Ecoacoustic monitoring of the endangered Pink Cockatoo (*Lophochroa leadbeateri leadbeateri*) in arid and semi-arid eastern Australia: insights into spatial and temporal patterns and distribution.

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Abstract

The eastern Pink Cockatoo (*Lophochroa leadbeateri leadbeateri*) faces significant threats in arid and semi-arid Australia due to habitat loss, habitat degradation and climate change. Despite being an iconic 'outback' endangered species, a substantial knowledge gap exists regarding the environmental drivers of temporal and spatial patterns in habitat use. Traditional bird survey methods are difficult to implement in remote drylands due to logistical challenges and high costs. In this research project, passive acoustic monitoring and automated species recognition of calls were utilised to address this knowledge gap.

Two complementary studies were conducted. The first, a six-month study at Bowra Wildlife Sanctuary in western Queensland, focused on the relationship between habitat characteristics and Pink Cockatoo distribution. It examined how call detections varied with vegetation type, vegetation greenness, temperature, and rainfall, providing insights into habitat preferences and key resource availability. The second study, spanning 20 months across Bowra Wildlife Sanctuary, Naree Station, and Fowler's Gap, took a broader approach by investigating temporal changes in Pink Cockatoo activity in response to environmental variability, particularly rainfall, temperature and vegetation greenness.

Findings from the spatio-temporal study indicated higher Pink Cockatoo call detections near permanent water sources and in habitats with larger trees, which are critical for nesting. While there was a significant positive relationship between call detections and River Red Gum and Coolabah habitats, Pink Cockatoos also demonstrated consistent use of the diverse habitat types available at Bowra Wildlife Sanctuary. The 20-month analysis revealed that following a severe drought (2017-2019), riparian zones served as vital refugia, supporting cockatoo populations during resource scarcity. An increase in rainfall, possibly influenced by La Niña conditions, was associated with a decrease in Pink Cockatoo detections in the monitored areas. This pattern may suggest that the birds dispersed across the broader landscape in response to the improved resource availability, or it could indicate that the population had not recovered from the severe drought, which potentially affected their survival or breeding success. There were no detections at Fowler's Gap, the only arid site in the study, and this may indicate a shrinking of their distribution due to increased climate extreme events in an already harsh environment.

In total, these results reinforce the importance of conserving heterogeneous habitats, including riparian zones and mature trees, to ensure the resilience of Pink Cockatoo populations and their ability to adapt to an increasingly variable climate.

Keywords

Passive acoustic monitoring, automated species recognition, Pink Cockatoo, *Lophochroa leadbeateri*, temporal patterns, spatial distribution, semi-arid Mulga Lands, western Queensland, western New South Wales, habitat use, rainfall, temperature, vegetation greenness, vegetation communities, conservation strategies, cavity-nesting birds, riparian zones, threatened species

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Chapter 1: Introduction

1.1 Climate Change and Avian Extinction

Mean land temperatures around the world have increased by 1.53 °C from 1850-1900 to 2006-2015 (IPCC, 2022). This has caused an increase in the occurrence, intensity, and length of heat-related events such as heatwaves and droughts (Greenville et al., 2018). Globally, higher land temperatures, reduced rainfall, and intensified human activities like land clearing and fragmentation have contributed to desertification, including in arid regions of Australia (IPCC, 2022). By the end of the 21st century, over 72% of the Earth's landmass is predicted to experience aridification, with arid and semi-arid regions predicted to expand by approximately 10% (Tabari, 2020).

Semi-arid landscapes, especially at ecotones, are expected to experience extreme and rapid vegetation shifts under future climate change scenarios (Allen & Breshears, 1998). Increased tree mortality associated with prolonged droughts and elevated temperatures is anticipated in forests worldwide (Allen et al., 2010) and can trigger large-scale vegetation shifts (Adams et al., 2009). Such vegetation shifts can alter ecosystem structure, leading to reduced availability and quality of habitats for wildlife, increased opportunities for invasive species, and modifications to the hydrological cycle (Gonzalez et al., 2010). In response to the shifting of suitable habitats, many species' distributions are changing to accommodate their unique environmental and resource requirements (Pecl et al., 2017). While this range shift may benefit some species by expanding their resource base under changed climatic conditions, it can be detrimental for others due to increased competition for resources, higher predation risks, or decreased mating opportunities (Soravia et al., 2021).

As a result of climate change and the constant degradation, fragmentation and destruction of natural landscapes, the Earth is facing an extinction crisis (Lee et al., 2015; Runge et al., 2015; Ward et al., 2022). Approximately 44% of Australian native forests and woodlands have been lost since European colonization (Ward et al., 2022). Furthermore, 163 bird species are listed as threatened under Australia's Environment Protection and Biodiversity Conservation Act 1999, with many at risk of extinction over the next 20

years, and 22 classified as already extinct (Commonwealth of Australia, 2024). Olah et al. (2016) explains that birds in the order Psittaciformes (parrots) are likely to be more vulnerable as they exhibit some of the known traits associated with extinction, such as having large body sizes and slower breeding rates (e.g., cockatoos), and most of them are ecologically specialised (e.g., forest-dependent and hollow-nesting). Globally, 28% of parrot species are classified as threatened under the IUCN Red List (Olah et al., 2016).

Understanding the ecological requirements of parrots and identifying the factors that make them vulnerable to climate change and human pressures is crucial for their conservation (Renton et al., 2015). Vegetation clearing and habitat degradation can significantly impact woodland and forest-dependent bird species (Olah et al., 2016). Parrots typically rely on pre-existing cavities for nesting, and their reproductive success depends on the availability and quality of these nest sites (Dénes et al., 2018). The Swift Parrot (*Lathamus discolor*) is a secondary cavity nester that breeds in Tasmania and migrates to woodlands of south-east Australia (Stojanovic et al., 2012). The quality of habitat for nomadic migrants, such as the Swift Parrot, depends on the availability and overlap of resources (e.g., food resources) and functional habitats (e.g., nesting sites; Webb. et al, 2017). In resource-dependant species, any small loss of habitat can have profound effects on breeding (Webb. et al, 2017). The Swift Parrot is endangered due to habitat clearing and degradation, climate change and high predation by sugar gliders (Saunders & Tzaros, 2011). Another species, the King Island Green Rosella (*Platycercus caledonicus brownii*), was recently uplisted from vulnerable to endangered after the lifting of a moratorium on land clearing (Garnett, 2021).

In addition to living in highly disturbed landscapes, birds must also cope with a changing climate. Shifts in weather patterns and climate have influenced the distribution, reproductive success, survival, and behaviour of numerous bird species (Chambers et al., 2005; Kearney et al., 2016). The vulnerability to climate change increases significantly as the habitat range of the species declines (Lee et al., 2015; Mac Nally et al., 2009). Certain species are especially susceptible to the effects of extreme weather events, including droughts, cyclones and floods (Chambers et al., 2005). For example, increased heat waves due to climate change have been correlated with mass mortality events in birds around the world and can lead to the extinction of entire species (Andreasson et al., 2020). In another example, the Paradise Parrot (*Psephotellus pulcherrimus*) has been declared extinct, with

the most likely causes of its loss thought to be habitat degradation combined with severe drought and loss of seasonal foods (native grass seeds) that it relied on (McGregor, 2021). Extreme weather events also led to the recent listing of the Wet Tropics Australian King-Parrot (*Alisterus scapularis minor*) and the Cape York Eclectus Parrot (*Eclectus polychloros macgillivrayi*) as endangered, as they experienced rapid declines due to direct mortality then loss of nesting trees and food shortages after cyclones (Garnett, 2021).

1.2 The Australian Climate

The El Niño- Southern Oscillation (ENSO) has a strong influence on the climate in Australia (Beaumont et al., 2015). During El Niño phases, Australia experiences drier and hotter conditions and during La Niña there is a significant increase in precipitation (Duursma et al., 2018). ENSO influences vegetation growth by affecting the regional climatic conditions, with rain and temperature being most important (Hao et al., 2020), particularly in semi-arid and arid (dryland) ecosystems (Wang et al., 2022). As a result, vegetation communities in these dryland ecosystems are well-adapted to low and sporadic rainfall, and exhibit intermittent resource pulses triggered by rainfall events (Gorta et al., 2023). Intermittent resource pulses cause fluctuations between brief intervals of resource abundance and extended durations of resource scarcity or absence (Kletter et al., 2009).

Resource pulses in these landscapes can generate an influx of nomadic bird species that take advantage of the abundance of resources, such as seeds, grains, flowers and fruits (Gibson et al., 2022). This has also been reported by Pascoe et al. (2021) who found changes in the abundance of birds were correlated with rainfall events. However, Pavey and Nano (2009) identified that during a period of unusually high rainfall, habitat type had a stronger influence on the ability of birds to forage and breed than spatial gradients of water and food. Their study, which focused solely on spatial variation and was conducted during an exceptionally high rainfall period, did not capture the dynamics of bird distribution and abundance during times of water scarcity. In addition to rainfall, other ecological requirements such as the availability of shelter and breeding sites drive bird population abundance and distribution during resource-abundant periods (Craig et al., 2022; Pavey & Nano, 2009). For example, riverine woodlands have a high abundance of hollow-bearing trees and high grass cover, making this vegetation preferred by cavity-nesting species and granivores such as parrots (Pavey & Nano, 2009). The high level of

habitat specificity reported by Pavey and Nano (2009) further demonstrates the importance of understanding both functional habitat requirements and temporal dynamics in population abundance for the conservation of threatened species (Webb et al. 2017).

Recent reports indicate that the intensity of weather events driven by ENSO cycles has become more severe due to climate change (Connell et al., 2022). In dryland ecosystems, increased temperatures exacerbate existing conditions, leading to reduced foraging rates, decreased growth rates, and lower reproductive success in birds (Andreasson et al., 2020). Additionally, the introduction of exotic herbivores, such as goats, sheep and rabbits in dryland Australia, has substantially impacted the recruitment and survival of various perennial plant species, affecting the structural diversity of vegetation and resources that are available for arid zone birds (Belder et al., 2022; Davies et al., 2010).

Biological events during a bird species' life cycle, such as migration, breeding and moulting, typically coincide with suitable environmental conditions and optimal resource availability (Beaumont et al., 2015; Duursma et al., 2018). Chambers (2008) found that lower precipitation and slight warming led to earlier breeding and fewer eggs produced by the Helmeted Honeyeater (*Lichenostomus melanops cassidix*) in south-east Australia. The breeding productivity of the Glossy Black Cockatoos (*Calyptorhynchus lathami*) in New South Wales was positively correlated to rainfall patterns, likely due to the effects of rainfall on the abundance of their main food source, *Allocasuarina* cones (Cameron, 2009). Mastrantonis et al. (2019) reported that variation in breeding productivity of the Forest Red-tailed Black Cockatoo (*Calyptorhynchus banksii naso*) in Western Australia was linked to changes in food availability resulting from rainfall patterns. Furthermore, Rowley and Chapman (1991) found that hot and dry weather during late spring in years with below-average rainfall led to the early maturation of annual plants, creating a scarcity of seeds with high moisture content during the crucial second half of the Pink Cockatoo nestling period. Elevated temperatures, low humidity, and decreased moisture in the food provided to hatchlings are thought to contribute to nestling mortality among Pink Cockatoos due to dehydration during particularly dry years (Rowley & Chapman, 1991). In hot and dry environments, breeding birds struggle to engage in normal thermoregulating behaviours while incubating (such as finding shade or alternating drinking and foraging behaviours) and end up leaving the nest, risking the survival of the hatchlings (Bourne et al., 2021).

While these studies highlight the critical role of climatic drivers like rainfall and temperature on bird population dynamics, there is a need for long-term ecological studies to fully understand the effects of extreme fluctuations in precipitation and temperature on biota and phenological cycles (Greenville et al., 2018). Such comprehensive research is essential for developing effective conservation strategies that can mitigate the adverse impacts of climate change on bird populations in Australia's dryland ecosystems.

1.3 Biodiversity Monitoring in Dryland Ecosystems

Quantifying the effects of resource changes on species biology and ecology in dryland ecosystems presents significant challenges due to the remote and often inaccessible nature of these regions, which can be both difficult and costly to access. These challenges can be overcome using autonomous or passive monitoring devices (such as acoustic sensors) which can be deployed and left to record in the field over extended periods. In recent years, acoustic monitoring has grown in popularity due to the availability of low-cost sensors (Krause & Farina, 2016). As a result, acoustic sensors can expand the capabilities of monitoring populations over time and space and have been used with success to detect changes in species' distribution patterns, abundance and phenology (Sugai & Llusia, 2019).

Acoustic sensors generate a permanent record of environmental sounds during the survey period, allowing for verification by multiple observers and minimizing observer bias (Smith et al., 2020). Although these sensors capture all types of sounds (biological, earth-driven, and anthropogenic), ecologists primarily focus on animal vocalizations, as they provide valuable insights into the ecological requirements of species (Sugai et al., 2019). Sound waves can travel in various directions, penetrate obstacles, and cover long distances, making animal vocalizations more readily detectable compared to traditional fauna surveys (Sugai et al., 2019). Moreover, acoustic monitoring is non-invasive, with little impact on wildlife, making it suitable for long-term studies that generate substantial datasets with minimal equipment maintenance (Smith et al., 2020). Advances in technology have further facilitated the processing of these vast acoustic datasets through artificial intelligence algorithms designed to identify specific animal species and their calls (Sharma et al., 2023).

1.4 Acoustic Monitoring of Pink Cockatoos

The Pink Cockatoo, an iconic Australian parrot, inhabits a wide range of arid and semi-arid woodlands throughout Australia (Higgins & Al-Dabbagh, 1999). Two subspecies have been described based on the pattern of the crest and body size (Ewart et al., 2021). One subspecies, the eastern Pink Cockatoo (*Lophochroa leadbeateri leadbeateri)*, is found on the east side of the Eyrean Barrier (South Australia), while the second subspecies, *L. l. mollis*, is distributed west and north of the Eyrean Barrier (Ewart et al., 2021). This semi-nomadic species forms large flocks that forage over wide areas (Rowley & Chapman, 1991) but return to the same breeding grounds each year (Higgins & Al-Dabbagh, 1999). Unlike fully nomadic species that undertake large-scale movements in direct response to resource availability, these flocks tend to remain within a relatively confined region of approximately 300 km^2 (Rowley & Chapman, 1991). They exhibit localized movement patterns, maintaining a continuous presence within specific areas rather than engaging in widespread nomadic dispersal (Rowley & Chapman, 1991).

Pink Cockatoos are unable to excavate their own hollows for nesting, making them highly dependent on large old trees (Hurley & Harris, 2014). Increased habitat clearing and fragmentation, especially of old growth vegetation, have negatively impacted the breeding success of this species (Hurley, 2022). Furthermore, overgrazing by livestock (sheep *Ovis aries*, cattle *Bos taurus*) and grazing by invasive herbivores such as feral goats (*Capra hircus*) and rabbits (*Oryctolagus cuniculus*), along with localised overabundant populations of kangaroos (*Macropus spp*.), have severely limited the establishment of new large hollow-bearing trees over the past century (Australian Government, 2023).

Pink Cockatoos are social birds that forage in large groups (10-50 individuals), even while nesting, but pairs will not nest in close proximity to each other (Rowley & Chapman, 1991). Therefore, in fragmented landscapes where vegetation has been cleared and only small, unconnected patches of habitat remain, it is unlikely that a breeding population will be able to persist. Another threat to Pink Cockatoos is poaching of eggs and hatchlings which usually results in the destruction of nests (Forshaw, 2002). Feral cats may pose a threat to Pink Cockatoos by preying on eggs, chicks, or even adult birds. These combined factors have likely contributed to a significant decline in Pink Cockatoo

numbers, leading to the eastern subspecies being listed as endangered in March 2023 under the Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth of Australia, 2024).

Currently, little is known about the ecology of Pink Cockatoos in Queensland and New South Wales. Research on this species has primarily taken place in Western Australia and Victoria, providing insights into their nesting preferences and habitat requirements in those regions. Specifically, only two scientific studies have been published on Pink Cockatoos in Western Australia (Rowley & Chapman, 1991; Smith & Rowley, 1995) and several government reports exist based on studies in Victoria (Hurley, 2006; Hurley, 2015; Hurley, 2022; Hurley & Harris, 2014). In Western Australia, Rowley and Chapman (1991) found that Pink Cockatoos exclusively nested in salmon gums (*Eucalyptus salmonphloia*), with nests spaced an average of 2,309 m apart and a minimum distance of 1000 m. In Victoria, long-term studies have documented that Pink Cockatoos primarily nest in tree hollows of Slender Cypress Pine (*Callitris gracilis;* Hurley, 2006). Nesting trees had an average height of 10.3 m (minimum 6 m) and an average diameter at breast height (DBH) of 73.1 cm (minimum 30 cm; Hurley, 2006). Cavity entrance dimensions averaged 13.3 cm in width (minimum 9 cm), with cavity heights ranging from 9 cm to 80 cm, and the trees used were estimated to be at least 200 years old (Hurley, 2006). Competition from Galahs (*Eolophus roseicapilla*), which use similar nesting hollows, has been identified as a significant threat to Pink Cockatoo nesting success in Victoria (Hurley, 2006).

Geographic variation in tree species use for nesting by parrots has been reported, as have changes in preferred tree species over time due to habitat clearing (Renton et al., 2015). Most species of parrots select tree-cavity nests that meet certain requirements such as cavity height above the ground, tree size, entrance width, cavity depth and thermal profile of the hollow (Renton et al., 2015; Hurley & Harris, 2016). Renton et al. (2015) found that these characteristics are selected by parrots to reduce competition and predation risk. In Wyperfeld National Park, Victoria, many years of conservation monitoring have been dedicated to understanding the habitat and ecological requirements of Pink Cockatoos (Hurley, 2022). Management strategies developed from these studies have aimed to increase Pink Cockatoo abundance and reduce competition for nesting sites by controlling Galah populations and installing artificial nests (Hurley, 2022). These efforts appear to

have been effective, as the highest number of Pink Cockatoo pairs occupying tree cavities since 1999 was reported in 2022, suggesting that these conservation measures have had a positive impact on their population (Hurley, 2022).

To effectively protect Pink Cockatoos and their habitats in Queensland and New South Wales, knowledge of their distribution, habitat use, and ecological requirements is essential. Queensland and New South Wales are critical for the conservation of the eastern Pink Cockatoo, as these regions encompass the core of their distribution, providing essential breeding and foraging habitats. Conducting traditional bird observational surveys in the remote dryland ecosystems of eastern Australia presents significant challenges due to high costs, logistical complexities, and limited human resources. Additionally, detection probabilities for threatened species are often low (Garrard, 2015), exacerbating these challenges. In this context, passive acoustic monitoring is a robust and effective method for conducting extensive surveys across both spatial and temporal scales. Understanding a species' movement patterns in response to fluctuating resource availability is critical for informing targeted conservation strategies (Stojanovic, 2017; Gorta, 2023). This is particularly important for species inhabiting ecosystems characterized by irregular rainfall and intermittent resource pulses, conditions that are projected to become even more erratic with the intensification of extreme weather events driven by climate change (Tischler et al., 2013). Additionally, extensive agricultural activities, such as land clearing and livestock grazing, have substantially altered these landscapes, further exacerbating resource scarcity and habitat fragmentation (Thompson & Eldridge, 2005).

1.5 Research Aim

The aim of this research was to investigate the spatial and temporal distribution of the endangered eastern Pink Cockatoo in semi-arid and arid dryland ecosystems of western Queensland and New South Wales using passive acoustic monitoring. The spatio-temporal component of the study examined Pink Cockatoo call detections across different vegetation communities at Bowra Wildlife Sanctuary (located west of Cunnamulla in the Mulga Lands Bioregion) from May to November 2023, assessing the effects of vegetation type, distance to permanent water, vegetation greenness, temperature, and rainfall on their spatial distribution. The temporal component focused on examining Pink Cockatoo call

detections in relation to climate variables (precipitation, temperature, and vegetation greenness) across three sanctuaries—Naree Station, Bowra Wildlife Sanctuary, and Fowler's Gap—in semi-arid and arid eastern Australia, spanning from September 2019 to April 2021. Due to the limited ecological knowledge of Pink Cockatoos in Queensland and New South Wales, the findings of this research will be crucial for informing future conservation management strategies for this threatened species.

Specifically, the study addresses the following research questions:

- Does the spatio-temporal distribution of Pink Cockatoos vary across different vegetation types and environmental characteristics at a local scale?
- Do Pink Cockatoo call detections vary over time according to changes in rainfall, temperature and vegetation greenness across a broader geographic and temporal scale?

Chapter 2: Spatio-temporal Habitat Use by Pink Cockatoos at Bowra

2.1 Introduction

Semi-arid landscapes are characterized by spatial heterogeneity, a feature increasingly impacted by land use changes and vegetation clearing (Maestre et al., 2012; Price et al., 2013). These landscapes experience intermittent resource pulses due to irregular rainfall patterns, leading to fluctuating availability of water and food resources (Jordan et al., 2017; Schneider & Griesser, 2009). Birds inhabiting semi-arid landscapes respond differently to such fluctuations: some exhibit nomadic movements to track resource availability, while others, like the Pink Cockatoo, endure by relying on their extensive knowledge of food and watering places (Rowley & Chapman, 1991).

Previous research on avian species in semi-arid ecosystems has established the importance of distance to water, large trees, and habitat complexity in providing critical resources for birds (Chesson et al., 2004; Dunkerley & Brown, 1995; Jordan et al., 2017; Pascoe et al., 2021). For cavity-nesting species like the Pink Cockatoo, large, old trees provide essential nesting sites, while proximity to water sources is vital for survival in dryland ecosystems (Gibson & Florentine, 2008; Rowley & Chapman, 1991). However, the specific environmental variables that influence the spatio-temporal distribution of Pink Cockatoos in Queensland, such as the types of vegetation they use for foraging or nesting or the impact of fluctuating rainfall and temperature, remain poorly understood.

Understanding how the endangered eastern Pink Cockatoo utilizes heterogeneous semi-arid landscape and copes with resource variability is essential for effective conservation, especially given the additional pressures from habitat loss and climate change (Harris et al., 2018; Kutt et al., 2012; Smith, 2015). Bowra Wildlife Sanctuary offers a unique opportunity to explore the spatial distribution of Pink Cockatoos in semi-arid western Queensland because it has a diversity of vegetation communities, it has several permanent water sources and Pink Cockatoos are regularly recorded on the sanctuary. Given the remote location of Bowra Wildlife Sanctuary and the logistical constraints this imposed,

this study used passive acoustic monitoring of Pink Cockatoo vocalizations to examine the spatio-temporal distribution of this endangered iconic species.

2.2 Methods

2.2.1 Study Location

Bowra Wildlife Sanctuary (hereafter Bowra), managed by the Australian Wildlife Conservancy, is in the Mulga Lands bioregion of semi-arid south-west Queensland. Bowra encompasses approximately 14,000 hectares and is characterized by a diversity (14) of regional ecosystems (Stanton et al., 2019). Bowra receives an average annual rainfall of 373 mm. Temperatures range from a minimum monthly average of 1.5°C in winter to a maximum monthly average of 41.7°C in summer (Bureau of Meteorology, 2024). The sanctuary is renowned for its rich biodiversity, providing habitat for over 200 bird species, including several threatened species (Australian Wildlife Conservancy, 2023)

2.2.2 Data Collection

AudioMoth acoustic sensors (Hill et al., 2018) were placed at 22 sites across eight different vegetation communities dominated by Coolabah (*Eucalyptus coolabah*), Cypress (*Callitris glaucophylla*), Gidgee (*Acacia cambagei*), Mulga (*Acacia aneura*), Poplar Box (*Eucalyptus populnea*), River Red Gum (*Eucalyptus camaldulensis*), Whitewood (*Atalaya hemiglauca*), as well as shrublands and grasslands. Sampling was stratified based on vegetation community, with between two and four sensors located in each vegetation community type (2 in Coolabah, 2 in River Red Gum+/- Coolabah, 3 in Cypress, 2 in Mulga, 3 in Poplar Box, 3 in Gidgee, 3 in shrubland/grassland, and 4 in Whitewood; Figure 1). This approach was designed to maximize coverage of the various vegetation communities found in the sanctuary, allowing a better understanding of habitat use by Pink Cockatoos across the landscape.

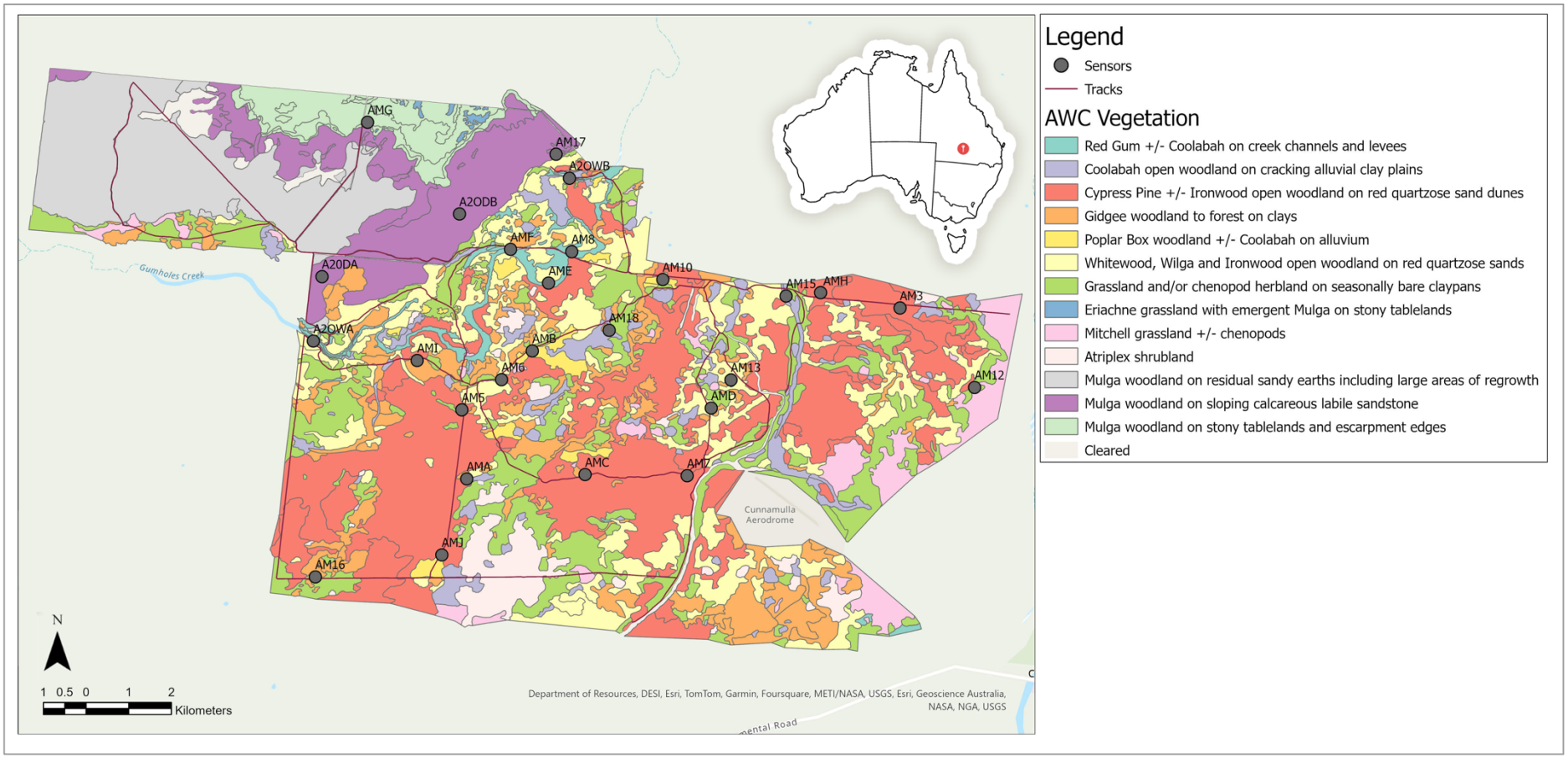

Figure 1. Vegetation map of Bowra Wildlife Sanctuary including acoustic sensor locations (grey circles). Inset map depicts location of Bowra Wildlife Sanctuary in south-west Queensland, Australia.

Due to the remote location of Bowra Wildlife Sanctuary, optimizing battery consumption and minimizing sensor servicing were crucial considerations. Therefore, the sensors were configured to record four hours a day: from 7:00 to 10:00 am and 4:30 to 5:30 pm between 22nd May 2023 and 26th September 2023, and from 6:00 to 9:00 am and 4:30 to 5:30 pm from 27th September 2023 to 20th November 2023. These time frames were selected based on analysis of Pink Cockatoo vocalizations from previous recordings at Bowra, using both AudioMoths and Australian Acoustic Observatory sensors (hereafter A2O; https://acousticobservatory.org/; Roe et al., 2021; data not shown). The AudioMoth sensors were programmed with a sampling rate of 32 kHz, providing a balance between capturing sufficient detail (since Pink Cockatoo vocalizations range up to 15 kHz) and conserving memory and battery life, making it suitable for extended field recordings.

The sensors were positioned at least 200 m apart to prevent overlap and ensure data independence. This decision was based on previous acoustic research undertaken at Bowra, which reported that AudioMoths could capture sounds emitted up to 100 m from the sensor (Scarpelli et al., 2022). Incidental observations of Pink Cockatoos using binoculars were made each time sensors were serviced (battery and SD card changes approximately every eight weeks). Birds were not approached within 30 m, and observations were made from vehicles or along designated walking tracks according to QUT Animal Ethics Clearance (AE OS 2023-6734-12465) and DES Resources Permit (P-PTUKI-100385773) approval conditions.

Acoustic data were also collected from four solar-powered BAR (Frontier Labs) sensors located at Bowra as part of the Australian Acoustic Observatory. The A2O sensors have a sampling rate of 22 kHz and record continuously. Two sensors were in Mulga and two in River Red Gum +/- Coolabah vegetation. Data from these recorders were analysed for the same dates and times as those from the AudioMoth sensors.

2.2.3 Spatial Variables

A range of spatial variables were examined in this study. These variables relate to environmental factors that were measured at a single point in time during the study and remained relatively constant throughout the research period.

2.2.3.1 Vegetation Field Surveys

At every sensor site a single-point-in-time perennial vegetation survey was undertaken using the line-intercept method (National Committee on Soil and Terrain, 2009), with four line transects of 25 m length located along the cardinal points around each sensor. The purpose of this survey was to identify tree and shrub species, their height, canopy and subcanopy cover (visual estimates) and tree diameter at breast height (DBH). Each shrub and tree that intercepted each of the four transects per site was measured and identified. The vegetation surveys took place between 25th and 29th September 2023 and 15th and 16th March 2024. A complete description of the variables measured can be found in Appendix A and the vegetation type per site according to the surveys is in Appendix B.

2.2.3.2 Vegetation Map Analysis

To analyse vegetation heterogeneity at each site, ArcGIS Pro v.2.7.0 (ESRI, 2011) was used to create and rasterise a 250 m radius circular buffer around each sensor, overlayed on the Australian Wildlife Conservancy (AWC) vegetation map (Stanton et al., 2019). This map is a vector layer that was created in 1994 by the Australian Wildlife Conservancy using aerial photography at a scale of 1:80,000, and later in 2015 the north-west area was re-mapped using 1:30,000 scale aerial photography (Figure 1). The map categorises vegetation and geology into broad habitat types. The percentage of each habitat type was calculated in each buffer per sensor, and is detailed in Appendix C.

2.2.3.3 Vegetation Type versus Habitat Type

The vegetation type refers to the predominant vegetation identified at each site through the on-ground vegetation surveys, representing a localized scale of vegetation characterization. In contrast, the habitat type is derived from the AWC vegetation map, which provides broader-scale habitat classifications, typically mapped at a larger scale (e.g., 1:80,000). Due to the differing scales of these assessments, some sites may exhibit variations between their vegetation type and habitat type, as the local vegetation identified during surveys did not always align with the broader habitat classifications from the AWC map.

2.2.3.4 Distance to Permanent Water

To understand the relationship between Pink Cockatoo call detections and proximity to water, the distance from each sensor to the nearest permanent water source was measured using ArcGIS. At the time of the study, the sanctuary had three permanent water sources: one artificial lagoon and two sections of a creek that retained water year-round. Although these two sections are part of the same creek system, they are separated by stretches that are ephemeral and do not consistently contain water. By calculating the distance to these permanent water sites, the study aimed to assess whether the distribution of Pink Cockatoos was influenced by their proximity to reliable water availability.

2.2.4 Temporal Variables

Temporal variables examined in this study relate to the environmental factors that change over the timeframe of the study.

2.2.4.1 Remote Sensing of Satellite Imagery

To assess the influence of vegetation productivity on Pink Cockatoo activity, fractional cover estimates were calculated from monthly VegMachine fractional cover datasets (30 m per-pixel resolution) covering the entire study period for each individual acoustic sensor using a buffer of 250 m (Beutel et al., 2019). The fractional cover datasets were derived from Landsat reflectance data that has been geometrically and radiometrically corrected using standard protocols (Flood, 2017). Cloud and cloud shadow were masked using the Fmask algorithm by selecting only images with less than 1% cloud cover to reduce the impact of undetected clouds and shadows (Flood, 2017). Fractional cover is estimated by dividing each pixel into a proportion of photosynthetic vegetation, non-photosynthetic vegetation and bare ground (Joint Remote Sensing Research Program, 2022). In this study, photosynthetic vegetation (hereafter vegetation greenness) was used.

2.2.4.2 Rainfall and Temperature

To assess the influence of climatic variables on Pink Cockatoos, rainfall and maximum temperature data were sourced from SILO (Jeffrey et al., 2001), an Australian database of climate data hosted by the Queensland Department of Environment, Science, and Innovation (DESI). SILO provides interpolated point data generated from meteorological

station records, using data from over 8,000 stations across Australia (Queensland Government, 2023). The dataset has a spatial resolution of approximately 5 km^2 and includes daily climate variables (Queensland Government, 2023). The use of interpolated data ensures coverage even in areas where direct measurements may not be available, although it introduces some uncertainty compared to direct station-based observations (Jeffrey et al., 2001). Monthly average rainfall and cumulative rainfall for three, six, and twelve months were calculated for each sensor location to compare the effects of different time lags on Pink Cockatoo call activity (Runge, 2015).

2.2.5 Behavioural Observations

While acoustic monitoring allows for the detection of the presence of Pink Cockatoos based on their calls, it does not provide information about their behaviours, or the number of individuals present. To supplement the acoustic data, AWC asked visitors at Bowra from June to August 2023 to complete a hardcopy 'visitor sheet' each time a Pink Cockatoo was seen. Visitors noted how many Pink Cockatoos were present, the date and time, observed behaviours, and the location on a map. Using ArcGIS Pro, these data were transferred to digital maps for each month, showing the locations, activities, and numbers of Pink Cockatoos spotted.

2.2.6 Acoustic data analysis

2.2.6.1 Training and Testing of the Pink Cockatoo Acoustic Recogniser

A Pink Cockatoo convolutional neural network recogniser was developed in January 2023 by Dr Lance De Vine from the Ecoacoustics team at QUT. The recogniser was built using a simple convolutional neural network with four convolutional layers without residual connections, implemented through the C++ interface to PyTorch, known as libtorch. The training process began with an initial dataset, and the network was trained until no further improvement in loss was observed. Additional training data, consisting of false positives and true positives, was then incorporated to refine the model. This cycle of training and data augmentation was repeated until the recogniser achieved the desired precision objective of over 90% accuracy. The audio spectrograms were constructed using a Fast Fourier Transform (FFT) window size of 512, covering a frequency range of 0–8 kHz. A time window of 2.5 seconds was applied, with a 50% overlap between consecutive

windows to enhance temporal resolution. This recogniser was trained using recordings from 13 AudioMoth sensors deployed for eight weeks at Bowra in September 2022. Recordings were listened to and segments of 2.5 seconds, with and without Pink Cockatoo calls, were clipped in Raven Pro v1.6.5 (hereafter Raven, https://www.ravensoundsoftware.com/) and uploaded into the recogniser software for training. A total of 37 true positive segments and 407 false positive segments were used in the training of the recogniser.

2.2.6.2 Acoustic Data Processing and Validation

A total of 18,928 hours of recordings were processed using the recogniser, with all detections manually verified. Verification involved reviewing 60 second segments using a colour scale spectrogram view. The spectrogram settings were configured with a focus of 2,132, brightness at 47, and contrast at 52. These settings provided the clearest visual representation of Pink Cockatoo calls during manual verification. From each detection, each call was counted individually (e.g., detection #4 in Figure 2 has three Pink Cockatoo calls). Fly-over calls (a distinct pattern of gradual intensification followed by a decline) and faint calls detected by the recogniser were not counted to avoid including calls made outside of the vegetation type in which the sensor was located.

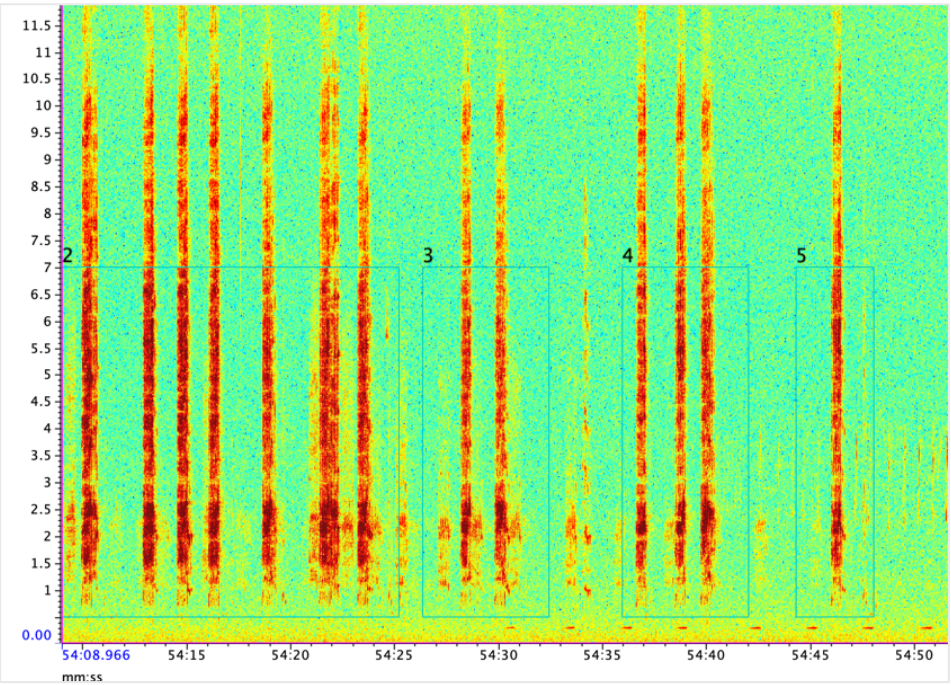

Figure 2. Spectrogram showing Pink Cockatoo detections. X axis showing time (minute:seconds) and Y axis showing kHz. Blue rectangles show the detections generated by the recogniser.

To validate the recogniser's performance, recall, precision, and F1 scores were calculated on a dataset of 100 hours of manually verified recordings, using the following formulas (Priyadarshani et al., 2018):

- Recall = TP / (TP + FN)
- Precision = TP / (TP + FP)
- F1 Score = 2 × (Precision × Recall) / (Precision + Recall)

In these formulas, TP represents the number of true positives (correctly identified Pink Cockatoo detections), FP denotes false positives (instances where the recogniser incorrectly identified a detection), and FN signifies false negatives (cases where the recogniser missed a Pink Cockatoo detection when there was one).

For spatial data analysis, the total number of Pink Cockatoo calls recorded over the entire study period was utilized. It should be noted that two sites, A2ODA (Mulga) and AMJ (Poplar), did not record data for one of the four deployments. However, these sites exhibited very low Pink Cockatoo detections, and the limited amount of missing data is unlikely to affect the overall analysis.

The study was conducted from 20th May to 20th November 2023, resulting in partial recording periods for both May and November. Therefore, for the temporal analysis, a detection rate was calculated to account for variations in the days of recordings for each month as well as missed recordings. This was done by dividing the total number of calls by the effective number of recording days for each month. Each day consisted of four hours of recording; therefore, the number of recording days was adjusted based on the available recording time. For instance, if a recorder was operational for only two hours on a particular day, this was accounted for as 0.5 effective days.

2.2.7 Statistical Modelling

All statistical analyses were performed using R statistical software (R Core Team, 2021).

2.2.7.1 Variation in Pink Cockatoo Detections Across Vegetation Types

As the data were not normally distributed (Shapiro-Wilk test, $W = 0.526$, $p < 0.001$), non-parametric Kruskal-Wallis tests (from 'base' package) were used to evaluate whether Pink Cockatoo detections varied across vegetation types. The response variable was the total sum of Pink Cockatoo calls in each vegetation type, and the independent variable was vegetation type (Appendix B).

2.2.7.2 Relationship Between Pink Cockatoo Detections and Environmental Variables

Four distinct sets of models were developed to assess the influence of environmental and temporal variables on Pink Cockatoo detections. This approach was necessary to avoid overfitting due to the relatively high number of variables compared to the number of survey sites. The first model set assessed the relationship between Pink Cockatoo calls and landscape characteristics (e.g., tree and shrub cover, distance to permanent water). The second model set focused on Pink Cockatoo calls in relation to the percentage of each habitat type per site. The third model set investigated vegetation characteristics (e.g., tree and shrub height, DBH), and the fourth model set explored the association between Pink Cockatoo calls and temporal variables.

A multivariate Poisson regression model was initially applied to check for overdispersion. Due to overdispersion in the data, Generalized Linear Mixed Models (GLMMs) were used instead, incorporating site as a random effect (via the 'lme4' package in R; Bates, 2015). The response variable was the total number of calls per site for spatial models (sets 1, 2 and 3), and the detection rate per day per site for the temporal models (set 4).

The independent variables were 16 spatio-temporal datasets (Table 1), which were scaled using a min-max normalisation to account for substantial variation in the distributions of values across the different explanatory variables. Model fit was assessed by comparing each GLMM with a null model, and model selection was performed using the MuMIn package to identify the best-fitting models. Following Burnham and Anderson (2002), the best-supported model(s) was determined as the model(s) within 2 ΔAIC of the lowest AIC and that models within 7 ΔAIC had partial support. Goodness-of-fit was measured using marginal R^2 and likelihood ratio tests (Burnham & Anderson, 2002). Model assumptions

were checked using diagnostic plots and tests for multicollinearity and autocorrelation (packages: 'corrplot', 'car', 'DHARMa', 'stats').

Table 1. Description of environmental variables used in the statistical modelling

Variable	***Description***	***Type***
Spatial		
DBH	Average diameter at breast height (cm)	Continuous
Canopy cover	Total canopy cover per site (percentage)	Continuous
Sub-canopy cover	Total sub-canopy cover per site (percentage)	Continuous
Shrub cover	Total shrub cover per site (percentage)	Continuous
Tree height	Average tree height per site (m)	Continuous
Shrub height	Average shrub height per site (cm)	Continuous
Vegetation type	Vegetation types obtained from vegetation surveys (Coolabah, Cypress, Gidgee, Grassland, Shrubland, Poplar, River Red Gum and Whitewood)	Categorical
% Habitat type	Percentage of different habitat types per site obtained with ArcGIS from the AWC vegetation map	Continuous
Habitat type/site	Number of different habitat types per site	Discrete
Distance to permanent water	Distance measured from site to closest permanent water (m)	Continuous
Temporal		
Rainfall monthly average	Average monthly rainfall (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous month	Cumulative rainfall previous month (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 3 months	Cumulative rainfall previous 3 months (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 6 months	Cumulative rainfall previous 6 months (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 1 year	Cumulative rainfall previous year (mm), calculated from daily rainfall from SILO	Continuous
Maximum monthly temperature	Maximum average monthly temperature (C°) calculated from daily maximum temperature from SILO	Continuous

Fractional cover	Percentage of photosynthetic vegetation obtained from Vegmachine	Continuous

2.3 Results

2.3.1 Acoustic Results

The final version of the Pink Cockatoo recogniser used in this study had a precision of 99%, a recall of 52%, and an F1 score of 68%. This indicates that the recogniser accurately identified Pink Cockatoo detections (i.e. rarely confused /mistakenly identified calls or sounds made by another species e.g. goat), but the low recall meant that true calls were sometimes missed.

In total, 7,871 Pink Cockatoo detections were found in 18,928 hours of recordings, across 26 sensors, and over the six-month period of the study. The data indicated a peak in detections during May, followed by September and June. This pattern suggests monthly variation in Pink Cockatoo calling behaviour, with increased detections at different times of the year (Figure 3).

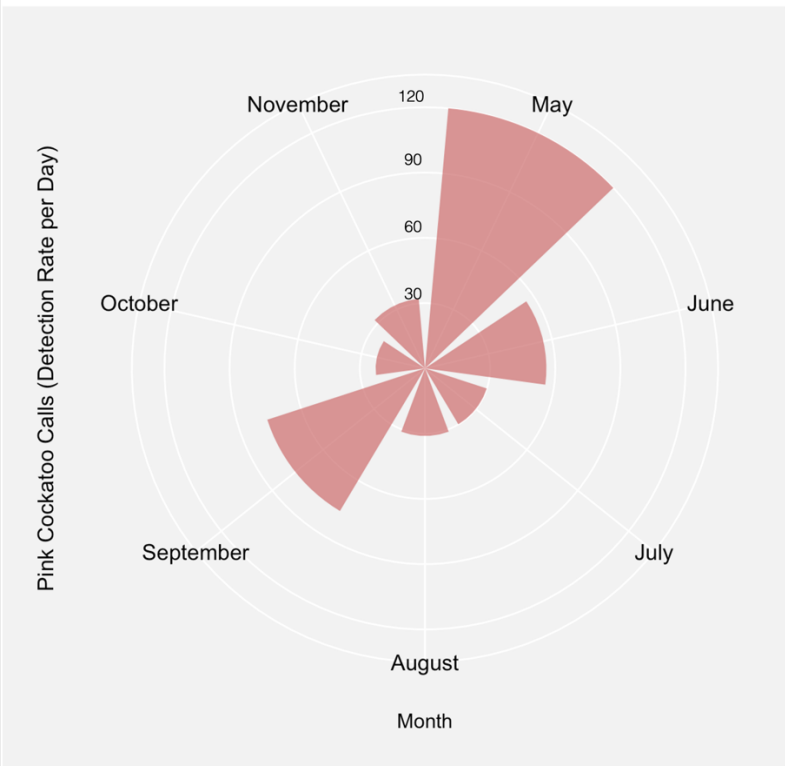

Figure 3. Monthly distribution of Pink Cockatoo calls from May to November 2023, across the 26 sensors at the Bowra Wildlife Sanctuary. The y-axis (in the middle of the graph) indicates the detection rate per day, summed for all sites.

2.3.2 Relationship Between Pink Cockatoo Detections and Vegetation Type

In May, 76% of all the calls were detected at one site located in Coolabah vegetation (A2OWB). Similarly, in June, 64% of all calls came from the same site (A2OWB). In September, 38% of all calls were detected in Cypress vegetation (AMH), with the remaining detections spread across a variety of other vegetation types. However, the total number of detections did not differ significantly between vegetation types (Kruskal-Wallis chi-squared = 12.21, df = 7, $p > 0.05$).

2.3.3 Relationship Between Pink Cockatoo Detections and Environmental Variables

The summary statistics for the mean, standard deviation, and range of both spatial and temporal variables are provided in Table 2.

Table 2. Summary statistics for spatial and temporal variables relevant to Pink Cockatoo activity, including overall mean, standard deviation, and range. Variables include measurements of vegetation structure, distance to permanent water, rainfall metrics, and temperature data

Variable	*Overall Mean*	*Standard Deviation*	*Range (min to max)*
Spatial			
DBH (cm)	34.69	21.93	1 to 200
Canopy cover (m)	27.24	20.41	0 to 70.40
Sub-canopy cover (m)	5.14	6.37	0 to 21
Shrub cover (m)	9.42	9.79	0 to 38.10
Tree height (m)	8.24	2.85	3.2 to 19.50
Shrub height (m)	1.66	0.70	1 to 3
Distance to permanent water (m)	2352.90	1769.42	3.70 to 5790
Temporal			
Rainfall monthly average (mm)	0.53	0.76	0 to 2.77
Rainfall cumulative previous month (mm)	16.03	21.67	0 to 91.2
Rainfall cumulative previous 3 months (mm)	74.17	18.86	46.80 to 114.30
Rainfall cumulative previous 6 months (mm)	89.63	23.64	52.50 to 141.50
Rainfall cumulative previous 1 year (mm)	341.61	117.40	152 to 487.4

Maximum monthly temperature (°C)	33.07	5.32	27.30 to 41.70
Fractional cover (%)	16.56	5.76	5 to 33

2.3.3.1 Pink Cockatoo Detections in Relation to Landscape Characteristics

The GLMM that best explained variation in Pink Cockatoo detections was the model including only distance to permanent water (AIC=340.01, R^2m=0.37; Table 3). This subset model outperformed the full landscape model with all variables, which included canopy cover, sub-canopy cover, shrub cover, and distance to permanent water (AIC = 344.9, R^2m = 0.43, Appendix D). Distance to permanent water had a significant negative effect on the total number of Pink Cockatoo detections (Estimate +/- SE =-0.964 +/- 0.257, z=-3.75, p<0.001; R^2m=0.37; Table 3; Figure 4).

Table 3. Parameters for the four best-supported models of total detections of Pink Cockatoos and different environmental variables, showing the effect size, standard error (SE), z-score and p-value for each variable in the model, and the degrees of freedom (d.f.), AIC and marginal R2 (R2m) for each model.

Model	***Environmental Variable (fixed effect)***	***Effect size***	***SE***	***z-score***	***p-value***	***d.f.***	***AIC***	***R^2m***
Subset of landscape model	Distance permanent water	-0.964	0.257	-3.75	0.0002	22	340.01	0.37
Subset of vegetation model	Tree DBH average	0.813	0.281	2.897	0.004	22	343.9	0.26
Full landscape model	Canopy cover total	0.179	0.269	0.665	0.506	19	344.9	0.45
	Sub-canopy cover total	0.063	0.298	0.211	0.833			
	Shrub cover total	-0.160	0.263	-0.609	0.542			
	Distance permanent water	-0.924	0.257	-3.591	0.000			
Subset of %habitat model	River Red Gum +/- Coolabah (% habitat type)	0.648	0.293	2.209	0.027	22	346.8	0.16
Null		4.67	0.318	14.74	2e-16	23	349.3	0.99

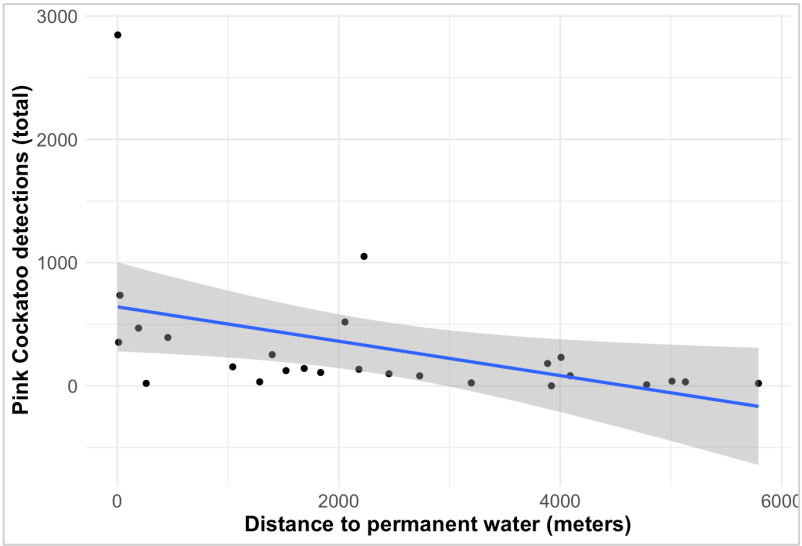

Figure 4. Predicted relationship between Pink Cockatoo detections (total) and distance to permanent water (meters) at Bowra Wildlife Sanctuary. Line shown is the prediction from the GLMM +/- 95% confidence intervals.

2.3.3.2 Pink Cockatoo Detections in Relation to Vegetation Characteristics

The second-best supported model was average tree DBH, with an AIC value of 343.9, which is higher than the best model's AIC of 340.01. The difference between the two models (ΔAIC = 3.89) falls within the 7 AIC unit threshold, indicating partial support for this model (Burnham and Anderson, 2002). The analysis revealed that larger (average DBH) trees were associated with an increased number of Pink Cockatoo detections (Estimate +/- SE = 0.813 +/- 0.281, $p = <0.05$, $R^2m = 0.26$; Table 3; Figure 5).

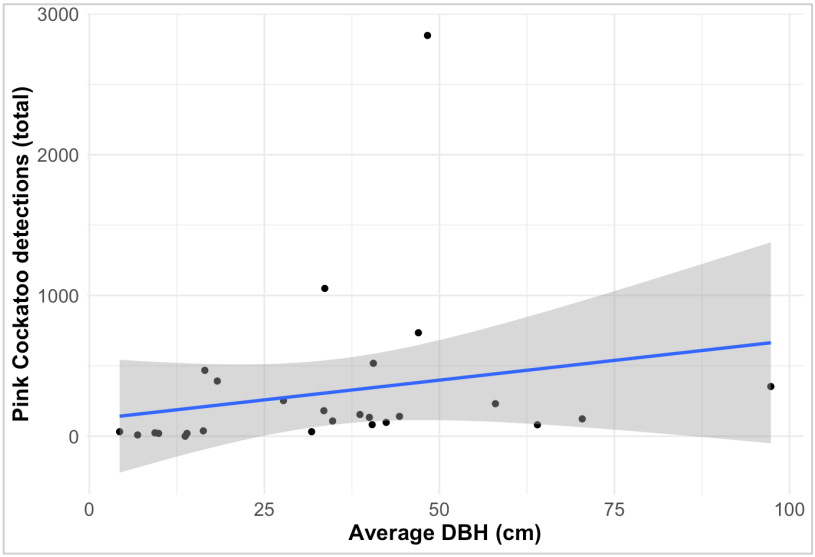

Figure 5. Predicted relationship between average diameter at breast height (DBH) and Pink Cockatoo detections (total). Line shown is the prediction from the GLMM +/- 95% confidence intervals.

2.3.3.3 Pink Cockatoo Detections in Relation to Percentage Habitat Type

The best-supported habitat model included only the River Red Gum ± Coolabah habitat type (AIC = 346.8, R^2m = 0.16; Table 3). The analysis revealed that this habitat type had a significant and positive effect on the total number of Pink Cockatoo detections (Estimate ± SE = 0.648 ± 0.293, p = <0.05 R^2m = 0.16; Table 3; Figure 6). This model falls within 7 AIC units from the best model (ΔAIC = 6.79) and is therefore partially supported. This habitat-specific model also outperformed the total model (AIC = 358.7, R^2m = 0.34; Appendix D), which included all habitat types (habitat type/site, Cypress, Whitewood, Coolabah, Grassland, Gidgee, Red Gum ± Coolabah, Mulga, and Poplar), emphasizing the importance of River Red Gum ± Coolabah habitat for Pink Cockatoos. The full model including canopy cover, sub-canopy cover, shrub cover, average tree DBH, average tree and shrub height was not supported (Appendix D).

In all GLMMs analysed, the R^2c (conditional) remained high at 0.99, indicating that site-specific factors significantly contribute to explaining the variability in Pink Cockatoo calls.

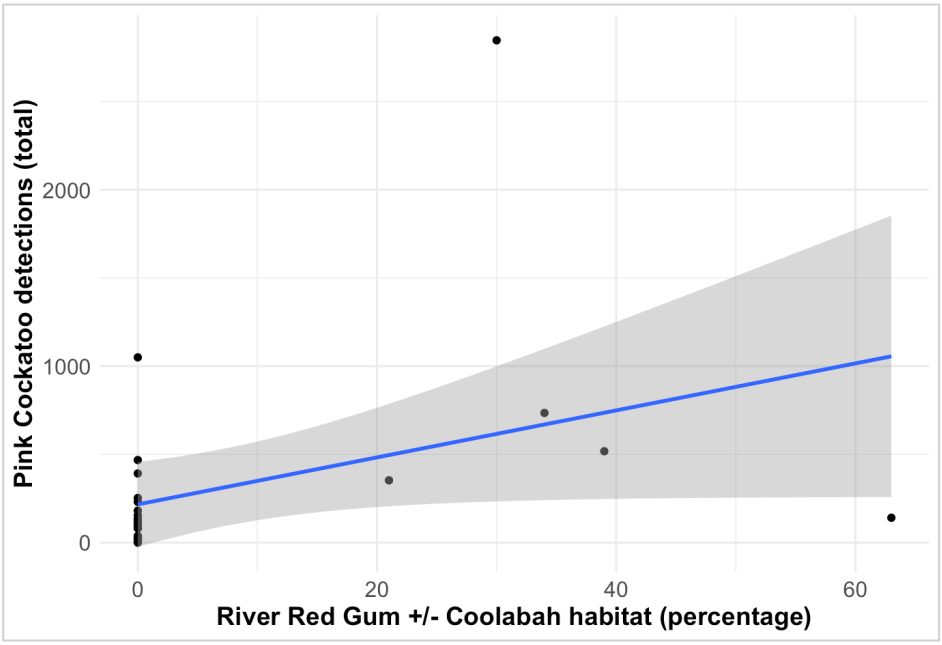

Figure 6. Predicted relationship between River Red Gum +/- Coolabah (% habitat type) and Pink Cockatoo detections (total) at Bowra Wildlife Sanctuary. Line shown is the prediction from the GLMM +/- 95% confidence intervals.

2.3.3.4 Pink Cockatoo Detections and Temporal Variables

Several significant correlations were identified among the temporal variables. The strongest negative correlation was between cumulative rainfall over the previous year and maximum temperature ($r = -0.96$, $df = 178$, $p < 0.001$). Cumulative rainfall over the previous 3 and 6 months exhibited a very high positive correlation ($r = 0.95$, $df = 178$, $p < 0.001$) and monthly average rainfall showed a strong positive correlation with cumulative rainfall from the previous month ($r = 0.88$, $df = 178$, $p < 0.001$). The full correlation matrix can be found on Appendix E. To address these multicollinearity issues, various simplified models with variables being iteratively removed were compared. None of the models showed significant effects, indicating that total Pink Cockatoo detections were not related to recent rainfall, temperatures or vegetation productivity (Appendix F).

2.3.4 Visitor Sheets

Bowra Wildlife Sanctuary is a popular birdwatching destination, particularly in areas with easy access, which may introduce some bias in the locations where Pink Cockatoo sightings were recorded.

In June 2023, 16 visitor sheets were collected describing the activity of 208 Pink Cockatoo sightings. Most of these observations were concentrated in the northern part of the sanctuary (Appendix G), particularly around the 'Mulga Walk,' a popular site for birdwatching due to its accessibility and rich birdlife. The most frequently recorded activity was foraging (Figure 7a). Flocks ranging from 10 to 23 birds were observed on seven occasions.

In July, eight visitor sheets were completed, documenting the activity of 70 Pink Cockatoos. The most frequently observed activity was foraging (Figure 7b). Aside from one large flock of 30 birds foraging on wild orange (*Capparis mitchellii*) and another flock of nine birds, smaller groups of two to three birds were more commonly recorded.

In August, seven visitor sheets were collected, detailing the activity of 51 Pink Cockatoos. One flock of 14 birds was observed, while all other sightings involved small groups of two to five individuals. A significant shift of Pink Cockatoo activity was observed in August, when perching became the dominant behaviour and time observed foraging was greatly reduced (Figure 7c).

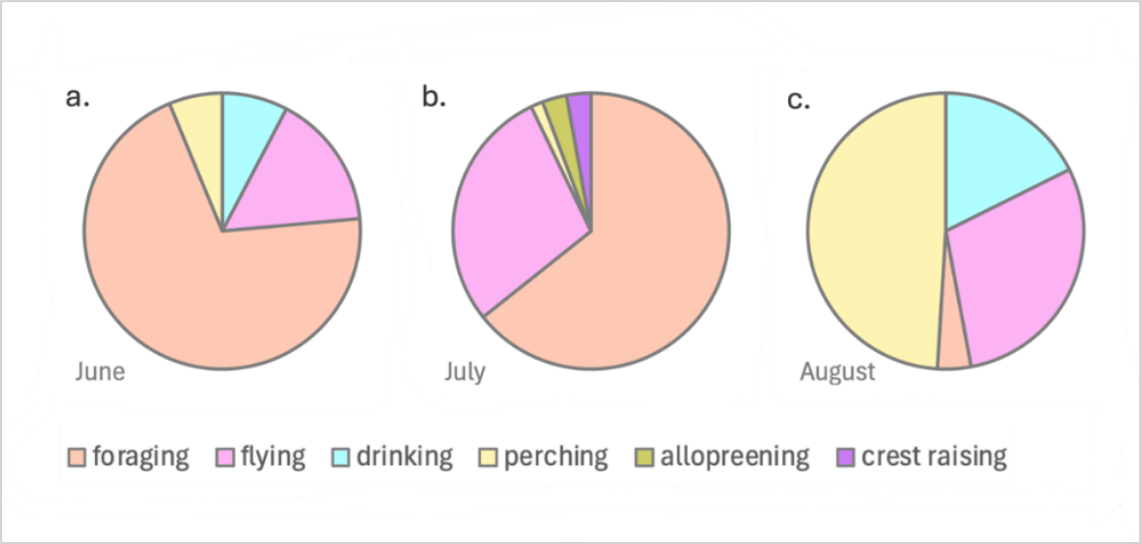

Figure 7. Comparison of the activity of Pink Cockatoos in June (a.), July (b.) and August (c.) in 2023, obtained from the visitor sheets collected at Bowra.

2.3.5 Incidental Observations

Pink Cockatoos were observed foraging on fruits and seeds from several plant species in the sanctuary, including White Cypress (*Callitris glaucophylia*), Umbrella Wattle (*Acacia oswaldii*), *Plantago cunninghamii, Tetragonia moorei*, wild orange (*Capparis mitchellii*), and *Eremophila mitchellii*.

In August and September of 2023, Pink Cockatoos were seen inspecting hollows in Whitewood, River Red Gum, and Coolabah trees. In September 2023, a Pink Cockatoo nesting hollow was found on the northern side of the property within a Coolabah tree (Figure 8). Two additional hollows were discovered in September 2024: one in a Whitewood tree (Figure 9) and the other in a dead Eucalyptus species, either a Coolabah or a River Red Gum (Figure 10).

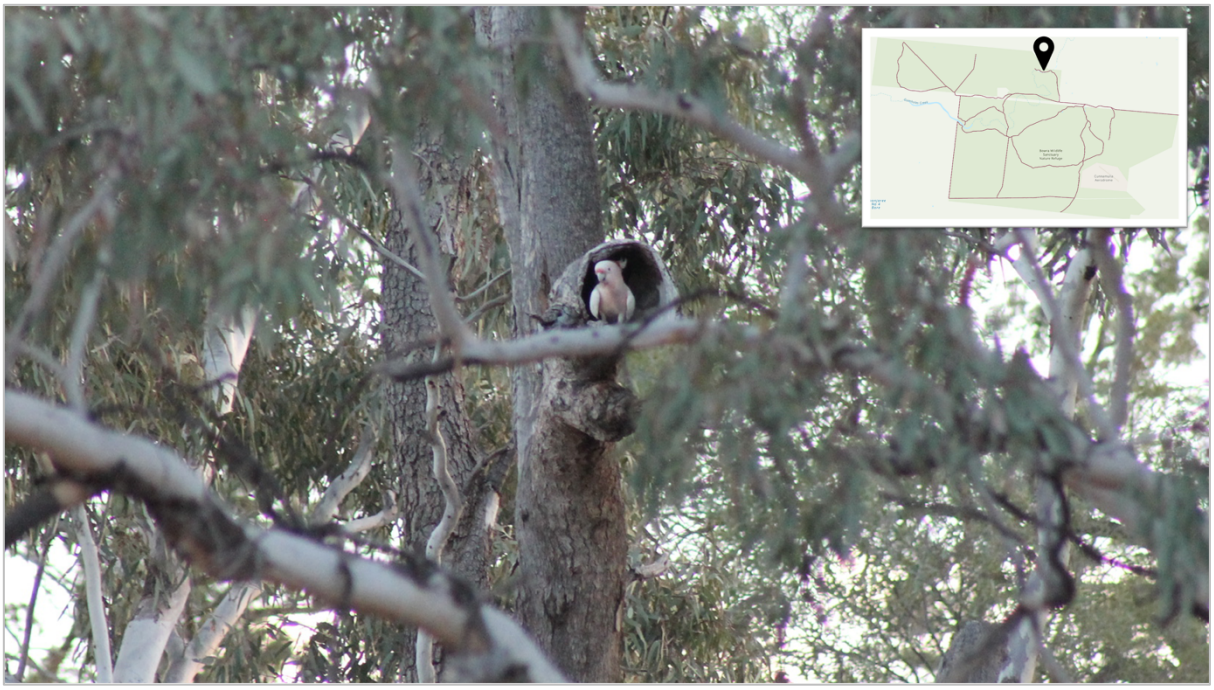

Figure 8. Pink Cockatoo at the front of the hollow in a Coolabah tree at Bowra Wildlife Sanctuary, September 2023. Photo credit: Aidan Bowes-McKee.

Figure 9. Pink Cockatoo nest hollow in a Whitewood tree (Atalaya hemiglauca) at Bowra Wildlife Sanctuary, September 2024. a. Close up image of the hollow in which the Pink Cockatoo is poking out from the nest. b. Whitewood tree in which the hollow is located. c. Map showing the location of the Whitewood tree hollow in the Sanctuary.

Figure 10. Pink Cockatoo nest hollow in a Eucalyptus sp. tree at Bowra Wildlife Sanctuary, September 2024. a. Close up image of the hollow in which two Pink Cockatoos are seen in the nest. b. Eucalyptus sp. tree in which the hollow is located. c. Map showing the location of the Eucalyptus sp. tree hollow in the Sanctuary.

2.4 Discussion

2.4.1 Distance to Permanent Water

A significant finding of this study was the strong influence of proximity to permanent water on Pink Cockatoo detections. The sanctuary's permanent water sources consist of one artificial lagoon and a creek traversing two sites. Two of the three most active sites for Pink Cockatoo detections were located near these permanent water sources, specifically within riparian zones. Riparian zones are productive ecosystems due to greater water availability and nutrient-rich soils (Ramey & Richardson, 2017). These areas support a diverse and abundant array of vegetation and a higher abundance of terrestrial invertebrates, providing essential food resources for a wide range of species (Ramey & Richardson, 2017), especially in semi-arid environments where critical resources are often scarce across the broader landscape (Schneider & Griesser, 2009; Selwood et al., 2015).

Previous studies in dryland ecosystems underscore the significance of riparian zones for avian species due to increased water availability, structural vegetation complexity, and enhanced resource productivity (Fleishman et al., 2003; Kingston et al., 2002; Schneider & Griesser, 2009; Westerhuis et al., 2020). For example, Kingston et al. (2002) found that over 50 % of bird species in the Mulga Lands of south-west Queensland were more abundant in riparian zones. Similarly, higher bird species richness and abundance have been reported in eucalypt woodlands and creek line habitats within riparian zones compared to adjacent areas, as these habitats provide diverse feeding opportunities, nesting sites, roosting areas, drinking locations, and protection from predators (Smith, 2015; Tischler et al., 2013).These findings suggest that the structural complexity and resource availability associated with riparian areas may provide the specific nesting and foraging requirements of Pink Cockatoos at Bowra.

Proximity to water and resources may be critical for breeding success (Craig et al., 2022; Rowley & Chapman, 1991). Rowley and Chapman (1991) observed that Pink Cockatoo fledglings stayed close to the nest until all their siblings were ready to leave, a process that can take anywhere from three days to two weeks. During this time, parents must access water and provide food for both the nestlings and fledglings simultaneously, highlighting the importance of nearby water and food for their survival (Rowley &

Chapman, 1991). The availability of key resources is a crucial factor influencing where many species choose to establish their nests (Craig et al., 2022; Webb. et al, 2017). For instance, Swift Parrots (*Lathamus discolor*) select nesting sites where essential functional habitats overlap, and Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*) have shown a preference for nesting hollows situated near permanent water sources (Craig et al., 2022; Stojanovic et al., 2012). This pattern may also apply to Pink Cockatoos, as three hollows were found in proximity to water and food sources. One hollow was found in a Whitewood tree, close to the permanent bore-fed lagoon and feeding resources including Native Orange, White Cypress trees and *Eremophila* shrubs. A second hollow was found in a Coolabah tree, adjacent to the creek and close to White Cypress habitat and open clay pan areas, in which they have been observed foraging in the past. Lastly, the third hollow was found in a dead *Eucalyptus* tree (Coolabah or River Red Gum) next to the creek. These observations suggest that Pink Cockatoos may be selecting nesting sites based on the resources available in the surrounding habitat rather than solely on tree species as has been documented in other regions. In Victoria, Hurley (2006) observed Pink Cockatoos exclusively nesting in Cypress Pine (*Callitris gracilis*), while in Western Australia, Rowley and Chapman (1991) noted Pink Cockatoos exclusively nested in Salmon Gum (*Eucalyptus salmonophloia*).

Results also indicate temporal variation in Pink Cockatoo detections across locations sampled in this study, that were not driven by temporal variation in weather or vegetation productivity. Kingston et al., (2002) reported that only a small number of bird species were exclusively found in riparian habitat in the Mulga Lands, suggesting that riparian areas might be utilized to fulfill specific needs rather than serving as the sole habitat for most species. This is consistent with our findings in which Pink Cockatoo detections fluctuated across the sanctuary, with more detections in riparian areas in the months of May-July and November. Furthermore, visitor observations revealed that at one of the sites located within a riparian zone, Pink Cockatoo activity shifted from predominantly foraging in larger flocks during June and July to mostly perching in pairs by August. These changes in behaviour over different times of the year suggest that riparian areas might serve multiple purposes for Pink Cockatoos, functioning as foraging sites during certain periods and as breeding territories during others.

Some studies have highlighted the role of riparian zones as dry refugia for wildlife during drought conditions (Kingston et al., 2002; Reside et al., 2019; Selwood et al., 2015). However, this was not observed in this study. During the drier months of August to October, Pink Cockatoo detections did not increase in riparian areas but rather increased in other habitat types. This could be related to the above-average rainfall from the previous year (609.2 mm), which may have produced plentiful resources throughout the sanctuary, masking the importance of dry refugia in Bowra during the dryer months (Holmgren et al., 2006). These results align with those of Selwood et al. (2015), who found that annual variations in rainfall and temperature did not directly correlate with species decline in riparian and floodplain areas, but rather the succession of low rainfall years had a cumulative effect on populations due to its impact on resource availability. Similarly, Votto et al. (2023) observed that use of waterholes by most species did not vary significantly between drier and wetter summers, suggesting that access to food resources at the waterholes may play a more influential role in determining their usage. Thus, while riparian areas can serve as critical refugia in certain contexts, their role may vary depending on environmental conditions such as rainfall patterns, which can influence resource distribution across habitats.

2.4.2 Habitat Type

2.4.2.1 River Red Gum +/- Coolabah Habitat

Eight different habitat types were selected to investigate the habitat use of Pink Cockatoos across the semi-arid Bowra landscape. The results revealed a significant positive relationship between Pink Cockatoo detections and River Red Gum +/- Coolabah habitat. These findings are consistent with those of Westerhuis et al. (2020) that documented higher bird abundances in River Red Gum habitats within semi-arid landscapes, irrespective of periods of high rainfall or drought. Other studies have shown habitat specificity in birds: Schodde (1994) found that 64 % of terrestrial bird species in inland eastern Australia are found in just one or two primary habitats, with only a limited number of species distributed across more than three habitats. Cody (2001) reported a regular and stable presence of specific bird groups in mulga vegetation across arid and semi-arid Australia, and Pavey and Nano (2009) identified strong habitat specificity (especially in chenopod, riverine woodland and mulga open shrublands), despite fluctuations in resources during high rainfall periods.

Rainfall plays a fundamental role in influencing the availability of resources and shaping the constitution of avian assemblages (Pascoe et al., 2021; Tischler et al., 2013). While seasonal phenological changes in vegetation can affect bird species distribution, there remains a core group of bird species that consistently depend on the amount and quality of habitat available in the landscape, regardless of seasonal changes (Brambilla & Saporetti, 2014; Price et al., 2013). In semi-arid Australia, River Red Gum woodlands found along ephemeral river channels are regarded as essential habitats for a variety of bird species, largely because of their unique structural features, expansive canopies, and abundance of tree hollows (Westerhuis et al., 2020). The presence of large trees with potential nesting hollows near water sources probably creates an optimal environment for both foraging and breeding, thereby explaining the elevated Pink Cockatoo detections observed in these habitats.

It is likely that distance to permanent water and the presence of River Red Gum +/- Coolabah habitat may be overlapping factors, as these tree species (particularly River Red Gum) are typically situated near water sources. However, because the primary aim of this study was not to investigate the potential interaction between these two factors, the sampling design did not stratify for them separately. Future research that focuses on disentangling the contributions of distance to water and River Red Gum +/- Coolabah habitat would be beneficial to better understand how these two critical resources support Pink Cockatoo survival, particularly in semi-arid landscapes where resource availability is highly variable.

2.4.2.2 Cypress

Despite the absence of a statistically significant relationship between Cypress habitat and Pink Cockatoo detections, one of the Cypress sites emerged as the second most active location for Pink Cockatoos within the sanctuary. The seeds of the White Cypress Pine (*Callitris glaucophylla*) provide a food source for cockatoos and Galahs (Thompson & Eldridge, 2005) and in Western Australia, Pink Cockatoos have been documented feeding on White Cypress Pine seeds (Rowley & Chapman, 1991), suggesting that this tree species is an important component of their diet across different regions. Field

observations in Bowra further support this finding, as Pink Cockatoos have been observed foraging in Cypress trees on various occasions.

Unfortunately, Cypress recruitment is low at the sanctuary (personal observation), probably due to grazing pressures from herbivores (such as goats and kangaroos). Seed production in Cypress trees peaks every three years on average, with fewer seeds produced during the intervening years (Thompson & Eldridge, 2005). Moreover, successful recruitment tends to occur after one or two years of wet summers combined with below-average summer temperatures (Thompson & Eldridge, 2005). This cyclical seed availability, combined with factors such as grazing pressure and increased droughts due to climate change (Maestre et al., 2012), hampers the successful regeneration of cypress populations. It is therefore essential that young Cypress seedlings and saplings are protected at Bowra, as they serve as a food source and potential nesting site for Pink Cockatoos. In Victoria, Pink Cockatoos exclusively nest in *Callitris gracilis*, which shares similar characteristics with *Callitris glaucophylla* found at Bowra (Hurley, 2022; Thompson & Eldridge, 2005). It is possible that Pink Cockatoos might also nest in *C. glaucophylla* at Bowra Wildlife Sanctuary, although no observations of nesting in Cypress were made in this study. Further research is needed to determine the importance of *C. glaucophylla* as a nesting tree, and the factors limiting regeneration on Bowra.

2.4.3 Diameter at Breast Height

A significant positive relationship was found between tree DBH and Pink Cockatoo detections. This finding aligns with numerous studies that have demonstrated a positive correlation between bird abundance and larger tree diameters (Gutzat & Dormann, 2018; Kebrle et al., 2021; Komlós et al., 2024). Older trees typically have a larger DBH and are more likely to contain suitable hollows that provide the necessary space and protection for nesting (Adkins, 2006; Gibbons et al., 2000; Lindenmayer et al., 1993; Westerhuis et al., 2019). Pink Cockatoos are secondary cavity-nesters that depend on existing cavities formed in trees (Rowley & Chapman, 1991). In Australia, it can take 120 to 220 years for large cavities to develop in *Eucalyptus* species (Adkins, 2006). Gibbons et al. (2000) found a strong association between tree diameter and the occurrence of hollows, further supporting the importance of mature trees for cavity-nesting birds.

Pink Cockatoos are highly selective in choosing their nesting sites. Rowley and Chapman (1991) found that they prefer hollows that are shallower than one meter and located more than eight meters above the ground. In Victoria, Pink Cockatoos choose nest hollows in large cypress pines over 80 years old (Gibson & Florentine, 2008) with an average DBH of 48.4 cm (Hurley, 2015). These specific requirements, along with limited nesting sites due to land clearing and low tree recruitment from grazing (Australian Government, 2023), further limit the number of suitable sites available, leading the species to repeatedly use favoured locations.

While increased detections of Pink Cockatoos around larger trees observed in the current study may in part be related to their reliance on tree hollows for nesting, it should be noted that the large trees at the sanctuary are mostly River Red Gums and Coolabah. Therefore, increased detections in this habitat type and relationship with DBH may also be due to the proximity of these species to permanent water (as discussed above in Section 2.4.2.1).

2.4.4 Temporal Patterns

No significant relationship was found between Pink Cockatoo detections and the temporal variables measured during the study. It has been reported that Pink Cockatoos can endure varying climatic conditions, including drought (Rowley & Chapman, 1991). Their survival mechanisms depend on their knowledge of water and food locations gained from older flock members (Dean et al., 2009; Rowley & Chapman, 1991). While more Pink Cockatoo detections were found in River Red Gum and Cypress habitats in the current study, they did use other habitats, such as Mulga, Whitewood, Gidgee and Poplar, suggesting that their foraging strategy allows them to exploit a wide range of seasonal resources across the sanctuary. This aligns with the findings of Tischler et al. (2013) who noted that birds utilize their environment dynamically, with habitat selection reflecting the episodic shifts in resource availability across different vegetation types over time.

In Western Australia, Rowley and Chapman (1991) observed dynamic foraging behaviour in Pink Cockatoos, suggesting that their survival and habitat use are closely tied to the seasonal phenology (seed and fruit production) of local plant species. Rowley and Chapman (1991) observed that the availability of food for Pink Cockatoos changed

throughout the year and varied from year to year. In Bowra, Pink Cockatoos were observed feeding in six different plant species. These plant species flower or seed at different times throughout the year. For example, *Callitris glaucophylla and Capparis mitchellii* typically fruit from spring to summer, while *Eremophila mitchellii* and *Acacia oswaldii*, flower during this same time. *Tetragonia moorei* and *Plantago cunninghamii* typically flower from winter to spring (Atlas of Living Australia, 2024a, 2024b; Charles Sturt University, 2024; Thompson & Eldridge, 2005). This seasonal succession of flowering and seeding may provide food for Pink Cockatoos at different times throughout the year. Additionally, Rowley and Chapman (1991) observed some plant species shed their seeds quickly after maturation, while others have fruits that take longer to mature, remaining available on the plant for several months, thus extending the period during which food resources were accessible. It is important to note that the phenology of plant species found at the sanctuary was not investigated in this study, and these observations are based on incidental findings during the study period. Further research is needed to better understand foraging behaviour and food resources used by Pink Cockatoos at the sanctuary.

While no relationship was found between Pink Cockatoo detections and rainfall patterns in the current study, it is important to note that the study spanned six months and was conducted within a small geographic area with relatively homogeneous rainfall and temperature, which limits our ability to detect such a correlation if it exists. This raises important questions about the influence that rainfall may have on Pink Cockatoos, which will be explored in Chapter 3.

2.5 Conclusion

This study highlights the critical influence that proximity to water and habitat type have on the spatial distribution of Pink Cockatoos within semi-arid ecosystems, particularly in relation to riparian zones and large trees (DBH). Riparian areas, with their abundant resources, are key hotspots for Pink Cockatoos. Additionally, large trees provide essential nesting sites. The findings also suggest that, although Pink Cockatoos exhibit some degree of habitat flexibility, they were most active in River Red Gum +/- Coolabah habitat during the six-month period of this study at Bowra Wildlife Sanctuary. Overall, results of this study highlight the importance of conserving a heterogeneous mix of vegetation communities across Bowra as these support a wide range of overlapping resources (water, foraging, nesting) that Pink Cockatoos require throughout the year. The availability and spatial configuration of overlapping resources, such as nesting sites near foraging grounds or water, are crucial for the fitness and population stability of mobile species in dryland ecosystems, as seen in other studies on birds (Craig et al., 2022; Schneider & Griesser, 2009; Webb et al., 2017).

An important consideration in this study is the potential for biases in the dataset, particularly those related to the performance of the acoustic recorders under different environmental conditions. One potential source of bias is the variation in call detection rates across sites due to factors such as vegetation density, topography, and background noise. For example, dense vegetation may attenuate sound more effectively, reducing the distance over which calls can be recorded, while open areas may facilitate clearer sound transmission (Royle, 2018). However, given that this study was conducted in a semi-arid environment with relatively flat topography, it is unlikely that terrain-induced sound attenuation played a significant role. Additionally, most activity was found in areas with higher vegetation density, particularly riparian zones, indicating that habitat structure did not prevent successful detection in key areas.

Despite these considerations, other factors such as background noise—wind, water flow, or calls from other species—may have affected the recorders' ability to capture Pink Cockatoo calls accurately, potentially leading to an underrepresentation of calls at certain sites. Future studies should consider validation approaches to quantify detection distances

and assess site-specific variations in recording effectiveness to better account for potential biases.

Future research should focus on providing a detailed investigation of the key food resources and their phenology at Bowra Wildlife Sanctuary to better understand the temporal availability of Pink Cockatoo foraging resources. Additionally, understanding the regeneration dynamics of White Cypress Pine populations is crucial for the long-term conservation of this food source and potential nesting habitat for Pink Cockatoos. Conservation strategies should prioritize the protection of large trees and riparian habitats, ensuring that both current nesting sites and known food resources of Pink Cockatoos are protected at Bowra. A longer-term study investigating the effects of different rainfall and temperature regimes on Pink Cockatoos is required and will be explored in Chapter 3.

Chapter 3: Insights into the Temporal Distribution of Pink Cockatoos

3.1 Introduction

Arid and semi-arid ecosystems are characterized by temporal variability in resource availability, driven primarily by unpredictable rainfall and extreme climate fluctuations (Maestre et al., 2012; Pavey & Nano, 2009; Price et al., 2013; Schwinning & Sala, 2004). Recent climate models forecast a rise in both the intensity and frequency of extreme weather events (e.g. droughts, heatwaves, bushfires and floods), which exacerbate resource scarcity and add stress to species living in already harsh environments (Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology, 2022; Harris et al., 2018; Kutt et al., 2012). Such conditions pose significant challenges to the survival strategies of many avian species, particularly those like the endangered Pink Cockatoo that rely on water and resources scattered across vast, heterogeneous habitats (Craig et al., 2022; Rowley & Chapman, 1991). Furthermore, for cavity-nesting species like the Pink Cockatoo, prolonged droughts threaten critical nesting sites and reduce the availability of food and water sources, further endangering their survival (Neate-Clegg et al., 2022; Westerhuis et al., 2020).

In arid and semi-arid environments, birds often exhibit distinct changes in breeding and foraging patterns in response to fluctuations in resource availability, primarily driven by rainfall and temperature (Pascoe et al., 2021; Rowley & Chapman, 1991; Westerhuis et al., 2020). Understanding these phenological responses is essential for comprehending how species adapt to changing conditions. Little research has been undertaken on the influence of climatic variables, particularly rainfall and temperature extremes, on the temporal distribution of eastern Pink Cockatoos. Addressing this gap is vital for the conservation of this endangered species, particularly as pressures from habitat fragmentation and climate variability increase (Gardner et al., 2022; Neate-Clegg et al., 2022; Reid et al., 2024).

In this study, three locations in eastern Australia were selected (Bowra Wildlife Sanctuary, Naree Station, and Fowlers Gap) as they are situated in semi-arid and arid ecosystems within the historical range of the eastern Pink Cockatoo (Australian Government, 2023) and passive acoustic monitoring is being undertaken at these locations through the Australian Acoustic Observatory (hereafter A2O, https://acousticobservatory.org/; Roe et al., 2021). A 20-month period of continuous recording was selected to coincide with the end of the severe drought in 2019, oscillation to La Niña in 2020 and subsequently into 2021, to provide an understanding of the temporal distribution of eastern Pink Cockatoos in response to changes in rainfall, temperature and vegetation greenness. Insights gained from this research are required to inform current and future conservation strategies for endangered eastern Pink Cockatoos in arid and semi-arid landscapes.

3.2 Methods

3.2.1 Study Sites

This study was conducted across three locations in New South Wales (Fowlers Gap and Naree Station) and Queensland (Bowra Wildlife Sanctuary), Australia (Figure 11). Bowra Wildlife Sanctuary and Naree Station are situated within the Mulga Lands Bioregion, in a semi-arid environment at the core of the Pink Cockatoo's distribution range while Fowlers Gap is located at the periphery of this range, within the arid zone.

3.2.1.1 Bowra Wildlife Sanctuary

See chapter 2, section 2.2.3

3.2.1.2 Fowlers Gap

Fowlers Gap Arid Zone Research Station (hereafter Fowlers Gap) is situated in western New South Wales. Encompassing 39,000 hectares, this research station offers a unique arid environment with varied topography, including rocky ranges, sand and clay plains, and ephemeral creek systems (Acworth et al., 2016). Vegetation at Fowlers Gap includes chenopod shrublands, dominated by saltbush (*Atriplex* spp.) and bluebushes (*Kochia* spp.), as well as sparse *Acacia* woodlands (Dunkerley & Brown, 1995). The area receives an average annual rainfall of approximately 249 mm, and temperatures can range from an average monthly minimum of -0.5°C in July to an average monthly maximum of 41.9°C in January (Bureau of Meteorology, 2024).

3.2.1.3 Naree Station

Naree Station (hereafter Naree) encompasses around 14,400 hectares of semi-arid floodplains, swamps, permanent waterholes, ephemeral wetlands and woodlands. The woodlands are dominated by Mulga (*Acacia aneura*), Whitewood (*Atalaya hemiglauca*), Ironwood (*Acacia excelsa*), Rosewood (*Alectryon oleifolius*), Coolabah (*Eucalyptus coolabah*), Yapunyah (*Eucalyptus ochrophloia*), and Leopardwood (*Flindersia maculosa*) (Bush Heritage Australia, 2023; Hunter, 2016). Naree receives an average annual rainfall of approximately 327 mm, with temperatures ranging from an average monthly minimum of 1.9°C in July to an average monthly maximum of 42.4°C in January (Bureau of Meteorology, 2024).

3.2.2 Data Collection

Acoustic recordings were obtained from the Australian Acoustic Observatory. At both Bowra and Naree, two sensors were selected per location for analysis: one positioned in a wet habitat and the other in a dry habitat (Bowra: BWA and BDA; Naree: NDB and NWB; Figure 11). The sensors placed in the wetter habitats were located near permanent waterholes (Mukudjeroo Waterhole in Naree and Gumhole Waterhole in Bowra). At Fowlers Gap, four sensors were chosen due to the limited historical sightings of Pink Cockatoos, ensuring comprehensive coverage of the area, two in wet habitat and two in dry habitat (FWA, FWB, FDB and FWB; Figure 11). The 'wet' sites at Fowlers Gap are adjacent to an ephemeral creek (Fowlers Creek) and an artificial, semi-permanent waterhole (Gum Creek). The classification of wet and dry habitats was based on local conditions at the time the sensors were deployed (Roe et al., 2021). The sensors deployed at these sites are solar-powered BARs (Frontier Labs) set at a sampling rate of 22 kHz. The study period spanned from 1st September 2019 to 30th April 2021.

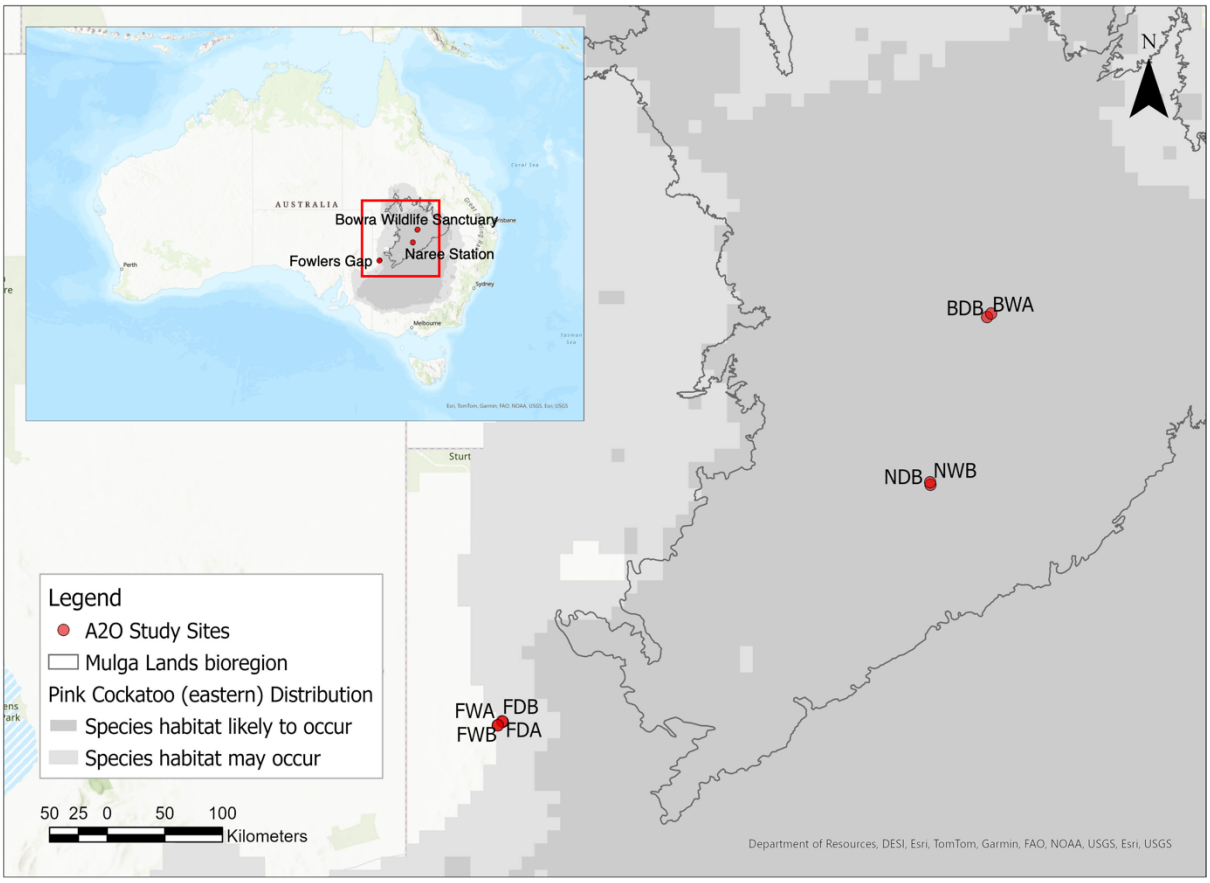

Figure 11. Map illustrating the locations of the study sites and their sensors: Bowra Wildlife Sanctuary, Naree Station, and Fowlers Gap. The distribution range of the Pink Cockatoo is shown in grey, alongside the Mulga Lands bioregion in black outline (Australian Government, 2024)..

3.2.3 Environmental Variables

3.2.3.1 Remote Sensing of Satellite Imagery

To assess vegetation greenness during the study, fractional cover estimates were used. The estimates were obtained from monthly VegMachine (Beutel et al., 2019) fractional cover datasets (30 m per-pixel resolution) covering the entire study period for each individual acoustic sensor using a buffer of 1000 m, to ensure a balance between capturing an adequate representation of vegetation within the sensor's surroundings and preventing overlap with other sensors. The VegMachine fractional cover datasets are derived from Landsat reflectance data that have undergone geometric and radiometric corrections based on standard protocols (Flood, 2017). To minimize the effects of undetected clouds and shadows, the Fmask algorithm was used, and only images with less than 1% cloud cover were used (Flood, 2017). Fractional cover is estimated in VegMachine by partitioning each pixel into proportions of photosynthetic vegetation (green), non-photosynthetic vegetation (non-green, or dry), and bare ground (Joint Remote Sensing Research Program, 2022). In this study, photosynthetic vegetation (green) values were used for analysis of vegetation greenness.

3.2.3.2 Rainfall and Temperature

To evaluate the impact of climatic variables on Pink Cockatoo detections, rainfall and temperature data were obtained from SILO (Jeffrey et al., 2001), an Australian climate database managed by the Queensland Department of Environment, Science, and Innovation (DESI). This dataset has a spatial resolution of approximately 5 km^2 and includes daily climate variables constructed from observational data obtained from the Australian Bureau of Meteorology and other suppliers. (Queensland Government, 2023). For each sensor location, monthly (interpolated) average rainfall and cumulative rainfall over three, six, and twelve months were calculated.

3.2.3.3 Convolutional Neural Network Recogniser Training

The same recogniser from Chapter 2 of this study was used in this chapter to detect Pink Cockatoos.

3.2.4 Acoustic Data Processing

All detections of Pink Cockatoos were manually validated by a single observer. Validation was done in Raven Pro v1.6.5 (https://www.ravensoundsoftware.com/; hereafter Raven) by uploading the one-hour files in 60 second segments in a colourscale spectrogram view. Focus was set up to 2132, brightness at 47 and contrast at 52. These settings provided the clearest visual representation of Pink Cockatoo calls during manual verification. From each detection, each call was counted individually. Fly-over calls detected by the recogniser were not counted.

3.2.5 Statistical Modelling

All statistical analyses were performed using R statistical software (R Core Team, 2021).

3.2.5.1 Variation in Pink Cockatoo Detections in Relation to Time of Day and Month

As the data were not normally distributed (Shapiro-Wilk test, $W = 0.333$, $p < 0.001$), non-parametric Kruskal-Wallis tests (from the 'base' package in R) was used to examine whether there were statistically significant differences in the number of detections in relation to time of day. The response variable was hourly Pink Cockatoo detections, and the independent variable was time of day and month.

3.2.5.2 Relationship Between Pink Cockatoo Detections and Environmental Variables

The environmental variables were scaled using a min-max normalisation to address the variability among the different explanatory variables. A Poisson regression model was initially used to investigate the relationship between Pink Cockatoo calls and various environmental factors ('base stats' package). Given the presence of overdispersion, a Generalized Linear Mixed Model (GLMM) was fitted, incorporating site as a random

effect (via the 'lme4' package; Bates, 2015). Model assumptions were checked through diagnostic plots and tests for multicollinearity and autocorrelation (packages: ‘corrplot’, ‘car’, ‘DHARMa’, ‘stats’). Model fitness was evaluated by comparing the test models to the null model, and model selection was carried out using the MuMIn package (Barton, 2024) to determine the best-fitting models. According to the approach outlined by Burnham and Anderson (2002), the most strongly supported models were identified as those with ΔAIC values within 2 of the lowest AIC, indicating strong support. Models with ΔAIC values up to 7 were considered to have partial support (Burnham and Anderson, 2002). The model's goodness-of-fit was evaluated through marginal R^2 calculations and likelihood ratio tests to assess the explanatory power and overall performance (Burnham & Anderson, 2002). The response variable was total Pink Cockatoo detections per month per site and the independent variables consisted of eight temporal environmental variables (Table 4).

Table 4. Description of environmental variables used in the statistical modelling

Variable	***Description***	***Type***
Rainfall monthly average	Average monthly rainfall (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous month	Cumulative rainfall previous month (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 3 months	Cumulative rainfall previous 3 months (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 6 months	Cumulative rainfall previous 6 months (mm), calculated from daily rainfall from SILO	Continuous
Rainfall cumulative previous 1 year	Cumulative rainfall previous year (mm), calculated from daily rainfall from SILO	Continuous
Maximum temperature	Maximum monthly average temperature (C°) calculated from SILO data	Continuous
Minimum temperature	Minimum monthly average temperature (C°) calculated from SILO data	
Maximum daily temperature	Maximum daily temperature (C°) obtained from SILO	Continuous
Vegetation greenness	Percentage of photosynthetic vegetation obtained from Vegmachine	Continuous

3.2.5.1 Variation in Pink Cockatoo Detections in Relation to Daily Temperature

To examine the relationship between Pink Cockatoo daily detections and maximum daily temperature, an initial Poisson regression model was applied, with the number of daily calls as the response variable and daily maximum temperature as the explanatory variable. Overdispersion was assessed using the AER package, and its presence was confirmed. To address this, a Generalized Linear Mixed Model (GLMM) was subsequently fitted using the glmmTMB package (Brooks et al., 2017). This model employed a negative binomial distribution (family = nbinom2) to better accommodate the observed data dispersion and included site as a random effect to account for variability in detection rates across different locations.

3.3 Results

3.3.1 Acoustic Analysis

A total 76,800 hours of recordings (18,210 from Bowra, 36,300 from Fowlers Gap, 18,208 from Naree) were analysed using the recogniser. Sites varied considerably in the number of detections of Pink Cockatoos between months and over the entire study period (Figure 12). Site BWA exhibited the highest overall number of detections with peaks in November 2019 (1,853 calls), May 2020 (1,531 calls), and July 2020 (1,417; Figure 12). BDB showed the highest detections in September 2019 (715 calls) and February 2020 (714 calls; Figure 12). Both NWB and NDB recorded their highest detections in November 2019 (1,404 calls in NWB and 370 in NDB; Figure 12), albeit with lower overall call counts compared to BWA and BDB. There were no calls detected from any of the four sites at Fowlers Gap.

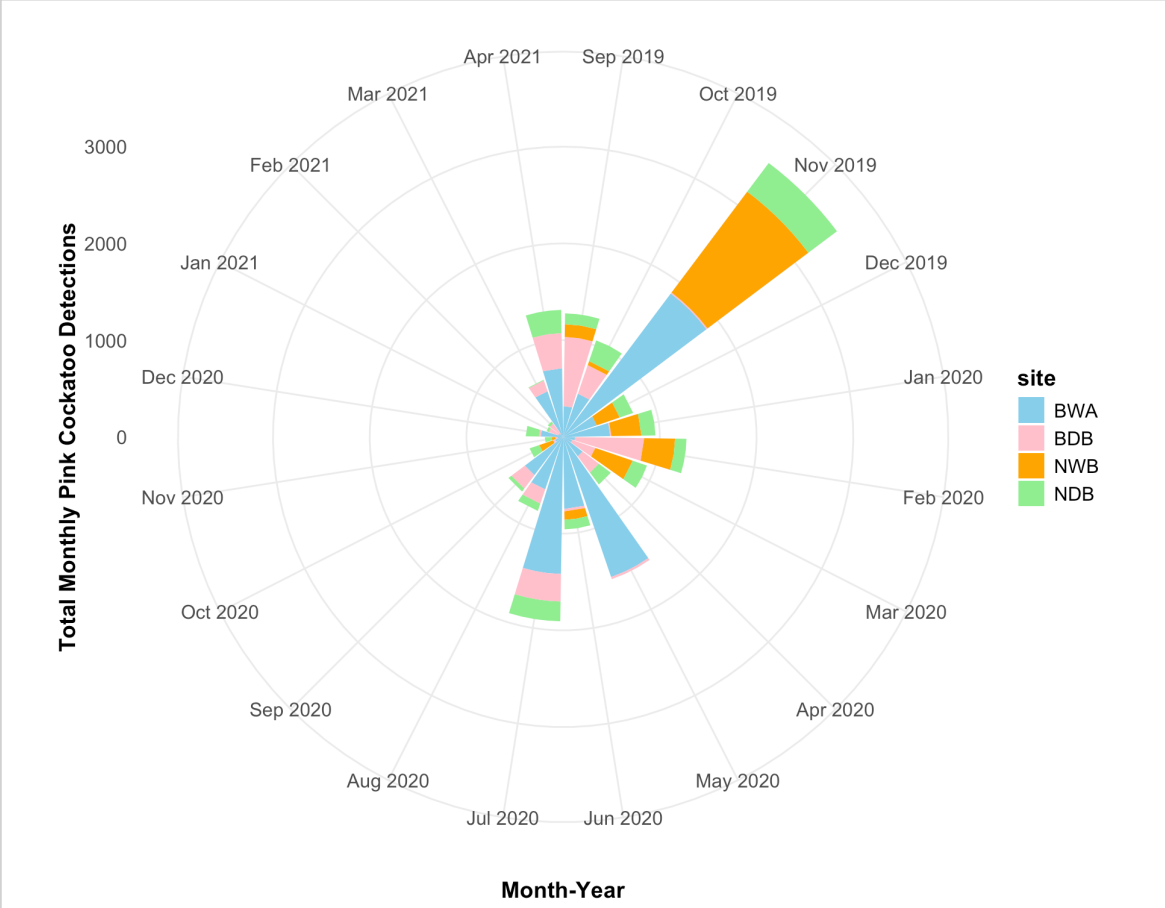

Figure 12. Monthly distribution of total Pink Cockatoo detections across four monitoring sites (BWA, BDB, NWB, and NDB) from September 2019 to April 2021.

3.3.2 Variation in Pink Cockatoo Detections in Relation to Time of Day

There was a significant effect of time of day on detections ($\chi^2 = 266.89$, df = 14, p-value < 0.001; Figure 13). Pink Cockatoo detections were highest during the early morning hours, with peaks observed between 6 am and 8 am. Call activity then decreased sharply, with minimal detections recorded from 10 am to 3 pm. A smaller peak in call activity was observed in the late afternoon, particularly around 4pm to 6pm.

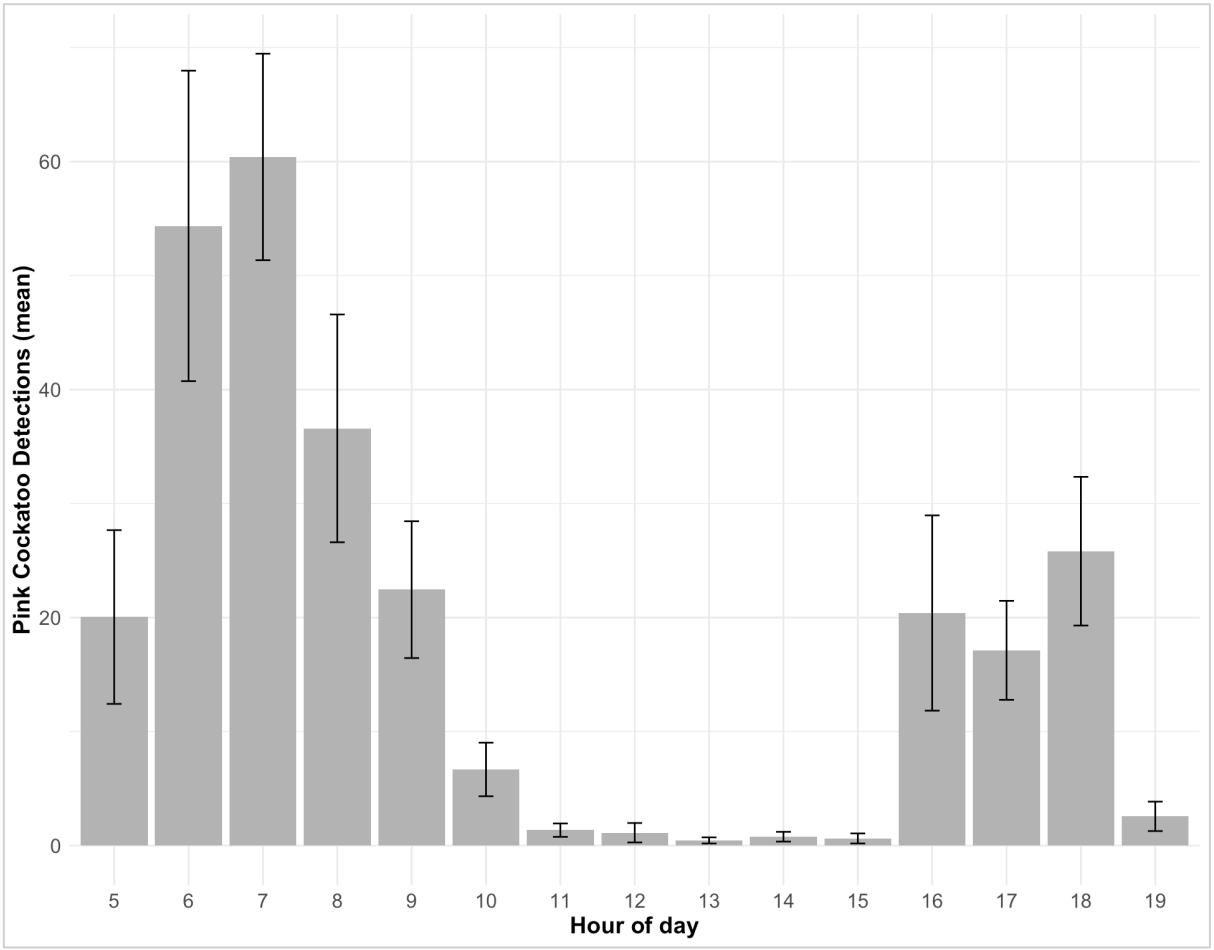

Figure 13. Mean hourly detections of Pink Cockatoos across all sites, showing peaks in detections during early morning (6-9 am) and late afternoon (4-6 pm). Error bars represent standard error, indicating variability in detections.

3.3.3 Vegetation Greenness

Vegetation greenness fluctuated throughout the study period in response to rainfall patterns (Figure 14). Greenness values were generally low during late 2019 and early 2020, corresponding with minimal rainfall. At site BDB, a minimum greenness of 5.73% was found in June 2020 and a maximum of 14.8% in March 2020 and 15.41% in January 2021, reflecting the site's rainfall patterns (Figure 14a). Similarly at site BWA, greenness reached its lowest value of 8.33% in June 2020, following a period of low average monthly rainfall (Figure 14b). Greenness at BWA peaked at 24.1% in March 2020, coinciding with increased rainfall from January 2020, and in April 2021 (28%) following increased rainfall from December 2020. Site NDB showed greenness levels ranging from a low of 17.02% in January 2020 to a high of 27.6% in April 2020 and 35.53% in April 2021 (Figure 14c). At site NWB, greenness varied from 17.94% in February 2020 to 40.19% in May 2020 and 40.17% in April 2021 (Figure 14d).

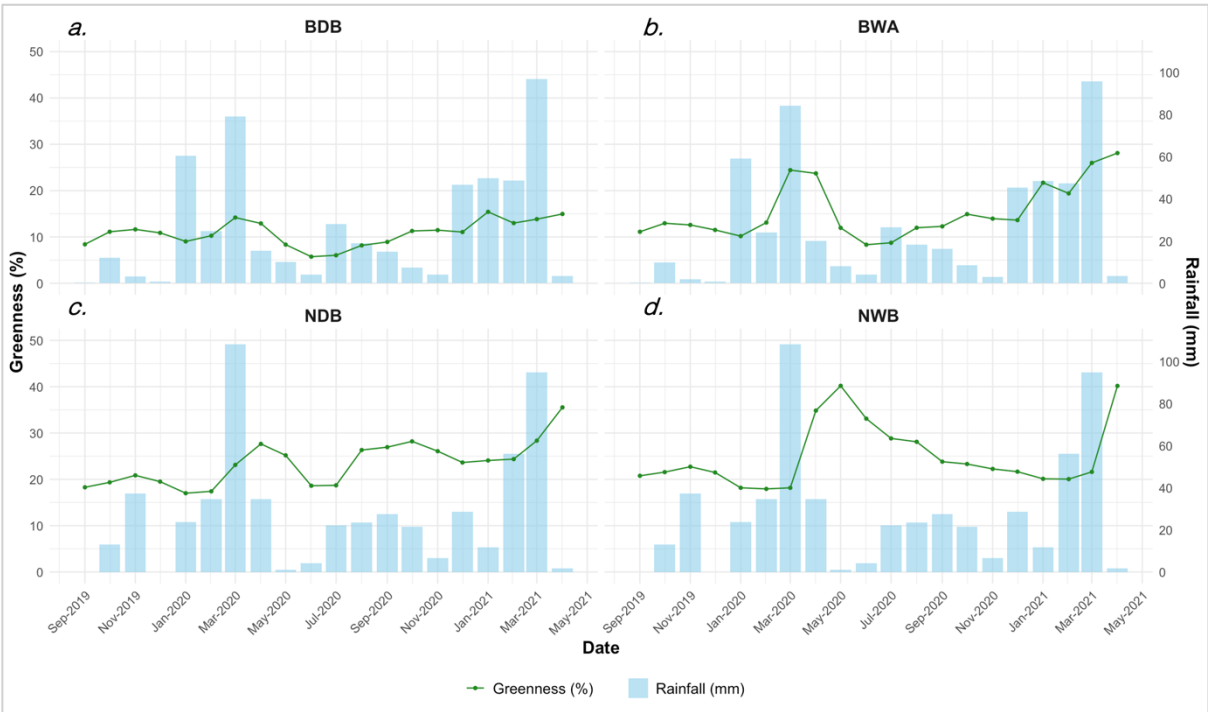

Figure 14. Vegetation greenness and rainfall across four sites (a.BDB, b.BWA, c.NDB, d.NWB) over time. Monthly values of vegetation greenness (green line, left y-axis, 0-50%) and monthly rainfall (blue bars, right y-axis, 0-110 mm) shown from September 2019 to May 2021.

3.3.4 Relationship between Pink Cockatoo Detections and Environmental Variables

Tests for correlation between environmental variables revealed a strong positive association between monthly average rainfall and cumulative rainfall from the previous month ($r = 0.91$, $df = 78$, $p < 0.001$). Additionally, cumulative rainfall over the previous six months showed a strong correlation with cumulative rainfall three months ($r = 0.70$, $df = 78$, $p < 0.001$). Monthly average minimum and maximum temperatures were highly correlated as well ($r = 0.87$, $df = 78$, $p < 0.001$). In contrast, a strong negative correlation was observed between cumulative rainfall over the previous 6 months and maximum temperature ($r = -0.79$, $df = 78$, $p < 0.001$). To address these multicollinearity issues, various simplified GLMMs models with variables being iteratively removed were compared using the Akaike Information Criterion (AIC) to determine the best-supported model. This approach aimed to identify the model with the lowest AIC value, indicating a better balance between goodness-of-fit and model complexity while addressing multicollinearity issues (Table 5). The best-supported model with the lowest AIC (989.2) included the following variables: maximum temperature, cumulative rainfall previous month, cumulative rainfall 3 months, cumulative rainfall previous year, and vegetation greenness. The results of the full correlation tests are provided in Appendix I.

Table 5. Comparison of simplified models using Akaike Information Criterion (AIC) and marginal R^2 (R^2m) values to evaluate model performance after removing various combinations of variables.

Variables	***AIC***	***R2m***
temp max, cumulative rainfall previous month, cumulative rainfall 3 months, cumulative rainfall previous year, and vegetation greenness	989.8	0.26
temp min, average monthly rainfall, cumulative rainfall 3 months, cumulative rainfall 6 months, and vegetation greenness.	1158.8	0.18
temp max, average monthly rainfall, cumulative rainfall 3 months, cumulative rainfall previous year, and vegetation greenness	1160.4	0.16
temp max, average monthly rainfall, cumulative rainfall 3 months, cumulative rainfall 6 months, and vegetation greenness.	1162.2	0.15

The GLMM relating environmental variables (maximum temperature, cumulative rainfall previous month, cumulative rainfall previous 3 months, cumulative rainfall previous year,

vegetation greenness) to Pink Cockatoo calling significantly improved the model fit compared to the null model, which only included the random intercept for site (Likelihood ratio test: $\chi^2 = 181.43$, df = 2, $p < 0.001$). The detailed results of the GLMM can be found in Appendix H. The best-supported model, identified using the MuMIn package on the simplified model, included cumulative rainfall over the previous three months and cumulative rainfall over the previous year as fixed effects, with site included as a random effect (AIC=985.5; Table 6).

Table 6. Model results for environmental variables and monthly detections of Pink Cockatoos at Bowra Wildlife Sanctuary and Naree Station combined.

Model	***Environmental Variable***	***Df***	***Effect size***	***SE***	***z-score***	***p-value***	***AIC***	***R^2***
1	Rainfall cumulative previous 3 months	75	0.35	0.21	1.64	0.10	985.5	0.16
	Rainfall cumulative previous year		-0.78	0.22	-3.48	<0.001		
Null		77	244.87	80.35	3.05	<0.05	1163	0.16

The results from the GLMM for the best model revealed a significant negative relationship between cumulative rainfall over the previous year and Pink Cockatoo detections (Estimate = -0.78, Std. Error = 0.22, z = -3.48, p = <0.001; Table 6; Figure 15). This indicates that higher rainfall in the previous year is associated with a decrease in the number of Pink Cockatoo detections.

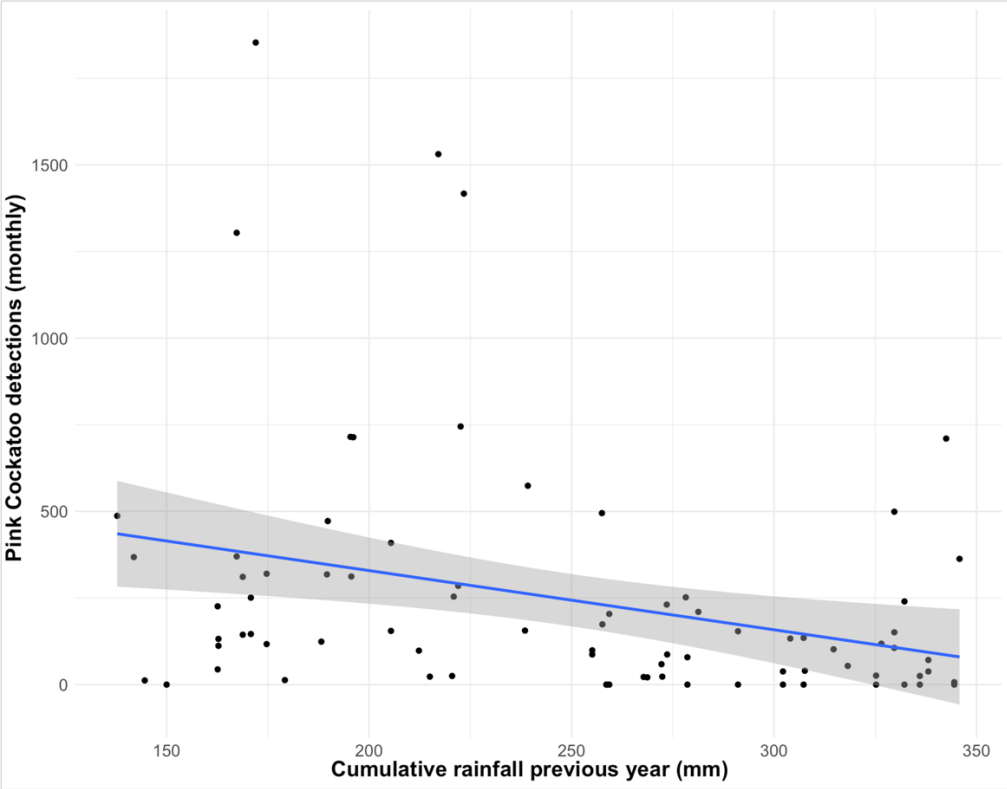

Figure 15. *Relationship between cumulative rainfall over the previous year and total Pink Cockatoo detections for both Bowra Wildlife Sanctuary and Naree Station combined.*

3.3.4.1 Variation in Pink Cockatoo Detections in Relation to Daily Temperature

The results of the GLMM indicate that the effect of maximum daily temperature on Pink Cockatoo detections was not statistically significant (Estimate +/- SE = -0.022+/- 0.013, z = -1.564, p = 0.118). Table 7 summarizes the key statistics of the maximum daily temperature (°C) for the four sites recorded during the study period, including the mean, standard deviation (SD), and the range (minimum to maximum).

Table 7. Summary statistics for maximum daily temperature for the four sites (BWA, BDB, NWB and NDB), including overall mean, standard deviation, and range.

Site	***Overall mean***	***Standard deviation***	***Range (min to max)***
BWA	30.8	7.03	13.3 to 46.1
BDB	30.6	7.04	13.2 to 45.9
NWB	30.2	7.38	13.4 to 46.8

NDB	30.2	7.38	13.4 to 46.8

3.4 Discussion

Over the course of this study, a total of 76,800 hours of continuous acoustic recordings were analysed from three locations: Bowra Wildlife Sanctuary, Naree Station and Fowlers Gap. The analysis resulted in 19,590 detections of Pink Cockatoos. Among the sites, the highest number of detections was recorded at Bowra 'wet' site (BWA) with 10,414 detections, accounting for over 53 % of the total detections. This was followed by Bowra 'dry' site (BDB) with 3,675 detections, Naree 'wet' site (NWB) with 3,047 detections, and Naree 'dry' site (NDB) with 2,454 detections. Notably, no detections were recorded at Fowlers Gap, the study location situated in the most arid part of their distribution range. Historically, Pink Cockatoos have been observed at Fowlers Gap, which lies at the periphery of their known distribution.

The absence of any detections across the monitored sites at Fowlers Gap may suggest a potential shift in the range of Pink Cockatoos. This could be due to extreme aridity making the environment too inhospitable for the species, possibly because of ongoing climate change affecting habitat suitability. Furthermore, Fowlers Gap lacks permanent water sources (Badgery et al., 2020; Dunkerley, 2008) that could have served as refugia during the severe drought of 2017-2019, potentially exacerbating typical harsh conditions for Pink Cockatoos (UNSW, 2023). Similar patterns have been observed in other arid regions worldwide. For instance, in the Mojave Desert of western United States, a recent study found that over the last century a desert bird community collapsed, with an average loss of 43% of species at various sites (Iknayan & Beissinger, 2018). They attributed these declines to climate change causing deserts to warm and dry faster than other ecoregions, and this is pushing desert birds to the brink of their physiological limits, leading to the decline or extinction of species. Further research is needed to explore these possibilities and to determine whether the lack of detections at Fowlers Gap reflects a change in Pink Cockatoo distribution, and to monitor into the future to see whether the species returns. Understanding these factors is crucial for the conservation of Pink Cockatoos, especially in the face of environmental changes impacting dryland ecosystems.

3.4.1 Time of Day

This study found a significant relationship between Pink Cockatoo detections and time of day, specifically more calls were detected in the morning and late afternoon, with few calls during the middle of the day. This relationship is consistent with findings from Western Australia. Rowley and Chapman (1991) observed that the daily routine of the Pink Cockatoo was dependent on the availability of daylight hours and food. For example, in midsummer, if plenty of food was available, Pink Cockatoos foraged for just a few hours around sunrise and before sunset, spending the middle of the day resting (Rowley & Chapman, 1991). Bird species in semi-arid and arid regions, including Pink Cockatoos, are most vocally active during dawn and dusk, with lowest call activity occurring during the middle of the day (Scarpelli et al., 2023). This is because cooler morning temperatures provide ideal conditions for foraging and social behaviours, mainly due to the reduced physiological strain associated with thermoregulation (du Plessis et al., 2012). In the midday heat, birds tend to reduce their movements to conserve energy and avoid overheating (du Plessis et al., 2012). As diurnal animals with small body sizes, birds are particularly susceptible to overheating, making thermoregulation a critical concern (Cooper et al., 2002; Saunders et al., 2011). In the late afternoon and early evening, there is typically another increase in activity and vocalizations as the birds resume foraging before roosting for the night (Rowley & Chapman, 1991). This pattern reflects an adaptation to their environment, optimizing foraging efficiency while minimizing exposure to extreme temperatures.

3.4.2 Cumulative Rainfall Previous Year

This study revealed a significant negative relationship between cumulative rainfall in the previous year and Pink Cockatoo detections. From January 2017 to December 2019, severe drought conditions, characterized by record-low rainfall, impacted the Murray-Darling Basin, where the study sites are located (Allan et al., 2023; Australian Government, 2024). This extended period of drought may have had a significant impact on Pink Cockatoos, likely concentrating bird activity near permanent water sources. The higher detection rates in the “wet” sites from September 2019 until September 2020 (Bowra) and September 2019 to March 2020 (Naree) indicate that, despite lower rainfall, these sites may have provided critical resources, leading to increased detections. These "wet" sites, where sensors are located near permanent water sources in riparian zones,

such as the Mukudjeroo Waterhole at Naree and Gumholes Waterhole at Bowra, likely provide critical refugia, buffering the effects of drought and supporting Pink Cockatoo populations when surrounding areas were resource scarce (Reside, 2019; Selwood, 2015)

Many studies have found that bird species concentrate in riparian zones during times of water scarcity, relying on these areas for survival (Kingston et al., 2002; Neate-Clegg et al., 2022). Areas near watercourses typically sustain higher vegetation biomass than what regional rainfall alone would allow, thanks to access to groundwater reserves and periodic flooding (Selwood et al., 2018). Greater moisture and nutrient availability in riparian areas foster diverse plant communities and enhanced structural complexity, creating favourable conditions that support a higher diversity and abundance of vertebrates (Reside et al., 2014). Additionally, structurally complex woodlands are typically found along artificial waterbodies and creek beds, such as Coolabah (*Eucalyptus coolabah*) fringing the Mukudjeroo waterhole at Naree and River Red Gum (*Eucalyptus camaldulensis*) fringing the Gumhole waterhole at Bowra. Although these woodlands cover a limited area, they serve as critical environments for bird species and hold considerable ecological value within arid ecosystems (Schneider & Griesser, 2009).

In the latter part of the study (end of 2020 to beginning of 2021), Pink Cockatoo detections decreased at "wet" sites for a period of over five months. No Pink Cockatoo calls were detected at the NWB site, a sharp contrast to the 1,291 calls recorded during the same period the previous year. Similarly, detections at BWA dropped from 3,183 to 1,592 calls. This decline occurred approximately one year after the start of substantial rainfall events (from November 2019 to April 2020, Naree recorded a total of 310mm and Bowra 189 mm). In environments with unpredictable and scarce resource pulses, like dryland ecosystems, bird movements are influenced by local resource dynamics, and their ability to detect distant resources (Dean et al., 2009). Rainfall events of varying magnitude result in different biological responses (Schwinning & Sala, 2004). For example, small rainfall events may lead to brief pulses of activity in surface-dwelling organisms, while larger rainfall events trigger more substantial responses, such as growth in deeper-rooted plants (Chesson et al., 2004). Significant rainfall can lead to ecological pulses that persist for extended periods, sometimes lasting several years, because soil moisture at deeper levels can carry over from one year to the next, particularly when water input exceeds the annual uptake capacity of vegetation (Connell et al., 2017; Schwinning & Sala, 2004).

Pink Cockatoos are omnivores with a varied diet of native plants (predominantly seeds) and sometimes insects (Rowley & Chapman, 1991). The increased availability of food sources across a broader range of habitats resulting from the sudden increase in rainfall after the drought may have encouraged Pink Cockatoos to explore and occupy new areas, reducing their presence at the monitored sites, particularly those near permanent water sources. As nomadic birds, Pink Cockatoos exhibit flexible movement patterns outside the breeding season, with their large-scale movements often tied to resource dynamics (Rowley & Chapman, 1991). These factors may explain their reduced presence at the monitored sites as they dispersed to exploit new resource-rich areas. This behaviour could account for the negative relationship observed between cumulative rainfall in the previous year and Pink Cockatoo calls, as increased rainfall leads to a wider distribution of resources and consequently a broader dispersal of the birds away from concentrated areas near permanent water sources (White et al., 2022). Additionally, in 2020, the onset of La Niña likely generated ephemeral water sources in other regions, further facilitating use of the broader arid landscape by these and other birds (Huang et al., 2024).

Another possible reason for the decrease in detections at these monitoring sites is that the previous drought may have significantly impacted Pink Cockatoo populations, reducing their numbers due to lower survival rates or decreased breeding success. Extreme climate events can have profound negative impacts on animal communities (Maron, 2015). While species that inhabit environments prone to low and erratic rainfall may be well-adapted to periods of drought, increased intensity and frequency of these disturbances, such as the severe drought experienced in 2017 to 2019, can push species beyond their tolerance thresholds (Allan et al., 2023; Australian Government, 2024; Chesson et al., 2004; Smith, 2015). Before significant human-induced land clearing, populations affected by drought were likely able to persist through movements to nearby refugia or dispersing to other areas (Maron et al., 2015). Habitat fragmentation and human land-use changes have reduced the accessibility of these critical refuges, limiting the ability of species, like the Pink Cockatoo, to survive extreme events, such as prolonged droughts (Opdam & Wascher, 2004). The resilience of species to such resource bottlenecks is further diminished when disturbances last longer or occur more frequently (Maron, 2015). In the case of Pink Cockatoos, the extended duration of the drought may have reduced their ability to endure the resource bottleneck. This may explain the decreased detections at

monitoring sites, as many individuals may not have survived or may have relocated to other resource-rich areas.

Drought conditions not only affect adult survival but also have a profound impact on the reproductive success of birds, including the Pink Cockatoo. Specifically, drought can exacerbate resource scarcity during critical breeding periods, affecting nestling development and survival (Neate-Clegg et al., 2022). In Western Australia, Rowley and Chapman (1991) observed that fluctuations in rainfall significantly influenced breeding outcomes for the Pink Cockatoos. Hot and dry weather in late spring, especially in years with below-average rainfall, causes annual plants to mature prematurely (Rowlings et al., 2013), and this may have led to a scarcity of seeds with high moisture content during the latter stages of nestling development. The combination of elevated temperatures, low humidity, and reduced availability of moist food sources may increase the likelihood of nestling dehydration and mortality (Neate-Clegg et al., 2022). These reproductive challenges may further compound population declines caused by adult mortality and limited dispersal options, emphasizing the potential negative impact of drought on Pink Cockatoo populations. To fully understand whether this decline is due to actual decreases in population numbers or the birds' use of the broader landscape, a longer-term monitoring study at these sites is necessary.

3.4.1 Other Rainfall Variables

No significant relationship was found between Pink Cockatoo detections and rainfall variables representing monthly or cumulative lagged conditions (e.g., monthly average rainfall and cumulative rainfall over 1, 3, and 6 months). This lack of correlation aligns with findings from a study on rainfall variability in irrigated versus natural areas in arid Australia (Pascoe et al., 2021). The study, which spanned eight years and included both normal and high rainfall periods, observed that the most pronounced changes in bird abundance in response to changes in rainfall occurred in the natural areas, where increases in granivores and insectivores were notable (Pascoe et al., 2021). In contrast, irrigated areas with consistently high productivity showed minimal changes in bird composition during elevated rainfall periods, suggesting that stable, resource-rich environments are less influenced by fluctuations in rainfall than more variable natural environments (Pascoe et al., 2021; Westerhuis et al., 2020). In this study, the highest detections of Pink

Cockatoos occurred near permanent water sources, specifically riparian zones like the Mukudjeroo Waterhole at Naree Station and Gumholes Waterhole at Bowra Wildlife Sanctuary. These riparian areas may function like irrigated zones, offering a stable, productive environment that buffers against rainfall fluctuations and supports higher bird activity, particularly during drought periods.

In another study, drought led to reductions in both bird abundance and diversity of species, although population shifts varied among resident, nomadic, and migratory species, as well as among various dietary groups and specific species (Smith, 2015). However, bird abundance and species diversity remained higher in creek lines and riparian zones despite overall declines (Smith, 2015). This variation underscores the importance of riparian zones, where the stable resources may mitigate environmental stressors like drought (Westerhuis et al., 2020). The different responses of species to fluctuating conditions indicate that drought likely impacts resources unevenly, with each species adapting differently to environmental variability. This complex interaction between species and resources further emphasizes the value of structurally complex, mesic habitats as refugia for a wide range of bird species, particularly in arid environments (Smith, 2015). Access to riparian zones in the study area may explain why Pink Cockatoo detections showed no strong relationship with short-term rainfall variability, as these birds likely relied on the stable resources found in riparian habitats rather than responding directly to rainfall variability. During drought periods, Pink Cockatoos may have retreated to these riparian areas as refuges, where permanent water sources and consistent vegetation provided critical resources to help them endure the dry conditions.

Another reason for the lack of significant relationship between Pink Cockatoo calls and rainfall variables may be the inherently ‘patchy’ nature of rainfall in arid and semi-arid environments. Rainfall in such regions can vary substantially over short distances, resulting in abundant vegetation productivity in some areas while surrounding patches stay dry (Pascoe et al., 2021). Rainfall data obtained from SILO is interpolated to estimate rainfall at each point in a roughly 5 x 5km area, but as a consequence of uneven rainfall these interpolations may lack precision, potentially leading to discrepancies between the recorded and actual rainfall experienced at specific study sites (Queensland Government, 2024). As a result, the rainfall data obtained for our sensor locations may not accurately

reflect the actual precipitation received at the specific sites where Pink Cockatoos were monitored. To explore the influence of rainfall variability on Pink Cockatoos in greater detail in semi-arid areas, local rainfall monitors at each sensor site should be installed in future research projects.

3.4.2 Temperature

This study found no significant relationship between Pink Cockatoo detections and daily maximum temperature. This is in contrast with previous research that has demonstrated that many bird species adjust their activity patterns in response to ambient temperatures to avoid thermal stress (Tieleman & Williams, 2002; Cooper et al., 2002; du Plessis et al., 2012). For instance, du Plessis et al. (2012) found that bird activity generally decreases as temperatures rise, with species in hotter climates showing pronounced reductions in activity during peak heat to minimize the risk of overheating. Similarly, Wolf (2000) reported that desert birds reduce their activity and retreat to thermal refuges when exposed to heat stress to conserve water and energy. Since acoustic detections may reflect activity levels, the lack of a relationship between Pink Cockatoo detections and temperature in our study suggests that Pink Cockatoo may have developed adaptations that enable them to sustain daily activity despite temperature fluctuations. For example, our time-of-day analysis showed increased detections during cooler morning and late afternoon periods, indicating that Pink Cockatoos may already adjust their behaviour to avoid midday heat, making daily maximum temperature less influential on their calling. Additionally, the use of refugia during droughts, as discussed earlier, might have further masked the effects of high temperatures on detections.

3.4.3 Vegetation Greenness

There was no significant relationship between Pink Cockatoo detections and vegetation greenness, despite greenness varying over time and between sites (Figure 14). This finding contrasts with previous research indicating that vegetation greenness, usually obtained from Normalized Difference Vegetation Index (NDVI), is generally correlated with bird abundance as it reflects primary productivity and habitat complexity (Pettorelli et al., 2011; White et al., 2022). High NDVI values are associated with increased photosynthetic activity and, consequently, higher primary productivity (Pettorelli et al.,

2011). Elevated primary productivity can lead to greater food abundance, potentially supporting greater bird populations (Neate-Clegg et al., 2022; Young et al., 2022).

Several factors may explain the lack of a significant relationship between bird detections and vegetation greenness observed in our study. Firstly, vegetation greenness metrics derived from remote sensing primarily indicate the presence of photosynthetic vegetation without differentiating between vegetation types or structural characteristics (Westerhuis et al., 2020). This means that green groundcover (e.g. forbs and grasses) that does not necessarily provide Pink Cockatoos with preferred food resources contributes equally to greenness to green tree cover (which may contain preferred food resources), and a site with 100% green groundcover is indistinguishable from a site with 100% green tree cover. While higher vegetation cover often translates to more resources, the quality of these resources and the structure of the vegetation are equally critical for supporting diverse bird communities (Westerhuis et al., 2020; White et al., 2022). In this study, the riparian zones—characterized by consistent water availability and denser vegetation even under drought conditions (Kingston et al., 2002)—likely provided essential resources that enabled Pink Cockatoos to survive during these periods, despite the low vegetation greenness following the drought. This is consistent with the findings of Neate-Clegg et al. (2022), who reported that in drier years, although overall vegetation greenness was reduced, riparian zones supported increased bird numbers due to their reliable water sources and associated resources. The diverse and layered structure present in riparian zones may enhance habitat suitability beyond what vegetation greenness alone can capture. Additionally, the temporal stability of resources in riparian areas, as opposed to the more variable conditions in non-riparian habitats, provides a reliable environment for birds, mitigating the impacts of climatic fluctuations (Kingston et al., 2002).

For species like the Pink Cockatoo, which can exploit a variety of food resources (Rowley & Chapman, 1991), the presence of critical resources in riparian zones and the seasonal phenology of certain plants may compensate for low vegetation greenness in the surrounding areas. For example, the flowering and fruiting of specific plant species, such as *Acacia* shrubs, are predominantly driven by seasonal changes rather than rainfall variability (Westerhuis et al., 2020). This seasonal phenology ensures the availability of food resources for Pink Cockatoos even during periods of low rainfall and reduced overall vegetation greenness. Consequently, while remote sensing metrics may indicate high

greenness in certain areas, they might not reflect the presence of essential habitat features like specific tree species used for foraging or nesting (White et al., 2022). Therefore, specific vegetation species and the availability of resources like water are likely to be stronger determinants of Pink Cockatoo presence than vegetation cover.

Given the association between Pink Cockatoo detections and water availability, future research may benefit from incorporating additional remote sensing metrics beyond NDVI to capture hydrological variability and vegetation moisture content. One such metric is the Normalized Difference Moisture Index (NDMI), which provides a more accurate measure of vegetation water content and may be better suited for identifying critical habitat features, particularly in semi-arid landscapes where water availability strongly influences vegetation structure and resource distribution (Assal et al., 2015; Acuña et al.2019).

3.5 Conclusion

This chapter has provided critical insights into the temporal distribution patterns of Pink Cockatoos within semi-arid ecosystems, demonstrating how climatic variability—particularly rainfall—shapes their behaviour and resource use. The results suggest that Pink Cockatoos rely heavily on riparian zones and permanent water sources, especially during prolonged dry periods, likely due to the availability of essential resources such as moisture-rich vegetation and shelter. These areas appear to function as ecological refugia, providing stable conditions that mitigate the impacts of extreme weather events (Reside et al., 2019). Increased rainfall following drought periods appears to disperse Pink Cockatoos across a broader landscape, reflecting their local nomadic tendencies in response to resource pulses typical of semi-arid environments. However, this dispersal may also indicate that the species has not fully recovered from the severe 2017-2019 drought. The absence of Pink Cockatoos in Fowlers Gap, the only arid location in this study, raises the possibility that the drought may have led to local extirpation, potentially shrinking their overall distribution range. Long-term acoustic monitoring is required to detect the presence and absence of this species in areas at the periphery of its known distribution and inform conservation planning.

This new understanding of the importance of riparian refugia for Pink Cockatoos, particularly during drought conditions, offers a possible explanation for the lack of detections at Fowlers Gap. Permanent water sources are absent at this location, suggesting that habitats without such resources may be unsuitable, especially during extended dry periods. It underscores the urgent need to protect and sustain these vital refugia in the face of climate change. These insights also raise crucial questions about whether the distribution of Pink Cockatoos is contracting to areas near permanent water sources and what the consequences might be if these critical water sources were to diminish further due to climate change and habitat fragmentation. The need for reliable access to water is not unique to Pink Cockatoos - many species in the arid and semi-arid zone are dependent on water refuges, including bats (particularly during lactation) (Adams & Hayes, 2008), butterflies (Scalercio et al., 2009), anurans (Niknaddaf et al., 2023) and freshwater fishes (Walters et al., 2024).

The study also highlights that Pink Cockatoo call activity is highest in the morning and late afternoon hours; an adaptation to avoid the physiological stresses associated with midday heat. This adaptation may offer some resilience against temperature extremes, but it emphasizes the potential risks posed by prolonged heat as climate change intensifies these events. Although vegetation greenness did not correlate significantly with detections, specific habitat features, such as water availability and plant phenology, probably play a more direct role in influencing Pink Cockatoo distribution patterns.

These findings underscore the importance of protecting riparian zones and permanent water sources within semi-arid ecosystems, particularly as climate change increases the severity and frequency of droughts. By enhancing our understanding of how Pink Cockatoos utilize their habitat in response to temporal and environmental changes, this study contributes valuable knowledge for developing targeted conservation strategies aimed at ensuring the survival of this endangered species in increasingly unpredictable environments.

While this study provides valuable insights into Pink Cockatoo activity and its relationship with environmental variables, it is important to acknowledge the limitations of the study design. The limited number of survey sites may have increased the influence of individual sites on the overall model outcomes. This limitation highlights the need for future research to expand the number of monitoring sites across a broader spatial scale. Doing so would help mitigate site-specific effects and improve the statistical power of analyses, enabling more robust conclusions about the factors driving Pink Cockatoo activity across semi-arid landscapes.

Chapter 4: Conclusion, Conservation Implications and Future Research

4.1 Conclusion

This study provides valuable insights into the habitat use of the endangered eastern Pink Cockatoo in semi-arid ecosystems in Queensland and New South Wales. The findings highlight that proximity to permanent water sources and specific habitat types, such as River Red Gum +/- Coolabah, play significant roles in determining the spatial distribution of Pink Cockatoos at Bowra Wildlife Sanctuary. Additionally, tree diameter at breast height was shown to be an important factor, likely related to the availability of suitable nesting sites. While Pink Cockatoos were detected across a variety of habitats, there were more detections in sites associated with critical resources such as water, large trees for nesting, and a variety of food sources.

Building on these findings, the temporal distribution patterns of Pink Cockatoos at two locations in Queensland and New South Wales revealed a significant negative relationship with cumulative rainfall from the previous year. During the severe drought between 2017 and 2019, Pink Cockatoos concentrated near permanent water sources, which served as ecological refugia providing essential resources (Reside et al., 2019). Higher detection rates at these "wet" sites during the drought underscore the reliance of eastern Pink Cockatoos on riparian zones when surrounding areas have scarce foraging and water resources. Following substantial rainfall events starting in late 2019, Pink Cockatoo detections at these sites decreased. This suggests that increased rainfall may have led to a wider distribution of resources, encouraging the birds to disperse across the broader landscape, reflecting their local nomadic tendencies in response to resource pulses typical of semi-arid environments (Reside et al., 2010; Runge et al., 2015). However, the absence of detections at Fowlers Gap and decline in detections at the other two locations may also indicate ongoing impacts from the severe drought, such as reduced survival rates or breeding success, emphasizing the need for long-term monitoring to fully understand these dynamics.

4.2 Conservation Implications

The results of this research have important implications for the conservation management of Pink Cockatoos and other avian species in semi-arid ecosystems.

4.2.1 Preservation of Riparian Zones

Increased detections of Pink Cockatoos at 'wet' sites during and after drought periods underscores their reliance on these habitats for survival and highlights the significant association between their presence and proximity to permanent water sources. Conversely, the lack of detections at Fowler's Gap, a site lacking permanent water sources, suggests that areas without such resources may become less suitable for Pink Cockatoos, especially during dry periods. This emphasizes the importance of conserving riparian habitats in the arid zone, especially in the context of climate change (Capon et al., 2013; Davis et al., 2013). As semi-arid regions become hotter and drier due to global warming (Neate-Clegg et al., 2022), riparian zones become increasingly critical as refuges that provide essential water, nesting and foraging resources (Neate-Clegg et al., 2022; Westerhuis et al., 2020). Protecting these habitats may involve mitigating threats such as wildfire, invasive weeds and feral animals, and restoring native vegetation along riverbanks to ensure their persistence in the face of changing climate conditions (Neate-Clegg et al., 2022; White et al., 2022; Smith et al. , 2017). By enhancing the resilience of riparian zones, the critical ecological functions that sustain avian populations during periods of drought can be supported (Seavy et al., 2009).

4.2.2 Conservation of Hollow Trees

The positive relationship between Pink Cockatoo detections and larger tree diameter at breast height underscores the necessity of protecting mature trees within these landscapes. These old-growth trees provide essential nesting sites, which are vital for the reproductive success of cavity-nesting birds like the Pink Cockatoo. A significant finding in this study was that Pink Cockatoos in Queensland nest in *Eucalyptus* species such as Coolabah (*Eucalyptus coolabah*) and River Red Gum (*Eucalyptus camaldulensis*), as well as in Whitewood (*Atalaya hemiglauca*). Additionally, Cypress trees are important for nesting in Victoria, and they might also provide nesting sites in Queensland, although this was not observed.

As for other cockatoos and hollow-dependent fauna in Australia (Gibbons et al., 2000)), ensuring the continued availability of preferred mature hollow-bearing trees is crucial for maintaining viable populations of Pink Cockatoos, particularly in the Mulga Lands bioregion which has already been extensively cleared (Jassim et al., 2022). This involves not only protecting existing old-growth trees but also promoting the recruitment of younger trees to become future nesting sites. Overgrazing by herbivores has greatly hindered the recovery and establishment of mature trees with hollows over the past century (Australian Government, 2023). Controlling grazing pressure is therefore essential to allow saplings and young trees to mature, ensuring the long-term availability of suitable nesting habitats (Lindenmayer & Laurance, 2017). By implementing management strategies that protect mature trees and promote their regeneration, we can enhance habitat quality and support the reproductive success of Pink Cockatoos and other cavity-nesting bird species.

4.2.3 Habitat Heterogeneity

The findings of this study indicate that although Pink Cockatoos detections were higher in the River Red Gum +/- Coolabah habitat, they were also found consistently in various other habitat types across Bowra Wildlife Sanctuary. These diverse habitats provide essential nesting sites, foraging grounds, and access to water - all critical resources that support the species throughout the year. Maintaining habitat heterogeneity supports the species' year-round needs and enhances resilience against climatic fluctuations (Virah-Sawmy et al., 2009). The availability and spatial configuration of overlapping resources, such as nesting sites in proximity to foraging grounds and water sources, are crucial for the fitness and population stability of mobile species in dryland ecosystems (Craig et al., 2022; Webb et al., 2017). Heterogeneous landscapes facilitate movement and resource access, which are essential for survival during periods of resource scarcity (Reside et al., 2019; Young et al., 2022). Therefore, conservation plans should focus on preserving and managing a heterogeneous mix of habitats to cater to the diverse ecological requirements of Pink Cockatoos and other semi-arid bird communities.

4.3 Future Research Directions

This study has provided foundational understanding of Pink Cockatoo habitat use in Queensland and the environmental variables that influence their spatio-temporal distribution in semi-arid ecosystems. Several areas warrant further investigation to deepen our ecological knowledge and enhance conservation efforts.

4.3.1 Long-term Monitoring of Pink Cockatoos

Extending the temporal scale of research to include longer-term data collection encompassing a larger range of weather conditions would enable a more comprehensive analysis of how Pink Cockatoos respond to variations in rainfall and temperature. During the last five months of this study, which was conducted after a two-year drought, a severe decline in detections was observed. This decline raises questions about whether the species failed to recover from the drought (as has been documented for other biota in Australia and overseas, e.g. (Hammond, 2019) or simply dispersed to other areas in search of resources. A longer-term study is required to determine the resilience of Pink Cockatoos to prolonged dry periods and to assess the potential impacts of extreme weather events on their populations.

To achieve an extended long-term monitoring program for Pink Cockatoos, several methodologies could be implemented. One approach is to utilize the existing permanent sensors of the Australian Acoustic Observatory that are located within the Pink Cockatoo's distribution range but extend the monitoring period to cover multiple years. This would provide valuable long-term data on the species' responses to environmental changes and help determine whether declines in detections are due to lack of recovery post-drought or dispersal to other areas. Additionally, installing acoustic sensors equipped with onboard recognizers (e.g. Sethi et al., 2020) could facilitate the research by reducing the need for frequent maintenance tasks such as changing batteries and servicing SD cards. These advanced sensors can operate autonomously for extended periods, automatically detecting and recording Pink Cockatoo vocalizations, thus improving data collection efficiency and enabling continuous monitoring with minimal human intervention. Employing these technologies would enhance our ability to monitor the species over longer time frames, providing critical insights and informing effective conservation strategies.

4.3.2 Distance to Water

Designing future research specifically focused on the role of distance to water could provide valuable insights into the relationship between Pink Cockatoos and water sources beyond periods of extensive drought. This research would help disentangle the effects of habitat type (such as River Red Gum and Coolabah trees commonly found near water) from the broader influence of riparian zones themselves. By examining Pink Cockatoo habitat use outside of severe drought conditions, researchers could assess whether the birds' association with water is primarily driven by the availability of specific tree species or by the benefits provided by riparian areas, such as microclimate regulation and increased food and hydration opportunities.

4.3.3 Phenology of Food Resources

Conducting detailed studies on the phenology of key food resources at Bowra Wildlife Sanctuary would provide essential insights into how seasonal changes in food availability influence Pink Cockatoo foraging behaviour and habitat use. Such studies could identify peak periods of food abundance and scarcity, revealing how these periods correlate with the cockatoos' movements, breeding cycles, and habitat preferences (e.g. Poulin et al., 1992). Seasonal fluctuations in food resources can significantly impact the energy budgets and reproductive success of Pink Cockatoos. For instance, a decline in the availability of seeds from key tree species during critical breeding periods could lead to reduced chick survival rates. By mapping out the phenological patterns of these resources, conservation biologists can anticipate periods when the cockatoos may be under nutritional stress. Such mapping of food availability is becoming increasingly available with high resolution satellite imagery such as Sentinel 2 (Funghi et al., 2020).

This information is critical for aligning conservation actions with periods of resource abundance and scarcity. For example, habitat management practices such as controlled burns or invasive species removal can be timed to avoid disrupting food availability during critical feeding periods. Additionally, restoration efforts can prioritize planting native vegetation that provides continuous or sequential food resources throughout the year, thereby reducing the impact of seasonal shortages.

Furthermore, understanding the phenology of food resources can help predict how climate change might alter these patterns. Recent studies have documented shifts in the phenology of various plant species due to climate change, indicating that flowering and fruiting times are advancing or delaying in response to changing temperature and precipitation (Beaumont et al., 2015; Gordo, 2007; Westerhuis et al., 2020; Young et al., 2022). This could lead to potential mismatches between food availability and the cockatoos' life history events, such as breeding. Anticipating these changes allows for proactive management strategies, such as creating corridors to facilitate movement to areas with more favourable conditions.

4.3.4 Breeding Ecology

Investigating the factors influencing the selection and success of nesting sites is essential for enhancing the understanding of Pink Cockatoo breeding ecology. Key factors to examine include tree species, diameter at breast height (DBH), proximity to water and food resources. Tree species are pivotal as different species offer varying structural attributes and availability of cavities, which are crucial for nesting. For example, in Victoria and Western Australia, Pink Cockatoos have been observed using different tree species for nesting, while in Queensland, they utilize at least two distinct species, suggesting regional variation in tree use and nesting preferences. Larger trees with greater DBH are typically preferred because they are more likely to possess suitable cavities that provide protection from predators and harsh environmental conditions (Adkins, 2006; Gibbons et al., 2000). Additionally, nesting sites located closer to water sources may offer enhanced foraging opportunities and more reliable access to hydration, thereby increasing the likelihood of breeding success (Craig et al., 2022).

To comprehensively understand breeding site dynamics, comparative studies across different semi-arid and arid ecosystems is necessary. Such studies can reveal how Pink Cockatoos modify their nesting preferences in response to varying environmental conditions and resource availability. For instance, in regions with scarce water resources, proximity to water might be a more critical determinant of nesting site selection compared to areas with abundant water availability. Furthermore, examining nesting success rates in relation to these factors can identify which habitat attributes are most beneficial for chick

survival and overall reproductive output. Additional considerations include the influence of anthropogenic factors such as habitat fragmentation, land use change, and the presence of invasive species, which can impact the availability and quality of potential nesting sites. Understanding how these factors interact with natural determinants like tree species and water proximity can inform targeted conservation strategies.

4.3.5 Development of a Species Distribution Model

To comprehensively understand Pink Cockatoo habitat use and predict their distribution under various environmental scenarios requires the development of a Species Distribution Model (SDM). SDMs integrate ecological data with spatial distribution to generate predictive maps that illustrate where a species is likely to be found based on key habitat attributes and environmental conditions (Elith & Leathwick, 2009).

Building a Species Distribution Model (SDM) for Pink Cockatoos would involve incorporating comprehensive data on key habitat features, resource availability, and environmental variables relevant to their distribution (Runge et al., 2015; Stojanovic et al., 2022). This SDM would not only help in predicting current habitat suitability but could also be used to forecast future changes under various climate scenarios. For example, understanding how potential mismatches between food availability and the cockatoo's breeding season might impact their distribution can guide adaptive management strategies. Additionally, these models could inform conservation actions, such as prioritizing areas for habitat restoration and protection or anticipating areas where the species might shift due to environmental pressures (Fleishman et al., 2003).

4.3.6 Interspecific Competition for Hollows

Future research should explore the role of interspecific competition between Pink Cockatoos and Galahs, as competition for hollows between these birds have been documented in both Victoria and in Western Australia (Hurley, 2022; Rowley & Chapman, 1991). This competition poses a significant threat to Pink Cockatoos, with competition for suitable cavities in Victoria escalating over the past two decades to a more pressing concern than the availability of hollows themselves (Hurley, 2006). Monitoring nest hollows with cameras can provide valuable insights into the dynamics of such

interactions, revealing how competition influences nesting outcomes, site fidelity, and chick survival. This approach can also help identify potential threats from invasive species or predators, enabling targeted conservation interventions to improve Pink Cockatoo breeding success and population stability.

4.4 Final Thoughts

This study represents the first scientific investigation of the habitat use and spatio-temporal distribution of the endangered eastern Pink Cockatoo in Queensland and New South Wales. It has provided critical knowledge regarding nest tree preferences and valuable insights on the importance of permanent water, as well as the influence of rainfall. Importantly, this research has developed a species recognizer that can efficiently scan hours of acoustic recordings to detect the presence of Pink Cockatoos, enhancing future monitoring capabilities. Additionally, we have identified the optimal times of day for configuring acoustic sensors to maximize survey efficiency and avoid resource wastage. Finally, this study establishes a baseline for future comparisons as climate change continues to impact Pink Cockatoo populations. Such knowledge is essential for the conservation and long-term survival of this iconic species.

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Appendices

Appendix A: Vegetation measurements recorded from single-point-in-time vegetation surveys using the line intercept method with four 25m line transects corresponding to cardinal points around each sensor

Measurement	*Description*	*Tools used*	*Unit*
Tree Species	Identification of tree species along a 25m transect line for every cardinal point.	A guide of plants of inland Australia (Moore, 2005)	Scientific name
Tree Height	Height of each tree along a 25m transect line for every cardinal point.	Rangefinder	Meters
Tree DBH	Diameter at breast height (DBH) of each tree was measured along a 25m transect line for every cardinal point.	DBH tape	Centimeters
Shrub Species	Identification of shrub species between 1-3m in height along a 25m transect line for every cardinal point.	A guide of plants of inland Australia (Moore, 2005)	Scientific name
Shrub Height	Height of each shrub along a 25m transect line for every cardinal point.	8m measuring tape	Meters
Canopy Cover	Percentage of canopy cover over the 25m transect line for every cardinal point.	60m measuring tape	Percentage
Subcanopy Cover	Percentage of subcanopy cover over the 25m transect line for every cardinal point.	60m measuring tape	Percentage

Appendix B: Site names and corresponding vegetation types based on vegetation survey data

Site	*Vegetation Type*
A2OWB	Coolabah
AMF	Coolabah
AMA	Coolabah
AM8	Coolabah
AM15	Coolabah
AMH	Cypress
AM7	Cypress
AM5	Cypress
AMI	Gidgee
AM10	Gidgee
AM16	Gidgee
AM12	Shrubland
A2ODA	Mulga
AM17	Mulga
A20DB	Mulga
AMG	Mulga
AM18	Poplar
AMB	Poplar
AMJ	Poplar
A2OWA	River Red Gum
AMC	Shrubland
AM3	Shrubland
AME	Whitewood
AM13	Whitewood
AMD	Whitewood
AM6	Whitewood

Appendix C: Percentage of habitat type based on AWC vegetation map per sensor in Bowra Wildlife Sanctuary

Abbr..	*Cypress*	*Whitewood*	*Coolabah*	*Grassland*	*Gidgee*	*River Red Gum +/- Coolabah*	*Mulga*	*Poplar*
Full name	Cypress Pine +/- Ironwood open woodland on red quartzose sand dunes	Whitewood, Wilga and Ironwood open woodland on red quartzose sands	Coolabah open woodland on cracking alluvial clay plains	Grasslands (Mitchell grassland +/- chenopods; grassland and/or chenopod herbland on seasonally bare claypans; Eriachne grassland with emergent Mulga on stony tablelands; Atriplex shrubland)	Gidgee woodland to forest on clays	Red Gum +/- Coolabah on creek channels and levees	Mulga (Mulga Woodland on stony tablelands and escarpment edges- silcrete, quartz sandstone and sandy conglomerate; Mulga woodland on residual sandy earths including large areas of regrowth; Mulga woodland on sloping calcareous labile sandstone and silicified ferruginised sediments)	Poplar Box woodland +/- Coolabah on alluvium
A20DB	0	0	0	0	0	0	100	0
A2ODA	0	0	0	0	0	0	96	0
A2OWA	0	63	0	3	0	34	0	0
A2OWB	26	25	11	8	0	30	0	0
AM10	26	0	3	17	3	0	0	51
AM12	17	8	0	75	0	0	0	0
AM13	0	70	0	0	30	0	0	0
AM15	12	24	43	21	0	0	0	0
AM16	3	0	0	47	50	0	0	0
AM17	0	28	0	3	0	0	70	0
AM18	0	1	51	30	17	0	0	0
AM3	100	0	0	0	0	0	0	0
AM5	80	8	0	7	5	0	0	0
AM6	18	63	0	8	11	0	0	0
AM7	100	0	0	0	0	0	0	0
AM8	14	21	0	0	0	63	0	1
AMA	42	12	12	14	20	0	0	0
AMB	14	7	0	17	18	0	0	43
AMC	87	0	0	0	13	0	0	0

AMD	0	51	0	22	26	0	0	0
AME	37	42	0	0	0	21	0	0
AMF	0	26	0	3	16	39	0	7
AMG	0	0	0	0	0	0	98	0
AMH	96	4	0	0	0	0	0	0
AMI	30	4	0	1	64	0	0	0
AMJ	86	0	0	0	0	0	0	14

Appendix D: Model results for all environmental variables related to total Pink Cockatoo detections

Model	*Environmental Variable*	*df*	*Effect size*	*SE*	*z-score*	*p-value*	*AIC*	*R2m*
1	Distance to permanent water	22	-0.964	0.257	-3.75	0.0001	340.01	0.37
2	Tree DBH	22	0.813	0.281	2.897	0.004	343.9	0.26
3	Canopy cover total	19	0.179	0.269	0.665	0.506	344.9	0.45
	Sub-canopy cover total		0.063	0.298	0.211	0.833		
	Shrub cover total		-0.160	0.263	-0.609	0.542		
	Distance to permanent water		-0.924	0.257	-3.591	0.000		
4	River Red Gum +/- Coolabah	22	0.648	0.293	2.209	0.027	346.8	0.16
5	Canopy cover total	17	0.071	0.331	0.216	0.829	351.3	0.33
	Sub-canopy cover total		-0.004	0.289	-0.016	0.988		
	Shrub cover total		0.001	0.303	0.004	0.997		
	Tree DBH average		0.477	0.363	1.315	0.189		
	Tree height average		0.472	0.404	1.169	0.242		
	Shrub height average		-0.173	0.283	-0.611	0.541		
6	Cypress	13	-1.066	5.830	-0.183	0.855	358.7	0.344
	Whitewood		-0.464	3.572	-0.13	0.897		
	Coolabah		-0.246	2.136	-0.115	0.909		
	Grassland		-0.719	2.174	-0.33	0.741		
	Gidgee		-0.542	2.791	-0.194	0.846		
	River Red Gum +/- Coolabah		-0.199	2.780	-0.072	0.943		
	Shrubland		-0.392	1.066	-0.368	0.713		
	Mulga		-0.681	5.529	-0.123	0.902		
	Poplar		-0.533	2.142	-0.249	0.804		
Null		23	4.670	0.318	14.74	2.00E-16	349.3	0.99

Appendix E: Correlation Matrix of Rainfall, Vegetation Greenness, and Maximum Temperature.

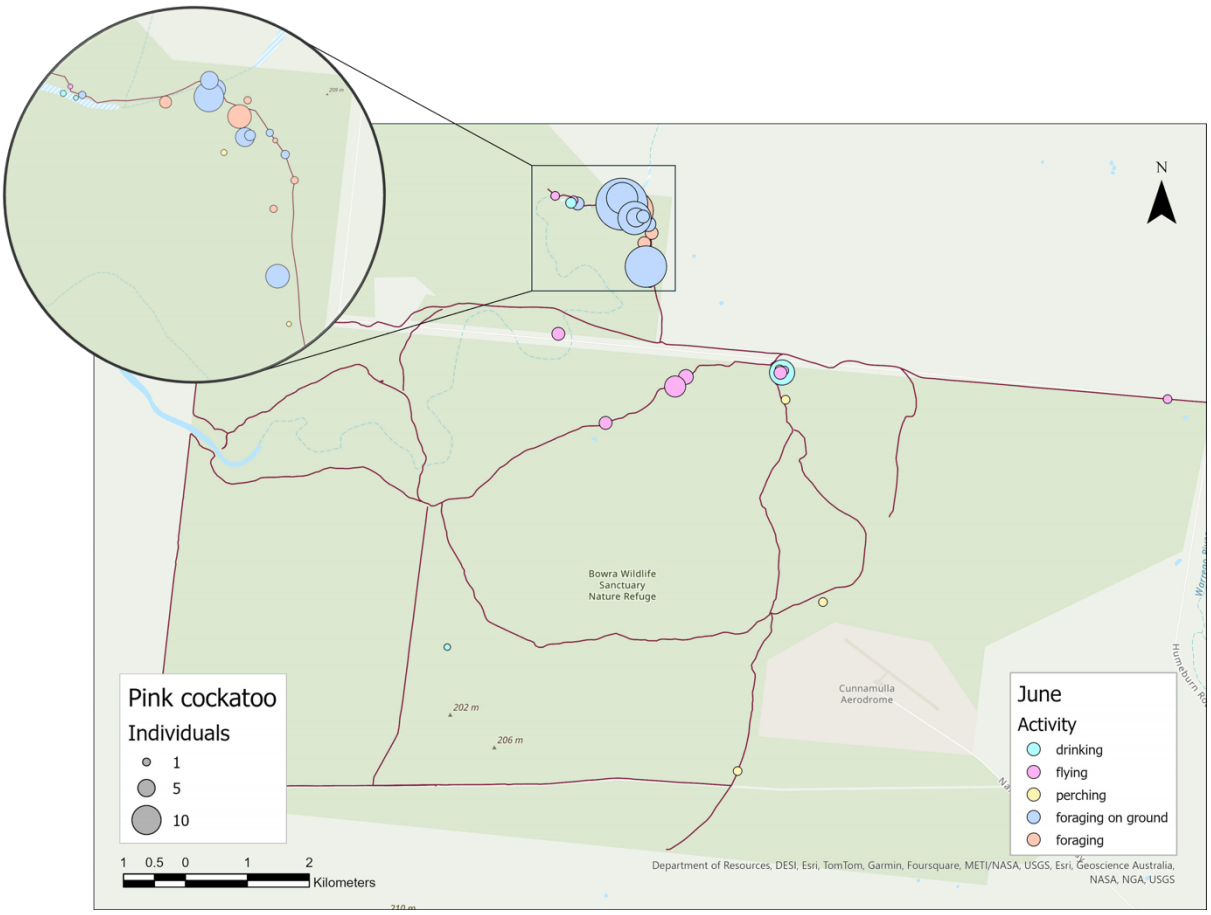
The table presents the Pearson correlation coefficients between monthly average rainfall, cumulative rainfall over various periods (previous month, previous 3 months, previous 6 months, previous year), vegetation greenness, and maximum temperature. Strong positive correlations are observed between monthly average rainfall and cumulative rainfall from the previous month (r = 0.88), cumulative rainfall over the previous 3 months and 6 months (r = 0.95) and a strong negative correlation between cumulative yearly rainfall and maximum temperature (r = -0.96).

	Rainfall (monthly Avg)	***Rainfall (cumulative prev. month)***	***Rainfall (cumulative prev. 3 months)***	***Rainfall (cumulative prev. 6 months)***	***Rainfall (cumulative prev. year)***	***Vegetation greenness***	***Temp max***
Rainfall (monthly Avg)	1.00	0.88	0.42	0.36	-0.25	0.26	0.41
Rainfall (cumulative prev. month)	0.88	1.00	0.63	0.59	-0.13	0.22	0.32
Rainfall (cumulative prev. 3 months)	0.42	0.63	1.00	0.95	0.64	-0.03	-0.50
Rainfall (cumulative prev. 6 months)	0.36	0.59	0.95	1.00	0.63	-0.01	-0.50
Rainfall (cumulative prev. year)	-0.25	-0.13	0.64	0.63	1.00	-0.26	-0.96
Vegetation greenness	0.26	0.22	-0.03	-0.01	-0.26	1.00	0.29
Temp max	0.41	0.32	-0.50	-0.50	-0.96	0.29	1.00

Appendix F: Model results relating total Pink Cockatoo detections and temporal variables

Model	*Environmental Variable*	*df*	*Effect size*	*SE*	*z-score*	*p-value*	*AIC*	*R2m*
A	rain_month_ave	175	-0.325	0.364	-0.895	0.371	467.3	0.02
	c.rain_pre3month	0	0.009	0.342	0.026	0.979		
	frac_cover	0	0.202	0.348	0.580	0.562		
	temp_max	0	0.157	0.340	0.462	0.644		
B	rain_month_ave	175	0.049	0.348	0.140	0.889	466.3	0.03
	c.rain_pre3month	0	-0.445	0.380	-1.171	0.242		
	c.rain_preyear	0	0.420	0.382	1.100	0.271		
	frac_cover	0	0.324	0.358	0.905	0.366		

Appendix G: Maps representing the activity of Pink Cockatoos during June-August according to the visitor sheets collected at Bowra. The size of the circles represents the number of individuals while the colour represents the activity of the individuals.



N
Bowra Wildlife
Sanctuary
Nature Refuge
Cunnamulla
Aerodrome
202 m
206 m
Pink cockatoo
Individuals
1
5
10
July
Activity
flying
perching
foraging on ground
foraging
allopreening
crest raising
1 0.5 0 1 2
Kilometers
Department of Resources, DESI, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS, Esri, Geoscience Australia, NASA, NGA, USGS

N
Bowra Wildlife
Sanctuary
Nature Refuge
Cunnamulla
Aerodrome
202 m
206 m
Pink cockatoo
Individuals
1
5
10
August
Activity
drinking
flying
perching
foraging
1 0.5 0 1 2
Kilometers
Department of Resources, DESI, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS, Esri, Geoscience Australia, NASA, NGA, USGS

Appendix H: Detailed results of the simplified generalized linear mixed model (glmm) relating environmental variables to Pink Cockatoo detections.

	df	*Effect size*	*SE*	*z-score*	*p-value*
temp_max	72	0.080	0.101	0.796	0.426
c.rain_premonth		-0.061	0.066	-0.935	0.350
c.rain_pre3month		0.095	0.088	1.080	0.280
c.rain_preyear		-0.033	0.082	-0.400	0.690
green_1000		-0.257	0.124	-2.082	0.037

Appendix I: Correlation Matrix of Rainfall, Vegetation Greenness, and Maximum Temperature.

The table presents the Pearson correlation coefficients between monthly average rainfall, cumulative rainfall over various periods (previous month, previous 3 months, previous 6 months, previous year), vegetation greenness, and minimum and maximum temperature.

	Rainfall (monthly Avg)	***Rainfall (cumulative prev. month)***	***Rainfall (cumulative prev. 3 months)***	***Rainfall (cumulative prev. 6 months)***	***Rainfall (cumulative prev. year)***	***Temp min***	***Temp max***	***Vegetation greenness***
Rainfall (monthly Avg)	1.00	0.91	0.05	-0.07	0.21	0.55	0.24	0.04
Rainfall (cumulative prev. month)	0.91	1.00	0.03	-0.08	0.17	0.50	0.20	0.07
Rainfall (cumulative prev. 3 months)	0.05	0.03	1.00	0.70	0.53	-0.13	-0.37	0.43
Rainfall (cumulative prev. 6 months)	-0.07	-0.08	0.70	1.00	0.58	-0.62	-0.79	0.37
Rainfall (cumulative prev. year)	0.21	0.17	0.53	0.58	1.00	0.01	-0.13	0.46
Temp min	0.55	0.50	-0.13	-0.62	0.01	1.00	0.87	-0.02
Temp max	0.24	0.20	-0.37	-0.79	-0.13	0.87	1.00	-0.10
Vegetation greenness	0.04	0.07	0.43	0.37	0.46	-0.02	-0.10	1.00