996). However, faunal responses to urbanisation are expected to manifest, and continue to change, over long time periods (e.g. Møller et al. 2012). To date, such changes have been poorly monitored within Australia. Thus, little, long-term quantitative evidence informs current conservation planning in urban landscapes (Garden et al. 2006). The ACTWBP sought to address this knowledge gap by examining the temporal dynamics of avian populations in peri-urban woodland remnants over a decade of urban expansion around Canberra (Rayner et al. 2014c).

The results of the ACTWBP supported the findings of other urban ecological studies conducted in temperate Australia (e.g. Tait et al. 2005), revealing an almost equal number of species responding positively and negatively to growing urban extent (Rayner et al. 2014c). However, we found that responses to urban development *were* temporally dependent. Species could be affected by the initial disturbance phase of urban development without showing any long-term attraction or intolerance to urban extent, and vice versa. In one case, a declining species (the Mistletoebird) exhibited a positive response to urban proximity, but was adversely affected by large encroachment events over short time frames (i.e. within 1 year, Rayner et al. 2014c).

Our results in the ACTWBP also showed that species whose reporting rate had declined over the preceding decade were more likely to be urban-avoiding species (Rayner et al. 2014c; Table 2), providing a quantitaive link between urban encroachment and population decline. Importantly, effects of urban encroachment on species extended up to 5 km from the urban boundary, exceeding the range of many exisiting urban ecological studies (e.g. Wood 1996; Sewell & Catterall 1998). While long-term research on the impacts of urbanisation on temperate woodland birds is limited, available evidence indicates that urban encroachment is important in shaping peri-urban avian communities in space and time.

Conservation lessons from long-term monitoring

Long-term studies reveal trends in woodland bird occurrence and abundance that cannot be detected with short-term research. Importantly, we have shown how such findings can be highly relevant to conservation. With respect to the three regulatory factors examined here, the ACTWBP has both confirmed and challenged existing paradigms on the effects of weather, reservation and urbanisation on temperate woodland bird assemblages, as we summarise below.

First, time-series data used in the ACTWBP revealed patterns in the response of woodland bird populations to weather variability that would have been masked by comparisons of pre- and post-drought data. This included the identification of a significant positive relationship between drought conditions and the abundance of some declining species. This finding challenges the notion that extreme weather events are a driver of long-term population declines, and are a threat to woodland bird persistence. It also emphasises that species responses to a given landscape are individualistic (sensu Manning et al. 2004a).

Second, monitoring data used in the ACTWBP improved our understanding of species *persistence* in ACT reserves, a core objective of protected area establishment that is critically understudied (Gaston et al. 2008). Findings of the ACTWBP confirmed that the position of reserves in the landscape was crucial to maintaining species diversity, and species of conservation concern, over long periods (at least 10 years). While we found significant improvements in reserve effectiveness over time, off-reserve areas made the strongest contribution to woodland bird conservation in the ACT.

Third, the ACTWBP supported short-term research showing that species occupying fringe habitats will vary in their tolerance of urban encroachment. However, long-term data revealed that species tolerance of urbanisation can change through time depending on the proximity, extent and speed of development. For most species, the response to rapid, large-scale development was negative, highlighting a previously undescribed threat to woodland bird populations.

Based on the findings of the ACTWBP, we have outlined key management directions for improving conservation outcomes for temperate woodland birds. These priority actions are summarised for each regulatory factor in Box 3.

Box 3: Directions for managing the effects of regulatory factors to improve conservation of temperate woodland birds.

Weather

- Quantify the influence of weather extremes on key resources for birds
- Collect movement data to enhance inference from regional population trends

Reservation

- Reserve vulnerable/irreplaceable woodland habitats on the urban fringe
- Protect native vegetation located on productive land
- Increase conservation efforts in areas of low urban land cover

Urbanisation

- Increase buffers between important woodland habitats and urban development
- Investigate the benefits of ecologically-sensitive urban design features
- Plan large urban developments in stages to reduce short-term impacts on avifauna

Weather

While we found that weather variability exerts a strong regulatory force on species populations (as other studies have), it does **not** appear to be a driver of avian declines in the ACT (Rayner et al. *in review*). Projected climate change impacts, such as increased drying during future El Niño cycles (Power et al. 2013), suggest that avian responses may not be so innocuous in future (Garnett & Franklin 2014), particularly in degraded habitats. Ongoing monitoring to capture population responses to multiple droughts, and to determine species capacities to adapt to climatic change, will be critical to assessments of population viability.

Indeed, if we falsely attribute population decline to contemporary drought effects, there is a serious risk of directing conservation attention to a process that is extremely variable and challenging to manage. A better focus would be: (1) quantifying the effects of weather variability on critical resources for birds across remnants of different condition, and (2) tracking population movements between regions as these resources fluctuate through time. For example, increases in species abundance in some areas may reflect movement from poorer conditions elsewhere (e.g. Manning et al. 2007). Resources of particular interest would be those of demonstrable value to species of conservation concern (e.g. tree hollows, Manning et al. 2004b; woody debris, Mac Nally & Horrocks 2007; mistletoe, Ikin et al. 2014a) and those potentially influenced by weather (canopy structures, Semple et al. 2010; nectar, Ford 2011). Quantifying interactions between weather, resources and movement will enhance our ability to forecast the habitat requirements of species under various climate scenarios.

Reservation

The most effective reserves for maintaining species diversity and persistence were large woodland remnants located on productive land, situated lower in the landscape and further from urbanisation. Peri-urban woodland habitats that are vulnerable to urban consumption, and irreplaceable in terms of their associated avifauna, need to be identified as they will require formal reservation to avoid local species extirpation. However, opportunities for formal reservation on public land will be constrained by land-use demands and cost (Gaston et al.

2002), and are likely to diminish as urban areas continue to expand (Radeloff et al. 2010). Fortunately, evidence suggests that formal reservation is not critical to the persistence of woodland birds (Rayner et al. 2014b), as long as management practices are sympathetic. This emphasises the need for whole-landscape conservation, irrespective of tenure or land use type.

What **is** critical to woodland bird persistence is the protection and management of native vegetation in productive landscapes, particularly in areas of low urban land cover (see also Donnelly & Marzluff 2004). In temperate Australia, these areas occur predominantly in travelling stock routes, road-side verges and on private land, where opportunities for strict legal protection are limited. The value of these areas for conservation is well established (Lindenmayer et al. 2010; Lentini et al. 2011), as is the evidence for improving woodland bird diversity through increased cover of native vegetation (Cunningham et al. 2014a, b). Thus, while formal reservation can make important contributions in urban landscapes, strong land-clearing controls and active restoration off-reserve will be critical to long-term woodland bird persistence at a national scale.

Urbanisation

Work in the ACTWBP revealed that urban-avoiding species were more likely to exhibit long-term population declines in the ACT (Rayner et al. 2014c). To abate threats to fauna occupying fringe habitats, conservation buffers are often recommended (Fischer et al. 2006). However, current buffer distances (usually < 100 m) need to be increased to improve their effectiveness, given that urban impacts on avifauna can extend up to 5 km from the urban boundary (Rayner et al. 2014c). Implementing buffers of such size around remaining peri-urban woodland remnants may not be realistic in areas of rapid urban growth and increasing urban density. Anticipatory restoration activities in urban-fringe environments (i.e. planting of native vegetation) could improve the effectiveness of future buffer zones for minimising urban-related threats to birds (Manning et al. 2006). However, it may be crucial to complement buffers with additional conservation measures in the urban matrix, such as increased urban green space (Ikin et al. 2013), retention of important habitat structures (Le Roux et al. 2014), modification of built structures (e.g. “green walls”, Chiquet et al. 2013) and reduced housing density (Tratalos et al. 2007), to soften the impact of development on adjacent woodland habitats, and in particular, urban-avoiding species.

Additionally, urban planning should aim to minimise the impacts of encroachment through time. Ideally, large developments should be avoided near critically important woodland habitats. Where development must occur, proceeding slowly and over smaller spatial increments may limit disturbance, providing the best opportunity for avian communities to move, re-assemble and adapt to novel environments. Further quantitative evidence of mechanisms that drive species urban tolerance over time will be needed to evaluate the effectiveness of ecologically-sensitive urban planning for woodland bird conservation, and to inform adaptive management.

Conclusion

The vast majority of research on temperate woodland birds and, in turn, the evidence underpinning their conservation, comes from short-term ecological studies. We have shown that the conclusions drawn from long-term population data can both confirm and challenge current knowledge on factors influencing woodland bird persistence. The ACTWBP has revealed some important temporal patterns in avian responses to regulatory factors that are globally relevant. We owe much to non-government organisations, such as the Canberra Ornithologists Group, who voluntarily collect this type of long-term data, which are otherwise rare in Australia. We emphasise that the research presented here requires additional information on woodland bird survivorship, reproduction and survival, and how these demographic parameters vary through space and time, to fully appreciate the mechanisms driving population responses to weather and land use change. Nevertheless, we hope the new knowledge presented in this article will encourage thoughtful policy responses by land managers, and expanded commitments to long-term woodland bird population monitoring.

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