Variable effects of protected areas on long-term multispecies trends for Australia’s imperiled birds

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Abstract
Protected areas are important for preventing biodiversity declines, yet indicators of species’ trends in protected areas rarely include threatened species. We use data from the first national Threatened Species Index developed in Australia to report on trends for threatened and near-threatened birds inside and outside terrestrial and marine protected areas. We adopted the Living Planet Index to calculate trends for 39 bird taxa at 16,742 monitoring sites (11,539 inside and 5,203 outside PAs) between 1985 and 2016. At a continental scale, the overall decline in the national index was smaller inside protected areas (66% decrease in average population abundance) than outside (77%), although after 2000 declines were greater within (36%) versus outside (26%) protected areas. Five out of seven jurisdictions showed similar switching in patterns over time. Protected areas initially had a greater net positive effect on trends of more imperiled birds than less imperiled birds, but between 2000 and 2016 declines of the most imperiled birds were greater inside protected areas than outside. Our analyses suggest that the effectiveness of Australia’s protected area network at improving trends in threatened species has weakened, and support the hypothesis that trends for terrestrial birds outside PAs might be improving due to increased conservation efforts on private land. Although this study represents the most comprehensive collation of threatened species population time series and trends ever for Australia, the number of monitoring sites inside PAs was double that outside PAs, even though on average, more than 70% of threatened bird distributions occur outside PAs, with important gaps in monitoring across space, time and taxa that need to be filled to fully understand the effectiveness of public and private conservation actions at a national level. The results underline the importance of active management plus monitoring to track and report on long-term trends across species.

KEYWORDS
imperiled birds, indicators, long-term ecological monitoring, management effectiveness, population trends, private land conservation, protected areas, threatened species
INTRODUCTION

Covering more than 15% of the Earth’s land surface and 10% of its territorial waters (UNEP-WCMC & IUCN, 2016), protected areas (PAs) are critical for maintaining the integrity of ecosystems, the populations of species that live within them (e.g., reviewed by [Geldmann et al., 2013]) and the services they provide to people (Campos & Nepstad, 2006). Additional reasons for establishing PAs include the preservation of cultural, social, or spiritual assets and values (Verschuuren & Brown, 2018) and the protection of iconic threatened species like the Giant Panda (Liu et al., 2001). Different goals of PA designation might be associated with different objectives and criteria for success. Through monitoring, PA managers and decision-makers learn the conditions under which PAs deliver desired goals (Brooks et al., 2004; Kleiman et al., 2000; Margules & Pressey, 2000), which enables more informed and effective future management decisions.

The ability of PAs to meet objectives of maintaining biological and ecological integrity is an area of active debate among the scientific community (e.g., Barber, Cochrane, Souza, & Verissimo, 2012; Barnes, Glew, Wyborn, & Craigie, 2018; Ferraro & Pattanayak, 2006; Kuempel, Jones, Watson, & Possingham, 2019). While there is good evidence that PAs have reduced the rate of degradation of forest habitat, evidence that PAs have effectively maintained threatened species populations remains inconclusive (Cazalis, Belghali, & Rodrigues, 2019; Geldmann et al., 2013), not least because indicators of PA effectiveness that focus on trends in species populations are poorly developed (Cook, Valkan, & McGeoch, 2019; Walpole et al., 2009). Despite the importance of understanding effectiveness through a temporal lens, the success of PAs has generally been evaluated using static measures such as the representativeness of PA networks in terms of species diversity, or spatial coverage of endemic and threatened species or ecosystems (Klein et al., 2015; Rodrigues et al., 2004; Rodrigues et al. 2004).

Such analyses assume that PAs provide effective protection once established. Those indicators that do incorporate trends over time generally focus on measures of effectiveness that are surrogates of species trends rather than direct measurements of population trends (Geldmann, Manica, Burgess, Coad, & Balmford, 2019). Such surrogates include governance and management elements (Geldmann et al., 2015), total extent of vegetation protected (Cook et al., 2019), vegetation condition (Muñoz Brenes, Jones, Schlesinger, Robalino, & Vierling, 2018), changes in human pressure (Cook et al., 2019; Jones et al., 2018), or avoided conversion of vegetation (Carranza, Manica, Kapos, & Balmford, 2014).

To evaluate the effectiveness of PAs at maintaining species populations, we must assess how biodiversity or population outcomes change over time in relation to protection or implementation of management actions (e.g., Craigie et al., 2010). Few studies have explored the question of whether PAs can be effective at ameliorating declines in populations of threatened species or at aiding species recovery at a national or global scale (Geldmann et al., 2013). Most of the studies that have applied time-specific data to evaluate the effectiveness of PAs at improving species population trends have been either small-scale case studies of individual PAs rather than multi-site or national-scale evaluations (e.g., Fiordland National Park in New Zealand (Whitehead, Edge, Smart, Hill, & Willans, 2008)), or have focused on common or easily counted species such as large mammals that have been intensively monitored over time and dominate publicly available datasets (Barnes et al., 2016; Kiffner et al., 2020) rather than threatened species for which data are often scarce (Cazalis et al., 2019). For well-monitored common species, there is evidence that actively managed PAs can maintain populations of monitored birds and mammals within their boundaries. For example, population trends of large-bodied mammals and waterfowl are more positive in PAs located in higher-income countries (Barnes et al., 2016). A global review of studies on PA effectiveness found positive effects of PAs on species populations, although for some species, populations in PAs still declined, but at a slower rate than those outside PAs or before a PA was established (Geldmann et al., 2013). A more recent review of marine PAs found similar results for fish populations, with 71% of marine protected areas (MPAs) associated with positive species population trends, despite many MPAs failing to meet desired thresholds for effective and equitable management processes due to shortfalls in staff and financial resources (Gill et al., 2017).

Overall, the effect of PAs on improving the trajectories of threatened species remains unclear because populations are almost never monitored both inside and outside PAs (Geldmann et al., 2013; Maron, Gordon, Mackey, Possingham, & Watson, 2016). There is some evidence that, in areas where habitat outside PAs remains intact, species have done no better inside than outside PAs (e.g., endemic birds in Australian Wet Tropics; Barnes, Szabo, Morris, & Possingham, 2015). In the United States, bird species richness is the same inside and outside PAs and, while forest species are more abundant inside PAs, the opposite is true for species that favor open habitats (Cazalis et al., 2019). Broadscale comparative studies of threatened species trends in relation to protection are lacking, even though preventing extinction is often an underlying reason for establishing PAs in the first place.

Gaining knowledge on whether PA designation and management are effective for maintaining or recovering
populations of imperiled species could help to inform better planning and management of PAs, highlight knowledge gaps for threatened species research to focus on, and stimulate a more targeted response to declines in biodiversity. We use the term “imperiled” to include species and subspecies listed as Near Threatened or worse (i.e., Vulnerable, Endangered, and Critically Endangered) by the International Union for Conservation of Nature (IUCN) or under relevant national legislation. Understanding the effectiveness of policies and actions to manage imperiled species is more important now than ever before. In Australia, 1892 species or subspecies are presently nationally listed as threatened under the Australian Environment Protection and Biodiversity Conservation Act 1999, and the list of threatened species is growing. Australia has one of the highest recent extinction rates of vertebrates of any country worldwide (Szabo, Butchart, Possingham, & Garnett, 2012; Woinarski et al. 2017a; Woinarski et al., 2019; Woinarski, Burbidge, & Harrison, 2015), with three vertebrate species lost in the past decade alone. Urgent actions are needed to stem declines and prevent further extinctions (Geyle et al., 2018).

In Australia, a Threatened Species Index (TSX) was developed as a dynamic tool for tracking annual changes in Australia’s imperiled taxa (threatened and near-threatened species and sub-species; Bayraktarov et al., 2021). The method for multi-taxon trend calculation is based on the Living Planet Index (LPI) (Collen et al., 2009; Loh et al., 2005; McRae, Deinet, & Freeman, 2017). Here, we use the aggregated data in the TSX (TSX, 2020) to evaluate the effectiveness of PAs in Australia over three decades (1985–2016) to gain knowledge on the persistence of imperiled bird taxa monitored at sites inside and outside PAs. We specifically ask:

1. What is the average change in abundance in imperiled bird populations inside and outside PAs at a continental level and between different jurisdictions, threat status, and functional bird groups?
2. Do multi-taxon trends of imperiled birds differ inside versus outside PAs over time?
3. Is there bias in monitoring of different groups of threatened species groups inside and outside PAs?

We hypothesize that, if PAs are effective, threatened bird populations within PAs should have a more stable or positive population trajectory (or, if populations are declining, a less negative trajectory) than those monitored at sites outside PAs over the same time. Our results highlight the importance of effective, continuing monitoring programs to track and report on long-term trends across species in PAs.

2 | MATERIALS AND METHODS

The Australian Threatened Species Index (TSX) tool was developed as a collaboration between 42 research partners across over 25 organizations from the research sector, civil society and government. The index is based on raw data consisting of point locations with date stamps and enough metadata information on taxonomy, monitoring method, unit of measurement, an abundance value (count) and standardization which was provided by multiple data custodians across Australia and integrated into one database containing quality-assessed time series information. Point locations were converted into annual time series of counts for each bird taxon at a fixed site using the same monitoring method over time. Each time series (row in the database) represents the values counted for the same taxon at the same fixed site using a consistent systematic monitoring method over time, that is, repeated monitoring. The first TSX was launched in 2018 at www.tsx.org.au and included more than 16,000 time series for threatened and near-threatened bird taxa, with the intention that it would be updated on an annual basis. The database in its second iteration in 2019 contained more than 18,000 time series for 122 threatened and near-threatened bird and mammal taxa. Detailed information on how data have been processed prior to upload to the database and assessed for its suitability for trends can be found in Bayraktarov et al. (2021) and the supplementary material therein. The time series data are open access and can be downloaded from www.tsx.org.au with a data dictionary explaining all data fields.

To apply the TSX to the problem of PA evaluation, we first disaggregated the 2019 TSX time-series data to derive Living Planet Index (LPI) trends in protected and nonprotected areas at a continental scale. We excluded mammals from this study as most time series (93%) collated during the 2019 iteration of the TSX were for bird taxa, and mammal data were unevenly distributed across jurisdictions (Bayraktarov, unpublished manuscript). Second, we disaggregated the TSX data further to investigate trends in protected areas and non-protected areas related to additional factors such as governance (State or Territory, since this is the level at which most protected areas are designated), taxon threat status (Near Threatened, Vulnerable, Endangered & Critically Endangered), and functional grouping (migratory shorebirds and terrestrial birds). For most groups, we evaluated the trends relative to a reference year of 1985 as before this date insufficient data were available. Where early data were scarce, a later reference year was chosen (1995 for terrestrial birds, birds listed as
Vulnerable or Endangered). We also carried out trend analyses using 2000 as a reference year, to investigate possible differences in long-term (past 30 years) versus more recent (past 15 years) trends.

### 2.1 Intersection of imperiled bird data with protected areas

For the period of interest (1985–2016), the bird subset of the Threatened Species Index contained data on 65 imperiled bird species and subspecies (i.e., taxa) from 17,243 sites across Australia (Bayraktarov et al., 2021; TSX, 2020) (Tables S1 and S2). The data represent longitudinal time series for a taxon at a fixed site monitored systematically at two or more time points using a consistent monitoring method to record the same unit of measurement (more information on the type of data is provided in Tables S3, S4, and Bayraktarov et al., 2021); hence, each time series corresponds to a unique, repeatedly monitored “site”.

Data on terrestrial and marine PAs were downloaded from the data repository of the Australian Government (Commonwealth of Australia, 2016) and were chosen to match the interval for index reporting between 1985–2016 and 2000–2016. Spatial data were projected onto the Australian Centre for Remote Sensing Lambert Conformal Projection (GALCC). Site locations from bird monitoring were intersected with PAs. Bird monitoring sites from the TSX inside marine and terrestrial PAs, as well as within a 500 m buffer outside protected areas, were considered within PAs. The buffer was chosen due to inaccuracy in GPS coordinates (median of 100 m for \( n = 8,432 \) time series with site accuracy information) of sites and because common monitoring methods were 500 m area searches and 20 min—2 ha searches (that typically cover a distance of 400–500 m). Not all PAs were already designated at the start of our reporting period (1985), meaning that some sites were considered “within-PA” at the end of the reporting period despite not being in a PA at the start. PA designation dates varied over the time period of the study, with some PAs being designated or expanded later than others (Supporting Information Table S5 and Figure S1). Of the sites categorized to be within PAs (6,061 time series), 51% were designated prior to 1985, another 16% were designated by 2000, and another 20% of PA-categorized sites (2,409 time series) belonged to just two MPAs designated after 2000 (Moreton Bay and the Great Barrier Reef). However, all Australian governments have agreed to a set of minimum standards that PAs must meet to be included and managed in the National Reserve System. This means that sites designated after 1985 should have met the scientific criteria to enhance the protected area network, and a change in tenure would have prevented future damage rather than rectify past damage. For these reasons, we decided that all sites designated as within PA at the end date of the reporting period (2016) would be categorized as within PA for the entire time of reporting. All spatial analyses categorizing each time series as either inside PA or outside PA were carried out in ArcGIS 10.7.1.

### 2.2 Calculation of multi-taxon trends to estimate the magnitude of change

We extracted time-series data from the TSX database for the 39 bird taxa that had been monitored both inside and outside PAs during the reporting period, resulting in a database with 16,742 sites (Supporting Information, Tables S1 and S2). A further 26 taxa for which data were available had been monitored only inside PAs (24 taxa) or outside (2 taxa—Plains-wanderer (Pedionomus torquatus) and Southern Black-throated Finch (Poephila cincta cincta)—these were excluded from this analysis. Following the methodology developed to build the TSX, we used the Living Planet Index (LPI) method (Collen et al., 2009; Loh et al., 2005; McRae et al., 2017) to produce multi-taxon trends to estimate a yearly change in average bird taxa data in relation to a baseline year for which the index is set to 1. This is done by first calculating a geometric mean of time-series trends for each taxon within a Generalized Additive Modelling framework. We used bootstrapping to resample taxon trends, taking the central 9,500 of 10,000 iterations to indicate the 95% confidence bounds of the multi-taxon composite relative to the baseline year (Collen et al., 2009). These confidence bounds indicate the heterogeneity among single-taxon trends relative to the baseline year used to build the composite. All analyses using the Living Planet Index methodology to calculate the TSX were performed using the rlpi package for R version 3.6.2 (https://github.com/Zoological-Society-of-London/rlpi) following the approach in McRae et al. (2017). Multi-taxon trends were calculated for bird taxa inside and outside PAs. Sub-trends were only calculated where data on at least 7 taxa were available as recommended by Bayraktarov et al. (2021), who identified the minimum data needed to reproduce trends of the full dataset and after randomly removing taxa.

We conducted sensitivity analyses to investigate the marginal contribution of each taxon trend (marginal
FIGURE 1  Bird taxa inside and outside protected areas. Australian Threatened Species Index (TSX) multi-taxon trend between 1985 and 2016 based on bird taxa with sites (a) inside and (b) outside protected areas. Spatial representation of monitoring locations of data included in the index for birds (c) inside and (d) outside protected areas. Summary of the number of taxa (in black circles) and number of time series (in blue diamonds) used to calculate the index for each year for bird (e) inside and (f) outside protected areas (see Figure S2 in Supporting Information for TSX trends benchmarked to 2000 instead of 1985)
Threatened Species Index values for imperiled (threatened and near-threatened) birds at the end of two periods: 1985 and 2000. We evaluate whether lumping all sites into the category “protected area” regardless of when sites were designated affected the overall multi-taxon trend across Australia (Figure S6). The multi-taxon trends were similar in sites that were designated as protected areas before compared with after 2000, so we did not explore differentiation between PA time of designation and multi-taxon trends further here.

2.3 Statistical analysis

We developed a set of models to test the hypothesis that, if PAs are effective, PAs should have a positive effect on population index size and trajectory by mitigating the threats that are causing declines outside PAs. We expected the population size and trajectory to be higher inside compared with outside PAs. To test whether the effect on the value of the TSX at a given time point was due to variation in year, the presence of a PA, or both, we built Generalized Additive Models in R version 3.6.2 using the packages mgcv (Pedersen, Miller, Simpson, & Ross, 2019; Wood, 2011) and “MuMIn” (Barton, 2014). Generalized additive models have been used for similar questions of tracking change in bird populations in other parts of the world and are well suited to datasets that vary across time and/or space (Fewster, Buckland, Siriwardena, Baillie, & Wilson, 2000; Knape, 2016). We created a full model with PA presence (0,1), year and the interaction between year and PA presence as fixed terms. The response variable was the output value from the TSX (i.e. the aggregate multi-taxon index value) in any given year (when the input TSX time-series dataset was subset to either time-series only within PAs or time-series only outside PAs). This model allowed us to test whether LPI values in and outside of PA were different, and if these differences were constant over time (no interaction) or changed over time (interaction). As present values of the

**Table 1** Threatened Species Index values for imperiled (threatened and near-threatened) birds at the end of two periods: 1985–2016 and 2000–2016, calculated using Living Planet Index methodology

| Index combination | No. of taxa | No. of sites inside | No. of sites outside | Total proportional change 1985–2016 | Total proportional change 2000–2016 |
|-------------------|-------------|---------------------|---------------------|-------------------------------------|-------------------------------------|
|                   |             |                     |                     | Inside PAs | Outside PAs | Difference in TSX inside compared with outside PAs | Inside PAs | Outside PAs | Difference in TSX inside compared with outside PAs |
| Australia         | 39          | 11,539              | 5,203               | -0.66     | -0.77      | 0.11                                           | -0.36     | -0.26      | -0.10                                           |
| NSW               | 21          | 673                 | 1,395               | -0.66     | -0.93      | 0.27                                           | -0.42     | -0.38      | -0.04                                           |
| NT                | 13          | 68                  | 66                  | 0.76      | 0.60       | 0.16                                           | 1.04      | 0.71       | 0.33                                           |
| Qld               | 21          | 4,341               | 721                 | -0.50     | 0.03       | -0.53                                          | -0.21     | -0.30      | 0.09                                           |
| SA                | 21          | 709                 | 228                 | -0.79     | -0.57      | -0.22                                          | -0.63     | 0.16       | -0.79                                          |
| Tas               | 13          | 183                 | 130                 | -0.73     | -0.72      | -0.01                                          | -0.42     | -0.52      | 0.10                                           |
| Vic               | 22          | 1,613               | 1,264               | -0.70     | -0.73      | 0.03                                           | -0.38     | -0.17      | -0.21                                          |
| WA                | 17          | 377                 | 644                 | -0.47     | -0.66      | 0.19                                           | 0.14      | -0.27      | 0.41                                           |
| Shorebirds        | 10          | 5,628               | 1,645               | -0.70     | -0.75      | 0.05                                           | -0.47     | -0.22      | -0.25                                          |
| Terrestrial       | 24          | 5,358               | 3,388               | -0.49     | -0.68      | 0.19                                           | -0.31     | -0.18      | -0.13                                          |
| Near threatened   | 13          | 5,691               | 3,236               | -0.44     | -0.29      | -0.15                                          | -0.27     | -0.15      | -0.12                                          |
| Vulnerable        | 7           | 700                 | 448                 | -0.61     | -0.80      | 0.19                                           | -0.44     | -0.60      | 0.16                                           |
| Endangered & Critically Endangered | 19 | 5,148 | 1,519 | -0.53 | -0.63 | 0.10 | -0.44 | -0.16 | -0.28 |

Notes: Total proportional change is determined as the baseline value (1) minus the final TSX value (a value between 0 and 1 if species on average declined over the entire time period, and >1 if species on average increased). Data for terrestrial birds and for birds listed as Vulnerable or Endangered & Critically Endangered commence in 1995. To comply with the rule of at least 7 taxa in a subindex, Endangered and Critically Endangered bird taxa are shown together. Only bird taxa that occur in both inside and outside protected areas were selected for trend analysis. See Table S4 for data on average (± standard error, lower, and upper confidence bounds) annual trends for each jurisdiction and bird group.
TSX are highly correlated with past values and thus we cannot assume independence of errors, we accounted for temporal autocorrelation in the index data by including an autoregressive model for errors nested by year (Box, Jenkins, & Reinsel, 2008). To do this, we used the function corARMA() from the package nlme (Pinheiro, Bates, DebRoy, Sarkar, & Core Team, 2021) in R version 3.6.2. The full model can be represented as:

**FIGURE 2** Generalized Additive Model (GAM) on trend data between 1985 and 2016 from Threatened Bird Index (TBX) with 95% confidence intervals. Plots are shown for (a) Australia, (b) Western Australia, (c) Northern Territory, (d) South Australia, (e) Queensland, (f) New South Wales, (g) Victoria, (h) Tasmania, (i) birds listed as Near Threatened, (j) birds listed as Vulnerable, (k) birds listed as Endangered and Critically Endangered, (l) shorebirds, and (m) terrestrial birds (see Figure S3 in Supporting Information for GAM trends benchmarked to 2000 instead of 1985, and Tables S7 and S8 for GAM outputs)
where \( g(\mu) \) is a link function, which in this case is a log() function, \( s() \) are the smooth functions, and \( \varepsilon \) represents the autoregressive model for errors nested by year. We ran this model at a national level (using all the time-series data to inform TSX values) then using the index outputs for each of the groups in the categories described above (governance, threat status and functional grouping) as response variables. All terms were dropped consecutively from the model and compared with chi-square likelihood ratio tests, and all terms whose removal did not result in a significant p-value (\( \alpha = 0.05 \)) were considered as nonsignificant. For each model, we also calculated the total variance explained by the model's set of predictors in comparison with other model structures for that taxon subset. The best models showed a high proportion of variance explained (> 85%) for governance, threat status and functional grouping (Tables S7 and S8). Therefore, we are confident that our results describe the general trends related to the effect of year and PA on the value of the TSX.

3 | RESULTS

3.1 | Comparison of population abundance and trends over time in and outside protected areas

Our analyses show that at a national scale between 1985 and 2016, bird populations monitored inside PAs decreased by 66% on average whereas those monitored outside PAs decreased by 77% (Figure 1, Supporting Information Table S6). The difference in the overall
trends of populations inside versus outside PAs was significant \((p < .0001)\). The national decrease was greater between 1985 and 2000 than between 2000 and 2016, regardless of whether birds were inside or outside PAs. Before 2000, monitored bird populations decreased by 46% inside and 68% outside PAs. After 2000, bird populations decreased by 36% inside and 26% outside PAs (Figure S2, Table S6). Variability between single-taxon trends that comprise the composite index was twice as large for the multi-taxon trend of birds outside PAs than inside PAs after 1992 (Figure 1a,b).

### 3.2 Variation in multi-taxon trends of imperiled birds among jurisdictions

At the jurisdictional level, long-term trends of imperiled bird populations show evidence for greater declines outside than inside PAs across most but not all jurisdictions (Table 1). Across the entire study period of 30 years, the total differences between the TSX inside and outside PAs were most pronounced for bird taxa monitored in the state of New South Wales (66% decline inside vs. 93% outside PAs) and for terrestrial birds (49% decline inside vs. 68% outside PAs; Figure 2). Three jurisdictions showed opposite patterns, with declines greater inside PAs over the 30-year period: Queensland (50% decline inside vs. an increase of 3% outside), South Australia (79% decline inside vs. 57% outside) and Tasmania (73% decline inside vs. 72% outside).

Most regional and status bird subsets exhibited change in trends over time both inside and outside of PAs, with significant interactions between PAs and time for most jurisdictions (Tables S7 and S8). For the time period of 2000–2016, bird populations showed greater declines inside versus outside protected areas in most jurisdictions (Table 1). The exceptions were birds in the Northern Territory (104% increase in PAs vs. 71% increase outside PAs), Queensland (21% decrease inside vs. 30% decrease outside PAs), and Western Australia (14% increase inside vs. 27% decrease outside PAs) (Supporting Information, Tables 1 and S6, Figure 2).

### 3.3 Difference in multi-taxon trends of imperiled birds among threatened categories

At a continental scale, bird populations that were more imperiled declined less inside than outside PAs over the 30-year period (Table 1). Declines of bird taxa listed as
Vulnerable (61% decline inside vs. 80% outside PAs) and Endangered/Critically Endangered (53% decline inside vs. 63% outside PAs) were lower inside than outside PAs. In contrast, the least imperiled birds, that is, those listed as Near Threatened, consistently showed smaller declines outside PAs compared with inside PAs over both the long term (30 years) and last 15 years (Tables 1, S7 and S8, Figure 2).

3.4 Bias in monitoring data availability in and outside protected areas

As of 2016, Australia had 10,813 terrestrial and MPAs, of which 775 had monitored bird sites in the Threatened Species Index (Figure 3). The number of individual time series for imperiled bird taxa collected since 1985 (65 taxa) that can be used to inform aggregated trend analyses across Australia was larger for sites inside PAs (12,006 time series, Figure 1e) than outside (5,237 time-series, Figure 1f) (Supporting Information, Tables 1 and S2). For the 39 bird taxa for which monitoring data were available both inside and outside PAs, functional groups and jurisdictions varied in their level of monitoring bias toward PAs (Figure 4). For example, in the state of Queensland, which had the most time series, many more sites were inside PAs (4,341, 86%) than outside (721, 14%), whereas New South Wales had twice as many time series outside PAs (1,395) as inside (673) (Figure 4).

Even inside PAs, monitoring of threatened species is hugely variable. Although more monitoring occurred inside PAs compared with outside, the number of time series collected both inside and outside PAs declined (by 40% for birds inside PAs and 50% for birds outside PAs) between 2011 and 2016. Additionally, despite bias in monitoring toward PAs, most PAs (>90%) remained unrepresented in this analysis, as time-series for threatened birds were collated from only 600 individual PAs. Of these, 36% of PAs contained only a single time-series for a single threatened species. The average number of time-series in any PA for the entire study period was 0.89 ± 35.18 SD (range 0–2,674, with the maximum number of time series from Christmas Island National Park).

4 DISCUSSION

Tracking change in threatened species is an urgent and difficult task, and evaluation of conservation efforts is critical to planning effective recovery actions (Cazalis et al., 2019). We used a multi-species index of threatened species trends over time to compare long-term aggregated population trends of threatened birds inside and outside of Australian PAs. We found that over three decades, bird populations declined less inside PAs than outside at a continental scale, an effect that was consistent across multiple jurisdictions, functional groups and threat statuses. However, the net benefit of PAs to the 39 imperiled bird taxa was smaller than might be expected from other studies that found positive effects of PAs (Geldmann et al., 2013). Furthermore, more recent trends across most jurisdictions indicate that since 2000, bird population trends inside PAs across a number of jurisdictions have been more negative than those outside PAs, a pattern that is mirrored for the most imperiled taxa as well as shorebirds and terrestrial birds at a continental scale. Our analysis was constrained by the lack of balanced datasets inside and outside PAs for threatened species. Despite this study using the most comprehensive collation of threatened species population time series and trends ever for Australia, we discovered more than twice as many monitoring sites inside than outside PAs, even though, on average, more than 70% of threatened bird distributions occur outside PAs where threats are in general more severe (Watson et al., 2011).

Although most jurisdictions (five out of the eight, including Australia as a whole) showed more stable bird population trajectories (i.e., less negative) inside versus outside PAs, this pattern was not universal. The total decline in threatened bird populations in three jurisdictions, Queensland, South Australia, and Tasmania, was more negative inside PAs than outside over the three decades (a difference of 53, 22, and 1% respectively; Table 1). More severe declines inside PAs suggest that either the location and size of PAs do not protect populations from threats, or that management outside PAs is more effectively mitigating threats to species than inside PAs. Both hypotheses could explain the more severe declines inside PAs for these jurisdictions. Queensland has the lowest proportion of its area protected of all Australian jurisdictions (only 7%). Many PAs might be too small to maintain a viable population of a threatened species. Even when gazetted, many PAs in Queensland and Tasmania are used for livestock grazing, mining, quarrying, water impoundment and logging (Adams & Moon, 2013; Kirkpatrick, 1987; Mosley, 1969), and there are numerous documented revocations of parts of reserves in Tasmania (Mercer & Peterson, 1986). South Australia, in contrast, has one of the highest proportional areas of PA gazetted (31%), but 89% of these PAs are in very remote locations with little targeted management and almost no funding ($2.45/ha in comparison with a national average of >$9/ha and up to $46.88/ha in New South Wales where the positive effect of PAs on trends was the highest; Craigie et al., 2015). Funding for PA management is biased across Australia and some
jurisdictions have much greater resources to manage PAs than others. For example, between 2006 and 2011, Western Australian World Heritage areas received seven times more funding from federal government funding allocation programs than those in South Australia, and funding in Western Australia increased fourfold (Mackay, 2011). It is no surprise then that imperiled bird trends in South Australian PAs continue to decline whereas those in Western Australian PAs started to increase during this time. Outside of the national protected area network, Queensland and South Australia also have the first and second highest area of private land under covenants (20,780 km² and 6,208 km² respectively; Archibald et al., 2020), supporting the hypothesis that efforts outside nationally recognized PAs have been greater than efforts inside PAs to mitigate threats in these jurisdictions.

Regardless of whether PAs had a positive or negative effect on bird trends, their influence was rarely constant, with our models discovering significant interactions between PAs and time on trends for most jurisdictions (Tables S7 and S8). Some jurisdictions and bird groups showed an overall positive influence of PAs on bird population trends across the entire study period (Table 1), but after 2000, trends inside PAs were more negative than those outside (e.g., NSW, South Australia, Victoria, shorebirds, terrestrial birds, endangered/critically endangered birds). One hypothesis for the change to less negative trends outside PAs is that PAs protected imperiled bird populations from higher clearing rates prior to 2000, but after 2000 birds outside PAs were no longer most at risk from high rates of clearing, perhaps due to the introduction of legislation protecting threatened species’ habitats from clearing, primarily the Environment Protection and Biodiversity Conservation (EPBC) Act in 1999. In support of this, the percentage of primary vegetation lost through conversion of natural habitats was greater for all Australian jurisdictions prior to 2000 compared to after 2000 (Metcalfe & Bui, 2016). For example, in South Australia the rate of clearing primary vegetation decreased after 2000, while the TSX for birds outside PAs increased by 16% during that time (Metcalfe & Bui, 2016). A few jurisdictions showed an overall negative influence of PAs on trends across the study period, but after 2000 trends inside PAs were more positive than outside (e.g., Queensland, Western Australia). In Queensland the rate of clearing remnant vegetation outside PAs doubled between 2010 and 2014 (Reside et al., 2017), and the TSX for this jurisdiction declined by 32% outside PAs during these years (Table 1), while populations inside PAs increased (Figure S3). However, large-scale changes in clearing rates do not explain why populations inside PAs across many jurisdictions (e.g., South Australia, Tasmania, Victoria) continued to decline after 2000 even after PAs were gazetted and threatened species legislation was enacted. Continuing declines in PAs suggests that the threats to imperiled birds have not been abated within these locations.

A lack of PA influence on threatened species recovery may be because many threats to Australian birds affect all tenures indiscriminately, and tenure designation as conservation land does not necessarily confer protection unless actively managed. Invasive species, particularly cats, have been, and continue to be, one of if not the most significant threats to Australian birds (Garnett et al., 2019). Cats occur Australia-wide in and out of PAs, impact 95% of all imperiled bird species (Kearney et al., 2019) and kill more than a million birds every day across Australia (Woinarski et al. 2017b). Threats from actions that convert or degrade habitat or ecological processes to improve human welfare (e.g., changes to hydrological regimes to improve agricultural production) also impact almost three quarters of Australian imperiled birds across protected and unprotected systems (Clemens et al., 2016; Healy, Tulloch, & Fensham, 2020; Kearney et al., 2019; Kingsford, Bino, & Porter, 2017). The impacts of climate change (including increased drought and fire) are also not restricted by tenure (although protecting climate refugia may help the persistence of some species; Keppel et al., 2015). Without a strategic broadscale approach to manage pervasive threats across tenure, negative trends in imperiled birds are likely to continue inside and outside PAs. Unfortunately, only 43% of threats to Australian birds are currently managed in any way at all, leaving 57% unmanaged (Garnett et al., 2019).

There is evidence that, when managed well, threatened bird populations can increase (Garnett, Crowley, & Balmford, 2003; Tulloch, Chadès, & Lindenmayer, 2018). In developed nations, well-managed PAs conserve natural land cover, reduce vegetation loss and reduce the impacts of other threats on species, compared with surrounding unprotected land (Geldmann et al., 2013; Joppa & Pfaff, 2011; Nagendra, 2008). For example, in northern Western Australia, the EcoFire program to recover fire-dependent bird species (Gouldian Finch Erythura gouldiae, Purple-crowned Fairy-Wren Malurus coronatus) has resulted in successful population recovery of imperiled species on PA estate managed by the Australian Wildlife Conservancy (Legge et al., 2015). Indeed, sensitivity analyses investigating the relative marginal contribution of each species or subspecies’ trend to our aggregate index suggest that these two species were key drivers of the Western Australian population declines in unmanaged sites outside PAs and the major drivers of the positive trends inside PAs since 2000 (Supporting Information Figure S5). One explanation for
recent stabilizing trends outside PAs in certain jurisdictions is that governments and land managers are enacting policies and actions that resulted in recent mitigation of threats outside of the national PA network. In addition to covenanting, there has been huge investment in private land and community conservation measures such as farmland restoration, exclusion of livestock, targeted pest eradication, nest monitoring, and even supplementary feeding over the past 30 years (Belder, Pierson, Ikin, & Lindenmayer, 2018; Benshemesh et al., 2018; Berris et al., 2018; Garnett, Latch, Lindenmayer, Pannell, & Woinarski, 2018; Ikin et al., 2018; Berris et al., 2018; Garnett, Latch, Lindenmayer, Pannell, & Woinarski, 2018; Ikin et al., 2019; Lindenmayer et al., 2018). Such investments often do not have immediate positive outcomes—there may be significant time lags of up to decades between when areas are first restored and when they might become suitable habitat for birds (Vesk, Nolan, Thomson, Dorrough, & Nally, 2008). Many such programs have demonstrated success at maintaining imperiled bird populations outside PAs (Munro, Lindenmayer, & Fischer, 2007). Broadscale private land conservation actions such as ecological restoration can also benefit species populations on public land, if there is connectivity between populations on public and private land, and/or if restoration improves connectivity between protected areas (Niemeyer, Barros, Silva, Crouzeilles, & Vale, 2020).

Improved site-level evaluation of management effectiveness is required to causally link species recovery efforts to the broad-scale changes in bird trends discovered in this study, and to help determine why terrestrial birds inside PAs have in recent years declined across most jurisdictions (Garnett et al., 2019). In our analysis, we did not control for biases related to PA size or environmental variation among PAs due to the opportunistic nature of the TSX dataset. Ideally, analyses investigating the effect of certain factors (e.g., PA network characteristics) on trends in biodiversity would involve statistical matching or paired treatment/nontreatment field datasets—instead, the TSX relies on an aggregate dataset of independent surveys and monitoring programs that are unlikely to be perfectly paired. Further studies should focus on controlling for possible differences between protected and nonprotected areas at site and regional scales. For this purpose, methods such as statistical matching can help to control for site selection bias related to environmental variables (e.g., elevation, land use type) and can provide further insights to understand the effects of protection status (Schleicher et al., 2020; Terraube, Van doninck, Helle, & Cabeza, 2020). Further studies could also shed light on the role of PAs in the persistence of vertebrate populations with contrasting functional traits (e.g., based on body size, home range, and mobility), as our analysis is restricted to birds which are in general considered a highly mobile group.

For some taxa, declines may continue both inside and outside PAs even in the face of intensive management. For instance, the strongest driver of declining shorebird populations in Australia is thought to be habitat loss on staging grounds in Asia (Clemens et al., 2016; Studds et al., 2017). Australia’s PA designation and management for shorebirds will have little impact if declines are driven by actions elsewhere along the migratory shorebird flyway (Nicol, Fuller, Iwamura, & Chadès, 2015). Despite increased habitat loss in Asia (Murray, Clemens, Phinn, Possingham, & Fuller, 2014), shorebird population declines slowed between 2000 and 2016, although populations declined more inside than outside PAs during this period (by 47 and 22%, respectively). One explanation for this difference is the implementation of conservation actions targeting shorebirds, many of which take place in local communities and urban wetlands that are not necessarily protected. Since 1996, the Australian Government has invested approximately $5 million in projects contributing to migratory shorebird conservation. Alternatively, some local shorebird populations are increasing in unprotected urban habitats due to changed bird behavior and habitat use while their global population continues to decline. For example, in northern Australia, local increases in shorebirds such as the Eastern Curlew (Numenius madagascariensis) have been attributed to recent increases in suitable high tide roosting habitat due to use of artificial sites at wharfs as roosts (Lilleyman, Garnett, Rogers, & Lawes, 2016). In support of this explanation for slowing declines outside PAs since 2000, our sensitivity analyses investigating the relative marginal contribution of individual taxa to the overall TSX suggest shorebird trends from the Eastern Curlew and Great Knot (Calidris tenuirostris) populations were the strongest driver of the TSX increase outside PAs in the Northern Territory (Figure S5).

In addition to discovering notable differences in threatened species trends inside and outside PAs across Australia, we discovered gaps and declines in monitoring across space, time and taxa. These monitoring gaps and biases need to be rectified if we want to fully understand the effectiveness of public and private conservation actions at a national level, but filling gaps in monitoring remains challenging due to the costs of collecting population time-series data for threatened species, especially for species that are hard to detect or located in remote places and may require greater efforts and investment than more common species (Tulloch, Mustin, Possingham, Szabo, & Wilson, 2013; Tulloch, Possingham, & Wilson, 2011). A cost-effective approach to begin to address gaps in monitoring would be to invest in
monitoring and data management for threatened species that complements existing programs (e.g., setting up paired monitoring sites outside PAs for species currently monitored only inside PAs) and resuming rigorous monitoring programs carried out in the past. The relatively small effort of implementing monitoring outside PAs for the 24 threatened bird species currently monitored only inside PAs would increase the number of taxa available for evaluating PA effectiveness using the TSX by 61% and enable an investigation of whether our results hold over a wider range of PA types, locations, and management approaches.

Funding models for monitoring outside the PA estate need to account for the fact that State and Territory government financing generally does not extend to monitoring outside PAs, nor do management agencies usually have the capacity to undertake activities outside of their jurisdiction. Additionally, most land clearing events outside PAs cause people to cease visiting sites to collect bird data, despite ongoing monitoring in the site where habitat has been lost being key to providing important benchmark information to compare to sites where habitat is maintained (e.g., within PAs). Finally, paired monitoring protocols are not possible for all taxa, as identifying both protected and unprotected populations of the same taxa is challenging and sometimes impossible (Watson et al., 2011). The critically endangered Western Ground Parrot (Pezoporus flaviventris), once widespread across thousands of kilometers of coastal heathland, is now restricted to a single national park due to a combination of habitat clearing, altered fire regimes and introduced predators (Mollov, Burbidge, Comer, & Davis, 2020). Additionally, some taxa have migratory ranges extending across boundaries and are difficult to monitor consistently in fixed sites (e.g., the Critically Endangered Regent Honeyeater [Anthochaera phrygia]).

Our study demonstrated the use of the Threatened Species Index to assess the contribution of conservation mechanisms, such as protected areas, to improving trends in imperiled taxa. Our results suggest that, while PAs might in some cases be helping to reduce the declines of threatened species, in most cases PAs alone are failing to recover threatened bird populations. Our results highlight that the simple existence of PAs is unlikely to ensure that national biodiversity goals are reached (Geldmann et al., 2013; Nagendra, 2008). Creation of PAs needs to be complemented by adequate management of threats both inside and outside those areas if threatened bird populations are to be maintained and recovered with limited conservation resources. Our results also highlight the value of long-term monitoring of multiple species at a national scale across different management areas. However, through our evaluation of population trends inside and outside PAs, we discovered important gaps in the representativeness of threatened species monitoring data, and an indication that data availability has declined in recent years. There is a need to strengthen monitoring programs to enable detection of long-term trends across a wider range of species and geographic areas. This would help to further evaluate the relative effectiveness of different conservation actions and inform decisions about prioritizing future efforts.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest

DATA AVAILABILITY STATEMENT
All data used in the Threatened Species Index are publicly available via the online data visualization tool (https://tsx.org.au/). Data have been aggregated to bioregional scales to mask the locations of sensitive species.

AUTHORS’ CONTRIBUTIONS
Elisa Bayraktarov, Ayesha I. T. Tulloch, and Hugh P. Possingham conceived the manuscript. Elisa Bayraktarov, Diego F. Correa, Andrés F. Suarez-Castro and Ayesha I. T. Tulloch analyzed the data. All authors interpreted the results. Ayesha I. T. Tulloch and Elisa Bayraktarov wrote the manuscript with the input from all authors.

ETHICS STATEMENT
Data custodians were surveyed under Human Ethics Approval number: 2018001572.

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