The Decline, Fall, and Rise of a Large Urban Colonising Bird

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Abstract

Context

The process of urbanisation results in dramatic landscape changes with long-lasting and sometimes irreversible consequences for the biota. Urban sensitive species can be eliminated from the landscape, while urban tolerant species can persist in or colonise the changed environment.

Objectives

Here we used historical atlas data to examine the changing distribution of the Australian Brush-turkey, a recent urban colonising species, at continental and city scales, and the changing land use in urban areas occupied by the species.

Methods

We assessed changes at the continental scale from 1839-2019. We then assessed colonisation of the cities of Sydney and Brisbane, located 900 km apart, over the period 1960-2019. At the city scale, we quantified the changing land use within Brush-turkey occupied areas over time using classification of satellite imagery.

Results

The Brush-turkey range has shifted over the last century, with the species receding from the western and southwestern proportions of their range, while expanding in the northwest. Areas occupied in both cities have expanded, with recently colonised areas containing less vegetation and more developed land.

Conclusions

Our results confirm that Brush-turkeys are successfully colonising urban areas, including major cities, and are likely to continue moving into urban areas, despite declines elsewhere in their natural range. This study highlights that species which were locally extirpated from urban areas and thought to be an unlikely candidate for recolonisation can adapt to human modified habitats; successful expansion is likely to be associated with urban greening and legal protection from human persecution.

1. Introduction

Urbanisation is a major land use change with often dramatic and long-lasting consequences for biodiversity (McDonald, Kareiva, & Forman, 2008; McKinney, 2002). Natural habitat is largely cleared and replaced by extensive areas of built structures, roads, and other impervious surfaces, while remaining vegetation is often highly fragmented (Grimm et al., 2008). Urban dwelling animals must also contend with increased levels of chemical and sensory pollutants, altered trophic interactions, potential competition with or predation from non-native species, and exposure to anthropogenic sources of
disturbance (Faeth, Warren, Shochat, & Marussich, 2005; McKinney, 2006; Mikula, 2014; Pickett et al., 2001). This often results in the loss of urban sensitive animals (Aronson et al., 2017; Banville, Bateman, Earl, & Warren, 2017) while a subset of species persists, leading to a depauperate and homogenized biotic community (McKinney, 2006; Callaghan et al. 2019).

While many species are unable to persist in cities, others can thrive in the modified landscape. In some cases, cities can even act as refugia for rare or threatened species (Ives et al., 2016; Soanes & Lentini, 2019). For some species, urban environments present advantages such as new resources, heterogenous greenspaces, high primary productivity, potential release from predators or competitors, and buffering against seasonal changes in resources (Anderies, Katti, & Shochat, 2007; Callaghan, Bino, et al., 2019; Crooks & Soule, 1999; Shochat, Warren, Faeth, McIntyre, & Hope, 2006). Highly successful urban species can reach higher abundances that would be possible in their natural habitat (Martin, French, & Major, 2010; McKinney, 2002). Successful city dwelling species are often characterised by combinations of traits that provide an advantage in urban environments. For example, common traits in successful urban bird species include a generalist diet, canopy nesting, behavioural flexibility, high dispersal ability, a short flight distance, and high fecundity (Bressler, Diamant, Tingley, & Yeh, 2020; Callaghan, Major, et al., 2019; Moller, 2009).

While many species can persist in cities as they expand, the return and reestablishment of formerly extirpated species in urban areas is a less frequent occurrence. Examples include large mammals such as deer (Duarte, Farfán, Fa, & Vargas, 2015), red foxes (Jackowiak et al., 2021), and wild boar (Stillfried et al., 2017). The Australian Brush-turkey (Alectura lathami, hereafter “Brush-turkey”) is an example of a species that was is actively recolonising urban areas in Australia, including large cities such as Sydney and Brisbane, which form part of its historic home range (Göth, Nicol, Ross, & Shields, 2006; Jones, Sonnenburg, & Sinden, 2004). The Brush-turkeys population was observed to be declining by the early 20th century in many popular accounts ("The Brush Turkey," 1881; "Outdoor Australia," 1930; "Rare Birds," 1952), likely as a result of overhunting, habitat clearing, and predation from introduced species (Jones & Göth, 2008). Brush-turkeys disappeared from most urbanised areas along the east coast, which have since greatly expanded. Despite their rarity over the past century, the species has now become a common sight in suburban areas over the last few decades, often leading to instances of human wildlife conflict as their foraging and nest building behaviour can damage household gardens (Jones & Everding, 1991).

While Brush-turkeys show recent successes in recolonising urban areas, the future of the species remains uncertain, with concerns that cities may act as ecological traps due to poorer reproductive success (Jones & Everding, 1991) and ongoing range declines in rural areas (Göth et al., 2006). Previous studies have estimated that a third of the species’ natural habitat has been lost due to land clearing (Simmonds, Watson, Salazar, & Maron, 2019) while an isolated population in the Nandewar region, at the far west of the species’ range, is listed as threatened under federal and state legislation (DPIE, 2017). Their ground foraging behaviour, obligate ground nesting, poor flight ability, and lack of parental care for chicks, make Brush-turkeys an atypical urban dwelling bird. However, their omnivorous diet, boldness, and broad climatic tolerance may benefit the species in urban areas (Blumstein, 2006; Hall, Burns, Martin, & Hochuli,
as has been observed for other generalists (Croci, Butet, & Clergeau, 2008; Moller, 2009). Resolving the contrast between their apparent success in urban areas and possible decline in rural areas requires a greater understanding of how the Brush-turkey distribution has changed over time in different regions.

In this study we investigated temporal shifts in Brush-turkey distributions at multiple scales. To investigate the Brush-turkey distribution at the continental scale, we mapped Brush-turkey sightings records and quantified changes in occupied bioregions for six time periods from 1839 to 2019. To investigate the Brush-turkey distribution at the city scale, we quantified the number of Brush-turkey occupied suburbs for four time periods from 1960 to 2019 for the cities of Sydney and Brisbane. We further investigated if changes to urban land-use at the suburb scale corresponded with changes to the urban Brush-turkey distribution.

2. Methods

2.1 Study Area

The study area for the continental-scale assessment includes approximately 3000km tract of the Australian east coast, from the tip of Cape York, Queensland, to the Southern Highlands, New South Wales, and up to 750km inland. The city-scale assessment focuses on the cities of Sydney and Brisbane, which are the largest cities within their respective states of New South Wales (NSW) and Queensland as well as the two largest cities within the estimated range of the study species. Sydney has a population of 5.37 million people (ABS, 2021) and a temperate climate (Herron et al., 2018). Brisbane has a population of 2.56 million people (ABS, 2021), and a subtropical climate. Both cities are bordered by national parks to the north, west, and southeast. Both cities contain many smaller patches of remnant vegetation alongside managed artificial greenspaces (Keith, 2004; Lunney, Hutchings, & Hochuli, 2010; Museum, 2003)

2.2 Historic and Recent Sightings

We downloaded all Brush-turkey occurrence records from the Atlas of Living Australia, as well a taxon-specific citizen science project, Big City Birds (formerly BrushTurkeys), on 25/3/2021. The Atlas of Living Australia (hereafter “Atlas”) is a collaborative digital platform that compiles Australian taxon occurrence records from multiple sources, including government databases, citizen science records, and museum collections, and provides information on data quality. Big City Birds is a targeted citizen science project that collected detailed ecological data on Brush-turkeys, including presence, counts, sex, and behavioural observations such as nesting and roosting locations (Hall, Martin, Burns, & Hochuli, 2021). These records were downloaded separately as they are not currently included in the Atlas.

Records with no latitude and longitude coordinates and records with no exact date were excluded. We included records prior to 1900 if the sighting had an exact year. We further eliminated records that were not human observations of a wild bird, nest, chicks/juveniles, or eggs, or museum specimens with a
collection location. Records indicating captive animals, such as those in zoos or pets, were removed. Data from one source, Queensland WildNet (hereafter “WildNet”), was redownloaded directly from the source website on 26/7/21 (Queensland Government, 2021) due to inaccuracies identified in the dates assigned to WildNet records in the Atlas.

To further filter the data, we mapped all remaining occurrence records using ArcMap 10.8. We spatially filtered data by removing records over water and records where the provided location description did not match GPS coordinates. Outliers were visually identified and eliminated if they met all of the following rules: the record was from an opportunistic survey by non-experts (e.g. citizen science data), the record was outside of previously published distribution maps for the species (Birdlife International, 2021; Göth et al., 2006), and there was no other sighting within the same bioregion or within 500km for the given time period. Four remaining outliers were also eliminated: a 14/7/2000 record from Diamantina National Park was removed as it was considered a misidentification by Ley, Tynan, and Cameron (2011); two Questagame records from Adelaide, South Australia, in 2019 were removed due to a lack of any other sightings from a highly populated urban area indicating these sightings are likely spurious; and one 1/12/1949 record from Adelaide, was eliminated as this record was of preserved eggs only with an uncertain collection location.

2.3 Continental Scale Distribution Time Series

To investigate distribution changes at the continental scale, we assessed the number and location of Brush-turkey records across bioregions. Bioregions represent large-scale environmental divisions of Australia based on common climate, soil, geology, and vegetation (DAWE, 2020; Thackway & Cresswell, 1995). Bioregions are commonly used as coarse landscape units in management and conservation at the regional scale. We categorised records temporally into six time periods: pre-1900, 1900-1939, 1940-1959, 1960-1979, 1980-1999, and 2000-2019. The longer time intervals for the periods prior to 1939 reflect the scarcity of records for the species compared to the more recent time periods.

To estimate the changing Brush-turkey range at the continental scale for each period, we plotted all filtered Brush-turkey records in ArcMap10.8 and aggregated sightings points into a single polygon. We used an aggregation distance of 1000km for the three earlier time periods and 500km for the more recent time periods to reflect the increasing availability and coverage of sightings data, resulting in a more conservative estimation of the Brush-turkey range in the more recent periods. We used the smooth polygon tool with Berzier interpolation algorithm to eliminate sharp angles and added a 0.1 decimal degree (11.1km) buffer to ensure sighting points were contained within the interior resulting polygon. We refer to the resulting polygon as the “estimated range”.

To visualise how the number and density of records changed in each bioregion over time, the estimated range polygon was then intersected with the bioregions layer and spatially joined with the Brush-turkey records point layer. We display the total number of records for each bioregion and time-period.

2.4 City Scale Distribution Time Series
To assess Brush-turkey distribution changes in the major urban centres of Sydney and Brisbane, we defined the spatial extent of each city using the “significant urban area” (SUA) classification used by the Australian Bureau of Statistics (ABS). SUAs represent contiguous large urban centres or clusters of related urban centres (ABS, 2017). The Sydney and Brisbane SUAs were subdivided into suburbs, representing officially recognised and named localities within cities and towns (ABS, 2019). To map changes in Brush-turkey suburb occupancy, we plotted all filtered sightings records for the two cities in ArcMap 10.8 for each time-period. We intersected the city suburbs layer with the sightings point layer to produce a density map displaying a count of Brush-turkey records in each suburb for each time-period.

To investigate change at finer temporal scales, we further categorised records from 1960-2019 into 5-year intervals and measured the number of Brush-turkey occupied suburbs for each city. Records prior to 1960 were not included due to a scarcity of records for both cities.

2.5 Land Use Analysis

To assess changing patterns of land use within Brush-turkey occupied areas in Sydney and Brisbane, we downloaded Landsat satellite imagery of the two cities from 1979, 1999, and 2019. These years were chosen as they represent the end-dates of the 1960-1979, 1980-1999, and 2000-2019 time periods used for the Brush-turkey range analysis. 1979 imagery was obtained from the Landsat 2 multispectral scanner, 1999 imagery from the Landsat 5 thematic mapper, and 2019 imagery from the Landsat 8 operational land image and thermal infrared scanner. Images were selected from July through September to obtain comparable images with minimal cloud cover. The satellite images were imported into ArcMap 10.8 and clipped to shapefiles of the Sydney and Brisbane SUAs.

We used supervised image classification with a maximum likelihood approach to quantify land use in each city for each year (see Fischer, Edwards, Weber, Garnett, & Whiteside, 2021; Hahs & McDonnell, 2006). Twenty training samples were manually assigned for each of the following land use classes: commercial, residential, dense vegetation, open greenspace, and bare land. We then ran the supervised image classification tool in ArcMap 10.8 to classify all images. The majority filter and boundary clean tools were used to remove isolated pixels and ragged boundaries, producing a more generalised output map. The classified images were then intersected with the Brush-turkey occupied suburbs layer to quantify the amount of each land use type within the Brush-turkey range for each city, in each year. Chi-squared tests of association were conducted in IBM SPSS 26 to test for associations between year and land use within Brush-turkey occupied suburbs. Post hoc Z-tests with Bonferroni corrections were conducted to determine which land use classes had significantly different proportions between time periods.

3. Results

3.1 Occurrence Records
A total of 116433 Brush-turkey occurrence records were collected from 34 different sources. Following data filtering, this was reduced to 98019 for the period 1839-2019 (Table 1). Of these, 69671 records were located within significant urban areas. The three largest contributing sources of Brush-turkey records were eBird (53.2%), the Office of Environment and Heritage Atlas of NSW Wildlife (24.6%), Big City Birds (8.3%).

Table 1 – Sources of Australian Brush-turkey records contained within the Atlas of Living Australia and Big City Birds citizen science project after data filtering as of 31/12/19. Total number of records, total number of urban records, date of the first record, and date of the most recent record shown for all sources with >1000 records.

| Source                                      | Total Records | Urban Records | Earliest Record | Latest Record |
|----------------------------------------------|---------------|---------------|-----------------|---------------|
| eBird Australia                              | 52093 (53%)   | 30265 (43%)   | 24/08/1952      | 31/12/2019    |
| OEH Atlas of NSW Wildlife                    | 24139 (25%)   | 23918 (34%)   | 1/01/1900       | 9/12/2019     |
| Big City Birds                               | 8115 (8%)     | 8007 (12%)    | 13/04/2008      | 31/12/2019    |
| Birdata, BirdLife Australia                  | 5589 (6%)     | 3086 (4%)     | 29/09/1993      | 20/02/2019    |
| WildNet - Queensland Wildlife Data           | 2270 (2%)     | 493 (0.7%)    | 31/10/1856      | 13/10/2019    |
| New South Wales Bird Atlassers               | 1940 (2%)     | 1937 (3%)     | 1/03/1839       | 29/12/2011    |
| Tamborine Mountain Weekly Bird Observations  | 1212 (1%)     | 0             | 26/07/1993      | 13/05/2019    |
| iNaturalist Australia                        | 1000 (1%)     | 700 (1%)      | 4/05/1978       | 31/12/2019    |
| Other Sources (n=23)                         | 1661 (2%)     | 1265 (2%)     | 3/05/1865       | 29/12/2019    |
| **Total**                                    | **98019**     | **69671**     | **1/03/1839**   | **31/12/2019**|

Seven bioregions were continuously occupied by Brush-turkeys throughout all time periods (1839-2019): Brigalow Belt North, Brigalow Belt South, Cape York Peninsula, NSW North Coast, South Eastern Queensland, Sydney Basin, and Wet Tropics (Fig. 1). Three additional bioregions were continuously occupied from 1900 to 2019: Central Mackay Coast, Nandewar, and New England Tablelands (Fig. 1b-f). These bioregions are mostly situated along the east coast of Australia, with a few located inland in Central NSW and Southern Queensland.

### 3.2 Continental Scale Distribution

Historical records prior to 1900 (n=68) report Brush-turkey presence in eleven bioregions, covering a total area of 1018348km². In two of these, the inland Cobar Peneplain and NSW Southwestern Slopes, Brush-
turkey records disappeared after 1900 and were not observed again in any period (Fig. 1a). Occupied bioregions increased to 12 during the 1900-1939 period, with additional records in the Central Mackay Coast, Mitchell Grass Downs, Nandewar, and New England Tablelands. However, records ceased in the NSW Southwestern Slopes, Southeastern Highlands, and Cobar Peneplain bioregions (Fig. 1b). This represented an overall decrease in area of the total Brush-turkey range to 1005970km$^2$. Ten bioregions were occupied during the 1940-1959 period, with Brush-turkey records disappearing from the inland Queensland bioregions of Einasleigh Uplands and Mitchell Grass Downs (Fig. 1c). This represented a decrease in total area of the Brush-turkey range to 684500km$^2$. Overall, from 1900-1959, the estimated Brush-turkey range expanded in the central-western part of the species distribution but receded from the north-western and south-western part of their pre-1900 distribution. The total area of the estimated Brush-turkey range declined by 333848km$^2$ during this period, or a decrease in total area of 32.8%, from the pre-1900 baseline.

Brush-turkey were recorded within 13 bioregions during 1960-1979, with new records from the Desert Uplands and Kanmantoo bioregions, and records resuming in the Einasleigh Uplands (Fig. 1d). This represents a total increase in area of the Brush-turkey range to 956441km$^2$. During the 1980-1999 period, the number of occupied bioregions increased to 16, with new records from the Mulga Lands and Gulf Plains. Records also resume in the South-eastern Highlands which had not had any records since before 1900 (Fig. 1e). This represented a further increase in total Brush-turkey range area to 1138037km$^2$. Brush-turkey occupied bioregions decreased to 14 in 2000-2019, with records disappearing from the Mulga Lands and Desert Uplands (Fig. 1f). This represented a decrease in the total Brush-turkey range to 1124483km$^2$.

Overall, from 1960-2019, the estimated Brush-turkey range appeared to have contracted in the central-western part of their distribution but has expanded in the north-west and south-east. From 1960-2019, the total area of the estimated Brush-turkey range increased by 168042km$^2$, or 17.6%, and by 106135km$^2$, or 10.4%, from the pre-1900 baseline.

### 3.3 City Scale Distribution

In both Sydney and Brisbane, Brush-turkey occupied suburbs show a large overall increase during the period 1960-2019 (Fig. 2), with the largest increase in occupied suburbs occurring in the last decade. In Sydney, the number of occupied suburbs remained consistently low, fluctuating between 1-3 suburbs, across the 5-year time intervals from 1965 to 1994, this increased rapidly through to the present day (2019), to a total of 310 suburbs. In Brisbane, occupied suburbs increased steadily in each 5-year interval from 1965 to 1989 to a total of 50, then decreased from 1990-1994 to 28. The number of occupied suburbs then increased through all 5-year intervals till 2019, to a total of 289 suburbs (Fig. 2).

In Brisbane, Brush-turkey occupied suburbs during the 1960-1979 period were scattered across the central-western part of the city, with more isolated records in the north and southeast. The highest percentage of sightings came from suburbs in the centre and central west of the city (Fig. 3a). During the
1980-1999 period an increasing number of suburbs were occupied in the central, southwestern, and northern parts of the city, as well as the suburbs of the southeast (Fig. 3b). By 2000-2019, Brush-turkeys occupied the majority of suburbs in northern and central Brisbane, with a further increase in the number of occupied suburbs in the south. The suburbs with the largest percentage of records were in the central-west part of the city, while large areas in the south of the city remained unoccupied (Fig. 3c).

In Sydney, Brush-turkey records first appeared in the north and northwest of the city during the 1960-1979 period (Fig. 3d). Increasing numbers of northern suburbs were occupied during the 1980-1999 period, as well as suburbs in the west of the city, however Brush-turkeys disappeared from the north-western suburbs (Fig. 3e). All northern suburbs of Sydney were occupied by the 2000-2019 period, along with the narrow strip of suburbs in the mountainous area to the west of the city, and an increasing number of suburbs in the northwest and southeast of the city. The northern suburbs contained the highest percentage of records from 1980-2019. The majority of the western suburbs of the city remain unoccupied by Brush-turkey’s; however, suburbs to the east and west of this area have been occupied during the 2000-2019 period (Fig. 3f).

### 3.4 City Scale Land Use

The total area occupied by Brush-turkeys in Brisbane increased from 588 m$^2$ in 1979 to 1753km$^2$ in 1999, and to 4801km$^2$ in 2019. The total area occupied by Brush-turkeys in Sydney increased from 95km$^2$ in 1979 to 180km$^2$ in 1999, and to 3132km$^2$ in 2019 (Fig. 4a). As Brush-turkeys occupied new suburbs, the proportion of their territory covered by different land use classes was significantly different between time periods for both Brisbane ($\chi^2(8) = 434.87, p < 0.001$) and Sydney ($\chi^2(8) = 189.87, p < 0.001$)

As Brush-turkeys occupied new suburbs in Brisbane, the proportion of their territory covered by dense vegetation and bare land the significantly decreased from 1979 to 1999, and from 1999 to 2019. The proportion their territory covered by open green space was significantly lower in 1999 than in either 1979 or 2019. The proportion of their territory covered by residential area was not significantly different from 1979 to 1999 but increased from 1999 to 2019. The proportion of their territory covered by commercial area significantly increased from 1979 to 1999 and did not significantly change between 1999 and 2019 (Fig. 4b).

As Brush-turkeys occupied new suburbs in Sydney, the proportion of their territory covered by dense vegetation remained constant from 1979 to 1999, and significantly decreased from 1999 to 2019. The proportion of their territory covered by open greenspace significantly decreased from 1979 to 1999 and significantly increased from 1999 to 2019. The proportion of their territory covered by bare land significantly decreased from 1979 to 1999 and remained constant from 1999 to 2019. The proportion of their territory covered by residential area significantly increased from 1979 to 1999 and from 1999 to 2019. The proportion of commercial area significantly increased from 1979 to 1999 and significantly decreased from 1999 to 2019 (Fig. 4c).
Table 2. Bioregions containing Australian Brush-turkey records for the time-period 1839-2019. The dataset was revised to remove erroneous and unverifiable reports (DAWE, 2020).

| Region Code | Region Name               | Area (km²) |
|-------------|---------------------------|------------|
| BBN         | Brigalow Belt North       | 136745.325 |
| BBS         | Brigalow Belt South       | 272197.759 |
| CMC         | Central Mackay Coast      | 14642.079  |
| COP         | Cobar Peneplain           | 73853.464  |
| CYP         | Cape York Peninsula       | 122564.572 |
| DEU         | Desert Uplands            | 69410.955  |
| EIU         | Einasleigh Uplands        | 116257.263 |
| GUP         | Gulf Plains               | 220418.251 |
| MGD         | Mitchell Grass Downs      | 334687.608 |
| MUL         | Mulga Lands               | 251883.334 |
| NAN         | Nandewar                  | 27019.772  |
| NET         | New England Tablelands     | 30022.127  |
| NNC         | NSW North Coast           | 39965.91   |
| NSS         | NSW South Western Slopes  | 86811.261  |
| SEH         | South Eastern Highlands   | 83759.611  |
| SEQ         | South Eastern Queensland  | 78049.211  |
| SYB         | Sydney Basin              | 36295.966  |
| WET         | Wet Tropics               | 19891.067  |

4. Discussion

After experiencing a catastrophic human-mediated decline in the early 20th century, particularly in and around urban areas, Brush-turkeys are actively recolonising the large global cities of Brisbane and Sydney. Their urban expansion was not limited to existing greenspaces, as we found that Brush-turkeys have increasingly colonised less vegetated and more developed suburbs over recent decades, indicating that the species is now thriving in urban areas. The changes in the Brush-turkey distribution were not limited to urban areas, with this species spreading consistently into rural and natural areas since 1960. Firstly, our assessment identified an estimated decrease in occupied land area of about 33% from 1900-1959, followed by an overall estimated increase of land area of about 18% from 1960-2019. Most of the
land area lost was in the western and southwestern portions of the species’ range, while expansion occurred in the northwest.

4.1 Continental Distribution Trends

Brush-turkeys expanded into one new bioregion, the Gulf Plains, in the last few decades. The Gulf Plains bioregion lies along the north coast of Australia and is adjacent to the Cape York Peninsula and Einasleigh Uplands bioregions, which have been continuously and near continuously occupied by Brush-turkeys respectively. Given the steady increase in records over the last four decades, it is likely that Brush-turkeys naturally expanded their range into the Gulf Plains bioregion from source populations in the adjacent bioregions as these neighbouring populations grew over recent decades.

There is a general trend of increasing Brush-turkey records from 1900-2019 in all continuously occupied bioregions, with the greatest increase in the number of observations occurring in the 2000-2019 period (Table S2). However, the increase in observations was more common in coastal and urban bioregions with larger human populations. The largest increase in records was in the NSW North Coast, South Eastern Queensland, Sydney Basin, and Wet Tropics bioregions, where the total number of records increased by several orders of magnitude. While Brush-turkey records increased over time in the Brigalow Belt South, Nandewar, and New England Tablelands bioregions, the number of records in these regions did not increase at a comparable rate to the four previously mentioned bioregions. This may be due to a lower human population in these areas, and hence fewer sightings, or it may indicate a smaller Brush-turkey population.

Brush-turkeys ceased to be reported from multiple bioregions, indicating the long-term local extinction of this species from those areas. Three of these bioregions, Cobar Peneplain, South Western Slopes (NSW), and Riverina are at the southwestern edge of the species’ distribution. A fourth bioregion, Desert Uplands, is to the northwest of their range. Previous research suggested that Brush-turkey numbers were in decline in these areas (Göth et al., 2006), including the threatened population in the Nandewar and Brigalow Belt South bioregions (DPIE, 2017). Previous studies have estimated that a third of the overall suitable habitat for Brush-turkeys has been cleared, with the most significant loss (61%) occurring in the Brigalow Belt North and South regions (Simmonds et al., 2019). Predation from introduced cats and foxes, as well as overhunting by humans have also been suggested as possible explanations for Brush-turkeys’ population and range decline (Göth & Vogel, 2002; Jones & Göth, 2008). It is likely that habitat loss, predation, and hunting have all contributed to the observed range contractions.

Estimation of the Brush-turkey range, and associated changes to the population, was considerably more difficult for earlier time periods due to the scarcity of records. Older records were primarily based on opportunistic reporting, incidental observations, museum specimens, and records collected from various published and unpublished literature. The first concerted national survey of Australian birds was conducted between 1977-1981 for the first Atlas of Australian Birds (Blakers, Reilly, & Davies, 1984). It is likely that our data, based on records prior to this survey, underestimated the Brush-turkey range for these
time periods. Additionally, some uncertainty exists for records prior to 1960. While all records used in this study included an exact date and coordinates, this was often based on the central point of a grid or locality for many records prior to the introduction of GPS technology (1980’s). The continental scale used in this study may also obscure population changes at a local scale. Despite these limitations, the presence and absence of records at the scale of entire bioregions can be clearly observed with the data used in this study. We can thus be confident of the broad scale changes in the Brush-turkey distribution.

### 4.2 Urban Distribution Trends

Prior to the 1960s, Brush-turkey records were conspicuously absent from Sydney and Brisbane, despite the existence of records from other parts of the Sydney Basin and South Eastern Queensland bioregions. Anecdotal evidence suggests that the species did occur in these areas prior to European colonisation and prior to the 20th century (Jones & Göth, 2008) and this aligns with the species existence in neighbouring bioregions. This indicates that Brush-turkeys became locally extinct around these urban centres prior to their return across both cities from the mid-1960s.

The rapid increase in Brush-turkey observations in the inner suburbs of Brisbane and Sydney in the 2000-2019 period counters an earlier suggestion that cities may act as ecological traps for the species due to reduced reproductive success in urban areas (Jones & Everding, 1991). The total number of suburbs occupied in both cities has greatly increased over the last 20 years, continuing previously identified trends (Göth et al., 2006; Jones et al., 2004), and our results show that Brush-turkey occupied suburbs have become less vegetated and more built-up over time: more urban. Part of this change is due to changing land use within previously occupied suburbs, however the majority of this change has been driven by a rapid, more than tenfold, increase in the total suburban area occupied by the species across both cities. More recently colonised suburbs have been overall less vegetated and more developed than earlier colonised suburbs. This trend is likely to continue as Brush-turkeys colonise new suburbs that are more remote from source populations in rural and natural areas at the city edge.

Emigration from populations in natural areas, translocations, and recruitment from local nesting have all been suggested as mechanisms for dispersal into suburban areas (Jones & Everding, 1991). Our results support the idea that new arrivals from non-urban populations are likely to be a source of replenishment for Brush-turkey populations in suburbs adjacent to bushland (Jones et al., 2004). Older occupied suburbs are geographically closer to non-urban Brush-turkey records in both Brisbane and Sydney. However, the importance of colonisation from non-urban populations likely diminishes in inner-city suburbs that are more distant from natural woodland areas. In these areas, the dense urban matrix constrains dispersal making movement from distant areas more difficult (Canedoli, Manenti, & Padoa-Schioppa, 2018; Fischer & Lindenmayer, 2007). Brush-turkeys have been reported to have a high juvenile mortality rate (Göth & Vogel, 2002), however their continued spread across Brisbane and Sydney indicates that urban breeding success is not only maintaining the population but sufficient to support the expansion of the population. While we anticipate that Brush-turkeys will continue to spread into currently unoccupied urban suburbs and increase in density, it remains to be seen if they will spread from the cities into unoccupied neighbouring vegetation. However, the establishment of a thriving Brush-turkey
population after introduction on Kangaroo Island (Jones and Göth, 2008) demonstrates the versatility and adaptability of the species in novel environments, making this a strong possibility.

On the surface, Brush-turkeys do not fit the profile of the typical successful urban dwelling bird. Their ground nesting, lack of parental care, and poor flight abilities contrast with the off-ground nesting and high dispersal ability (through flight) common to most successful urban birds (see Bressler et al., 2020; Evans, Chamberlain, Hatchwell, Gregory, & Gaston, 2011; Moller, 2009). However, they have a generalist omnivorous diet (Jones & Göth, 2008), and have been observed feeding on novel food resources including introduced plants and anthropogenic food sources (Brookes, 1919; D. N. Jones & Everding, 1991). Brush-turkeys are also considered to be a highly disturbance tolerant species (Blumstein, 2006), and show reduced fear behaviour in urban areas compared to reserves and natural bushland (Hall et al., 2020). A generalist diet and increased boldness are common traits among urban birds (Callaghan, Major, et al., 2019; Moller, 2008) and likely help the species colonise and persist in urban areas where disturbances and unnatural food sources are common. This suggests that a species may only need a few urban suitable traits to thrive in urban areas under the correct conditions; this highlights that a wider list of candidate species may be able to effectively colonise cities.

The increasing movement of Brush-turkeys into less vegetated suburbs will likely lead to more frequent encounters with suburban residents. Proximity of wildlife and humans can occasionally lead to situations of human-wildlife conflict, particularly in urban areas (Soulsbury & White, 2015). Brush-turkey presence in suburban areas has resulted in complaints from residents in response to damage to gardens caused by foraging and the construction of 3 tonne nest mounds, both of which involve raking soil and leaf litter (Jones & Everding, 1991). Complaints regarding chasing pets and small children, stealing food, noise, and fouling have also been reported (Jones & Göth, 2008), leading to calls for the management of predominantly urban Brush-turkey populations. While Brush-turkeys are not considered to be a threatened species across their distribution, their apparent decline in the western and southwestern ends of their range necessitates careful consideration when managing their population in urban areas. Further surveys of the connectivity between urban and non-urban Brush-turkey populations are needed to determine the importance of urban habitats as refugia for the species.

4.3 Limitations of Atlas and Citizen Science Data

The dramatic increase in the number of Brush-turkey records in the new millennium is facilitated by the creation of citizen science projects and community uptake of smartphone apps and online platforms for reporting wildlife observations (Pocock, Tweddle, Savage, Robinson, & Roy, 2017). Data sourced from citizen science projects can contain limitations, specifically concerns around data quality, uneven participation rates, and observer bias (Brown & Williams, 2019; Tulloch, Possingham, Joseph, Szabo, & Martin, 2013). However, there is a growing body of evidence that citizen science generated data can be of comparable quality to data generated by professional researchers (Callaghan et al., 2020; Gollan, Lobry de Bruyn, Reid, & Wilkie, 2012), can contain considerable amounts of ecological information (Hall et al., 2021), and can be used to answer a variety of research questions (McKinley et al., 2017). Two of the top three sources of Brush-turkey records in this study were citizen science projects eBird (Sullivan et al.,
2009) and Big City Birds (Hall et al., 2021), while the third, the OEH Atlas of NSW Wildlife, receives significant contributions from citizen scientists (DPIE, 2021). This trend suggests that greater insights into the Brush-turkey population, including finer scale presence and habitat preferences, will be possible over the next 20-years with increasing citizen science participation.

A particular challenge of observing trends using citizen science data is disentangling a biological signal from the effects of human population and the accompanying spatial and temporal clustering of observations (Isaac et al., 2014). The greatest increase in the number of Brush-turkey reports was in the Sydney Basin and Southeast Queensland bioregions. These areas also have the highest human population densities within the Brush-turkey range (ABS, 2021). Importantly, irrespective of the accessibility of reporting sightings, it is clear from the data that Brush-turkeys have spread across urban Brisbane and Sydney over recent decades. However, the upwards trend in the number of observations appears to begin in some bioregions as early as the 1960s, where modern technologies to assist citizen scientists did not exist. Given the increasing availability of methods and technology to record and report observations, the complete absence of Brush-turkey records from some bioregions in the 2000-2019 period is strong evidence that the species is rare or absent from these areas, including the regions where they were historically observed.

5. Conclusions

Understanding how species distributions have changed over time and in response to human derived land use change is foundational to inform their management and conservation, as well as predicting how they will respond to future landscape changes. Using a blend of historic records, ecological surveys, and citizen science data our study determined that the Brush-turkey has undergone a complex range shift over the past century, disappearing from the edges of their range in the southwest while recolonising the heavily modified urban areas on the Australian east coast. Over the last sixty years, the species has successfully colonised more built-up and less vegetated areas of Brisbane and Sydney. The Brush-turkey has become an incredibly successful urban dwelling species, despite its specialised reproductive strategy and poor dispersal ability, broadening scientific understanding of the traits that can characterise successful city dwelling wildlife. Future research should focus the following areas: tracking finer scale distribution changes for the species at continental and city scales, particularly at the edges of their range; determining the drivers behind Brush-turkey declines in the western parts of their range and expansion in urban areas; and quantifying Brush-turkey responses to different land uses within urban areas.

Declarations

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Figures

Figure 1

Density of Australian Brush-turkey records in each occupied bioregion (IBRA 7), within the estimated 2019 species range (black line). Only parts of the bioregion containing Brush-turkey records are shown. Darker shading indicates a greater number of records. Single records were excluded. Data downloaded from the Atlas of Living Australia and the Big City Birds citizen science project. Basemap layer credits: ESRI, USGS, NOAA
Figure 2

Suburbs occupied by Australian Brush-turkey for each 5-year interval (1960-2019) in the cities of Brisbane and Sydney. Data downloaded from the Atlas of Living Australia and the Big City Birds citizen science project.

Figure 3

Percentage of Australian Brush-turkey records from each occupied suburb in Brisbane (a-c) and Sydney (d-f) from 1960-1979, 1980-1999, and 2000-2019. Darker shading indicates a greater proportion of records. White areas indicate no records. Individual records outside the city boundary are shown as blue dots. Inset map shows the location of Brisbane (black) and Sydney (white). Data downloaded from the
Atlas of Living Australia and the Big City Birds citizen science project. Basemap layer credits: ESRI, USGS, NOAA

Figure 4

Total suburban area occupied by Brush-turkeys in a) Brisbane and Sydney, and changes in the proportion of land use in Brush-turkey occupied suburbs of b) Brisbane and c) Sydney. Data downloaded from the
Atlas of Living Australia and the Big City Birds citizen science project. Basemap layer credits: ESRI, USGS, NOAA

**Figure 5**

Eastern Australian Bioregions containing Brush-turkey atlas records after data processing and filtering. Bioregions are labelled by code (Table S1). Bioregion layer downloaded from the Australian Government, Department of Agriculture, Water and Environment website (DAWE, 2020). Basemap credits: ESRI, USGS, NOAA.