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Gang-gang Cockatoo breeding in relation to altitude, latitude and long-term and concurrent temperature and rainfall, across parts of the ACT, NSW and Victoria

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Abstract. Rising temperatures are a factor linked to Gang-gang decline. A large citizen science effort over three years recorded the number of fledglings raised and the timing of fledging for 85 nesting events from 11 regions across south-east Australia. The timing of fledging was related to altitude, but not latitude, at the nest site location, with earlier fledging at lower altitudes. We tested whether the timing of fledging was associated with measures of rainfall and temperature over the last 50 years. Of these, we only found a correlation between earlier fledging and a measure of high breeding season rainfall. The number of chicks fledged from successful nests was not significantly related to altitude or latitude. However, the number of chicks fledged was significantly higher, on average, from nests at long-term warmer and wetter sites, but lower from nests with higher maximum temperatures during the concurrent breeding seasons. Predicted increases in the regularity and earlier timing of extreme daily temperatures under climate change may cause greater loss of chicks from heat exhaustion. This risk is exacerbated by the predicted increases in intense rainfall events as this may lead to more frequent drowning of young in hollows. Gang-gangs may have some resilience to these increasing risks of climate change. At lower altitudes, early fledging enables Gang-gang nestlings to largely avoid the hotter and stormier days of mid and late summer. Conversely, later fledging at high altitudes means chicks are more likely to avoid cold snaps and frosts in late spring, but are then more exposed to unfavourable late summer climate. Gang-gang nest hollow selection of well-insulated hollows in hot seasons and good draining hollows in wet seasons may provide additional resilience.

Keywords: Gang-gang Cockatoo; *Callocephalon fimbriatum*; fledging date; nest hollow; breeding success; temperature; rainfall; altitude

INTRODUCTION

The Gang-gang Cockatoo *Callocephalon fimbriatum* (Cacatuidae) is a small (230-334g) stocky cockatoo. It is a wide-ranging species endemic to the forests, woodlands and urban areas in cool-temperate south-eastern Australia. On 2 March 2022 the Gang-gang was listed as nationally endangered. Key threats to the Gang-gang are thought to be wildfire and other climate change impacts, competition for suitable nesting hollows and loss of nesting and foraging habitat through logging, agriculture and urban encroachment (DAWE 2022). Concern on the degree of loss caused by the 2019-2020 wildfires, led to Commonwealth bushfire recovery funding, some of which was utilised to cover our research costs.

Smith and Smith (2019) in their 2018 survey of Gang-gangs in Hornsby Shire, NSW, failed to record any Gang-gangs in areas where from 1970-2010 they were commonly sighted. They concluded that this species in the Hornsby and Ku-ring-gai Local Government Areas was then very close to extinction, if not already so. They noted that a similar decline had occurred within a 20 km radius of their study area and at the lower elevations of the Blue Mountains. These areas are within the most northern and lower extent of the Gang-gang's range. They noted that this species is adapted to cooler conditions and has always been more common at higher elevations and more southern latitudes. They hypothesized that as the climate warms up, Gang-gang Cockatoos can be expected to decline at lower elevations in the northern parts of their distribution.

During the 2019-2020 breeding season, Canberra experienced record high temperatures and high levels of smoke haze. Davey and Mulvaney (2020) suspected that heat exhaustion caused the death of two nestlings and caused four others to prematurely leave the nest and three fall from the nest hollow prior to fledging. In late December 2019, a dead chick was also found at the base of a nest tree during a run of very high temperatures and smoky conditions at Woodhill Mountain, NSW. Premature exit from a tree hollow in Canberra has only been observed three other times over an additional six years of hollow watching from 2017-2024. Sindel and Lynn (1988, p. 154) noted that in aviaries chicks from pin feather stage to fledging are vulnerable to death from heat exhaustion if left in their nesting log during temperatures above 35°C.

This paper reports on Gang-gang breeding activity identified and monitored by citizen scientists in south-eastern Australia over three breeding seasons. We recorded the timing of nesting and fledging, as well as breeding success, in order to gauge whether these differ across an altitudinal or latitudinal gradient

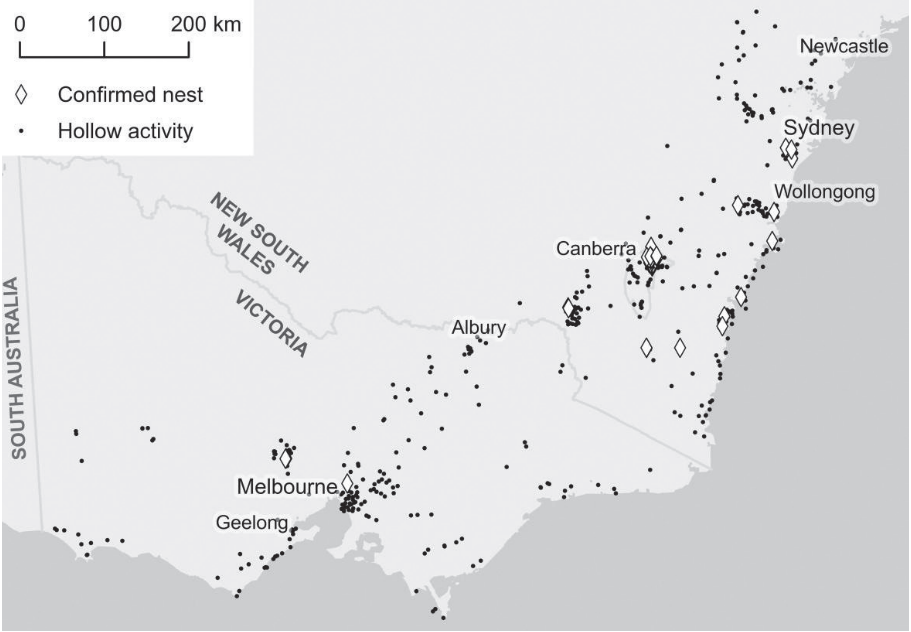

Figure 1. *Location of Gang-gang tree hollow activity reports (black points) and confirmed nests (open diamonds).*

over the Gang-gang's range, and whether such a difference might be linked to variation in long-term or contemporary temperatures and rainfall.

METHODS

Gang-gang breeding activity was recorded over three spring-summer breeding seasons: 2021-22, 2022-23 and 2023-24. Monitored sites included 23 known active nest trees, located as part of surveys over the three previous seasons in the Canberra area (Davey *et al.* 2021). Fifteen of these nests were used at least once in the three breeding seasons of the current study. To locate further nests across the Gang-gang's distribution, we invited users of the online wildlife sighting platforms NatureMapr (then covering the ACT and south-eastern NSW) and iNaturalist (global coverage) to record and upload images of Gang-gangs entering or looking into tree hollows, together with the date and location of each sighting. Talks and promotional material were provided to bird clubs in the Blue Mountains, Campbelltown, Canberra, the NSW South Coast and to Birdlife Australia, while interviews on ABC radio in Canberra, Sydney and Bega encouraged people to report any Gang-gang activity in or around tree hollows, via the online platforms. During the study period, 1312 tree hollow activity sightings were added to the NatureMapr platform, and 460 to iNaturalist. Seventy-nine percent of all sightings were from the ACT, largely because it had an established team of enthusiastic reporters prior to the study commencing. Additionally, in 2021 COVID restrictions limited travel and on-ground encouragement of participants outside the ACT; and finally, more direct encouragement of and communication with users was possible on the Canberra-based NatureMapr platform compared to iNaturalist. Additional observations from the Campbelltown, NSW area and Plenty Creek in Melbourne (Vic.) were organised via Facebook. Hollows in the Campbelltown area were identified with the assistance of the local Council and tapped into the knowledge of local bird observers (Munson 2021). The locations from which citizen scientist sightings were received are shown in Figure 1.

Hollows with multiple sightings reported, or where Gang-gangs were recorded within them, were prioritised for further investigation. Over the three seasons, 391 hollows were checked for Gang-gang nesting occupancy across 11 regions: Canberra, ACT (n=267), Melbourne, Vic. (43), Cooma, NSW (21), Southern Highlands NSW (21), NSW South Coast (10), Central Victoria (8), Tumbarumba, NSW (8), Campbelltown, NSW (5), Albury, NSW (5), Blue Mountains, NSW (2) and East Gippsland, Vic. (1). Hollow checking involved direct observation from the ground, scratching of tree trunks to draw a hollow occupant response and in the Canberra and Cooma areas the use of 10, 12 or 18 m squid or antennae telescopic poles to which a plumber's WiFi endoscope was attached, which relayed images of the insides of a hollow to a handheld mobile phone. Ground observation and scratching occurred across the breeding season, while pole checking occurred in late November and early December, which is towards the end of the 3-4 week incubation period or early in the 7-8 week nestling development period. In the Canberra area, if no Gang-gang activity was observed after repeated visits to a nest in which eggs were laid it was again pole-checked to determine whether the nest had been abandoned or predated. Fourteen of Canberra's nest trees were climbed and hollows visually inspected. Motion sensor cameras were erected on two of these hollows during the 2022-2023 season and on four hollows during the 2023-2024 season. Pole-checking was limited outside of the Canberra region due to COVID travel restrictions and the much higher height of hollows on the NSW coast and Victoria (≈20 m, in contrast to ≈6.5 m in Canberra). In these areas, observers were provided with a guide to Gang-gang hollow nesting behaviours (Mulvaney *et al.* 2022) and asked to regularly watch hollows and record any indicative activity.

At all hollows identified as a Gang-gang nest hollow, observers were asked to record the number and sex of fledglings and the date they left the nest. Once a chick was sighted, near daily visits to a nest were made in an effort to observe fledging. For a period of up to 11 days prior to fledging, adults tend to only feed young from the rim of the hollow, during which time chicks may be visible and adult feeding behaviour can be observed.

Statistical analyses

We used linear mixed-effects models (LMMs) in R version 4.4.0 to analyse whether 1) the number of chicks fledged ('fledging success') and 2) the fledging date of the first-fledged chick from each nest ('fledge timing') were related to nest altitude and latitude, or to climate variables at the nest location. We did not include nest longitude in our analyses as it is strongly correlated with nest latitude in our dataset. Fledging data was derived from 59 successful breeding events over three seasons. The effects of locational and climate predictor variables were analysed in separate models due to differences in sample size resulting from how these variables were sourced (see below).

For the models examining the timing of fledging, the response variable was 'number of days after December 8' (the earliest fledge date in any season). Twenty-six unsuccessful nesting events were excluded (Davey *et al.* 2025), leaving 59 successful nests included in the fledge timing analyses. Where more than one chick fledged from a nest, only the fledging date of the first-fledged chick was used in the analysis. Of the 20 nesting events from which two chicks fledged, the average time between each fledging event was 2.25 days, with a range of zero to seven days. At five nesting events, adults were observed feeding chicks near the hollow entrance but chicks were not sighted. Estimates of fledging date for these nesting events were determined on the basis that such feeding is usually only observed within 11 days of fledging, with the estimate derived by subtracting the number of days birds were observed feeding from the 11 day maximum.

For the models examining the number of chicks fledged, unsuccessful nests, as well as five nests where the exact number of fledglings was uncertain, were excluded from analyses as the use of pole-checking in the Canberra region made the detection of unsuccessful nests more likely, introducing a bias. This left 54 nests for inclusion in these analyses.

Nest altitude and latitude were obtained for each nest tree using a handheld GPS device on the ground. For the models examining fledging success and fledge timing in relation to nest altitude and latitude, we included breeding season as a random effect to account for unmeasured differences between years.

We obtained climate data for the 50-year period July 1974 - June 2024, interpolated across a 5 km grid covering the entire study region, from the Scientific Information for Land Owners database (SILO: https://www.longpaddock.qld.gov.au/silo/). Each nest was assigned the temperature and rainfall values of its nearest grid point. We examined both long-term and concurrent climate variables. Long-term variables were calculated across the period July 1974 - June 2024 and included the median total rainfall for each month from November to February and the long-term average maximum temperature for each month from November to February, as well as the highest recorded temperature and the average number of days per year above 35°C and above 40°C, at each grid point. Concurrent climate variables reflected the given breeding season (2021-22, 2022-23, or 2023-24) and included the total rainfall for each month from November to February, the average maximum temperature for each month from November to February, and the highest maximum temperature recorded in the given breeding season, at each grid point. We also divided monthly rainfall and maximum temperature values over the 50 years into deciles, to explore whether there was any relationship between the number of chicks fledged or timing of fledging and whether concurrent rainfall and temperatures were comparatively high or low.

Given the large number of related climate variables, we identified a subset of variables for use in analyses by examining the correlation matrices for the set of long-term climate variables and the set of concurrent climate variables. Within the long-term dataset, rainfall variables were highly correlated and temperature variables were highly correlated, but temperature variables were not significantly correlated with rainfall variables. We selected the long-term maximum recorded temperature and the median February rainfall as representative predictors for inclusion in analyses, as these were related to the most other temperature or rainfall variables, respectively, and were strongly related to nest site altitude, latitude and longitude. Within the concurrent climate dataset, rainfall variables were moderately correlated and temperature variables were moderately correlated, but most rainfall variables were not significantly correlated with temperature variables. We selected the highest maximum temperature recorded, December rainfall, and the January rainfall and temperature deciles for inclusion in analyses.

The nest hollow locations of the 59 successful nesting events were distributed unevenly across the total study area, and were represented by interpolated climate data from 19 distinct grid points (Table 1). While most of these grid points corresponded to a single nest tree, three grid points corresponded to clusters of nests within Canberra (6 – 18 nest trees per grid point, with up to 10 nests sharing a grid point in the same breeding season). The nests in each cluster are assumed to have experienced the same temperatures and rainfall in our dataset. Using climate grid point as a random effect in our models cannot resolve this pseudoreplication as the groups created by this method have invariant climate predictors. Instead, we used the median fledge date for each cluster of nests in each breeding season as a single representative data point in place of the individual nesting events.

The model for fledging success in relation to climate variables was constructed identically to the model for fledge timing in relation to climate variables. Again, where clusters of nests shared the same climate grid point, we calculated a single data point for each cluster and breeding season, taking the mean number of chicks fledged, to avoid pseudoreplication in the model. We included breeding season and climate grid point ID as random effects in both models to account for unmeasured differences between locations and years. The climate variables detailed above were mean-standardised (centred and scaled) and used as fixed predictors in the analyses.

We examined the variance inflation factor (VIF) of each fixed predictor in the models to identify any strongly correlated predictor variables, and inspected the model marginal and conditional R^2, which respectively estimate the variance explained by the fixed effects and the fixed + random effects (i.e. the full model) of a mixed-effects model (Nakagawa and Schielzeth 2012). We used hierarchical partitioning to assess the individual contribution of each fixed predictor to explaining the observed variation in the response variables. Statistical significance of individual model predictors was calculated using type III anova via Satterthwaite's degrees of freedom method (Kuznetsova *et al.* 2017).

Table 1

Climate grid localities at which nests that successfully fledged chicks were observed. Note that a few nest trees housed active nests in two, or all three of the seasons studied. Of the large Canberra cluster with 18 nest trees sharing the same nearest grid point, 10, 7 and 9 housed active nests in the 2021-22, 2022-23, and 2023-24 breeding seasons, respectively.

Locality	No. nest trees	Nest altitude (m.a.s.l.)	Habitat
NSW: Smith's Creek, Campbelltown (North)	2	80-90	Coastal Valley Grassy Woodlands
NSW: Smith's Creek, Campbelltown (South)	1	85	Coastal Valley Grassy Woodlands
NSW: St Helens Park, Campbelltown	1	115	Coastal Valley Grassy Woodlands
NSW: Woodhill	1	375	Sydney Coastal Dry Sclerophyll Forests
NSW: Penrose	1	680	Sydney Hinterland Dry Sclerophyll Forests
NSW: Huskisson	1	6	Coastal Dune Dry Sclerophyll Forests
NSW: South Durras	1	25	Southeast Dry Sclerophyll Forests
NSW: Moruya	1	10	Southern Lowland Wet Sclerophyll Forests
ACT: Black Mountain Sandstone (inner NW Canberra)	6	600-670	Dry Sclerophyll Forest (3 nests), Box Gum Woodland (2 nests), Amenity Planting (1 nest)
ACT: National Botanic Gardens	1	610	Amenity Planting
ACT: NE Canberra (including Mt Majura)	7	580-725	Dry Sclerophyll Forest (3), Box Gum Woodland (2), Urban street tree (1), Urban school (1)
ACT: Southern Mt Ainslie	1	650	Box Gum Woodland
ACT: Campbell Park	1	595	Box Gum Woodland
ACT: North Woden (including Red Hill Reserve)	18	610-690	Box Gum Woodland (12), Urban Open Space (4), Dry Sclerophyll Forest (1), Urban Street Tree (1)
NSW: Tumbarumba	2	650	Rural residential (Candlebark Woodland)
NSW: Wadbilliga	1	880	Southern Escarpment Wet Sclerophyll Forests
VIC: Plenty Gorge	2	55	Ribbon Gum Riparian Forest
VIC: Wombat State Forest (East)	1	750	Herb-rich Foothill Forest
VIC: Wombat State Forest (West)	1	750	Herb-rich Foothill Forest

RESULTS

Over the three years of this study, 69 different nest sites and 85 nesting events were observed. Successful nests (those that fledged chicks) were found at 19 localities (Table 1). Eighty-seven fledglings were observed at 46 nest sites (54 nesting events) across all three years, with a further five nesting events considered to have been successful based on the behaviour of the adults. Eighty percent of the total nesting events were observed in the Canberra area.

The earliest fledging event was recorded in the 2021-22 season and occurred on December 8 at Campbelltown, NSW. Another Campbelltown nest and a nest at Moruya on the NSW south coast had both fledged by December 13. These nests from low-lying areas in the north-eastern part of the range fledged around three weeks earlier than nests elsewhere in the Gang-gang's range. The median fledge date for that year was January 14, 37 days after December 8. The median fledge dates for the 2022-23 and 2023-24 seasons were January 18 and January 5, respectively (i.e., 41 and 28 days after December 8). During the 2022-23 season, chicks from Campbelltown and the NSW south coast fledged quite late, while fledging dates among the nests observed in the Canberra area spanned the range seen across all localities that season. In the 2023-24 season, chicks from Campbelltown and the NSW south coast again fledged around two weeks earlier than elsewhere.

There was very little variation in the number of chicks fledged from successful nests in our study, with either one or two fledglings produced, and an average of 1.6 ± 0.4 fledglings per successful nest.

Fledging in relation to altitude and latitude

Lower-altitude nests fledged earlier in the season than those from higher-altitude nests (slope ± standard error: 0.03 ± 0.01 days, $F_{1,56} = 9.6$, $p = 0.003$; Fig. 2). The timing of fledging was not related to nest latitude ($F_{1,56} = -0.8$, $p = 0.43$). Marginal R^2 for this model was 0.15, indicating that together these two fixed-effect predictor variables account for around 15% of the observed variation in fledge timing. The number of chicks fledged from successful nests was not related to either nest altitude ($F_{1,56} = 0.0001$, $p = 0.99$) or nest latitude ($F_{1,56} = 1.3$, $p = 0.25$).

Fledging date, temperature and rainfall

The model for fledge timing in relation to climate variables had a conditional R^2 of 0.46, indicating that the variables included in the full model (including both the fixed and random effects) explained nearly half of the observed variation in fledging dates. However, the marginal R^2 was also 0.46, and the lack of difference between marginal and conditional R^2 indicates that the random effects (a nest's nearest climate grid point and the breeding season) were not responsible for any of the variation explained by the model. Of the variation explained by the fixed predictor variables, hierarchical partitioning found that the long-term maximum recorded temperature and the long-term median February rainfall were responsible for the largest partitions, followed by the concurrent December rainfall (29.2, 26.1, and 23.5 % of the fixed-effect variance, respectively). Of these, only long-term median February rainfall was significant: fledging dates were earlier at nest sites with higher median February rainfall (-8.71 ± 3.86, $F_{1,22} = 5.1$, $p = 0.03$; Fig. 3), which is reflective of long-term rainfall levels over the summer breeding season. The effect of long-term maximum temperature

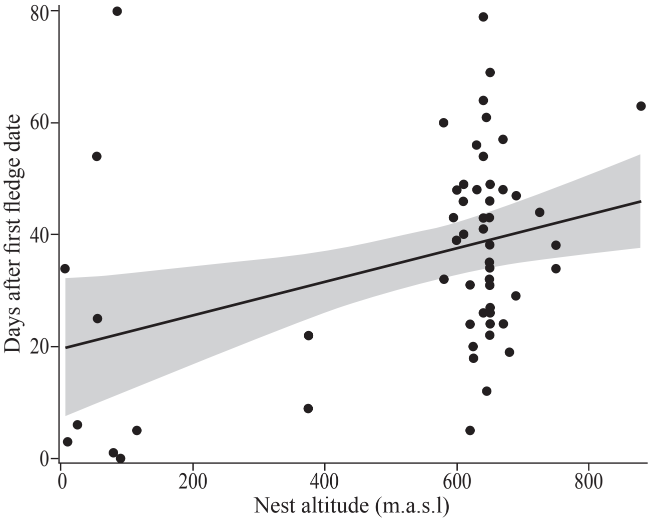

Figure 2. *Fledging date (days after the first recorded fledging date, December 8) was significantly earlier for nests at lower altitude (metres above sea level) among the 59 successful Gang-gang nests observed over the three seasons of the study (LMM: 0.03 ± 0.01, $F_{1,56}$ = 9.6, p = 0.003; R^2 marginal = 0.15).. The black line shows the simple regression line for the relationship, with the grey ribbon indicating 1 standard error above and below the estimated mean slope.*

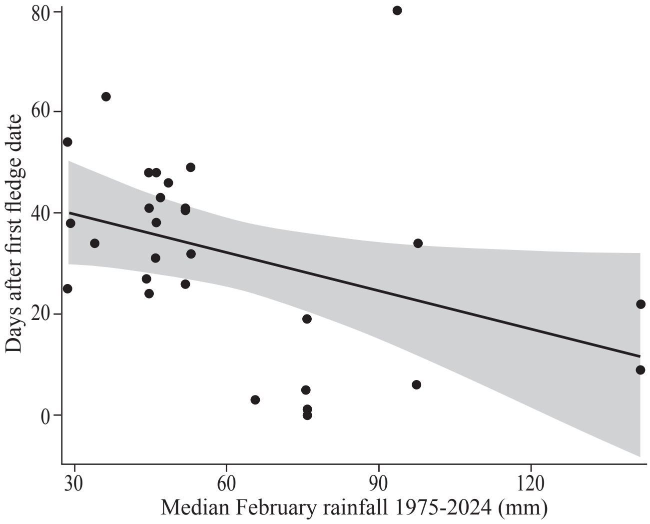

Figure 3. *Fledging date (days after the first recorded fledging date, December 8) was significantly earlier for nests at localities with higher long-term median February rainfall (LMM: -8.71 ± 3.86, $F_{1,22}$ = 5.1, p = 0.03; R^2 marginal = 0.46). The black line shows the simple regression line for the relationship, with the grey ribbon indicating 1 standard error above and below the estimated mean slope.*

was of marginal significance, with fledging dates tending to be earlier at nest sites with higher maximum recorded temperatures (-9.01 ± 4.48, $F_{1,22}$ = 4.1, p = 0.056). Fledging dates also tended to be earlier for nesting events where concurrent January rainfall was in a higher decile (-9.48 ± 4.63, $F_{1,22}$ = 4.2, p = 0.053); however, this effect was also of marginal significance, and responsible for only 7.5 % of the variance in fledge timing explained by the model. VIFs for all predictor variables were below 5, indicating little multicollinearity between predictors.

Fledging success, temperature and rainfall

The model for fledging success in relation to climate variables had a conditional R^2 of 0.61, indicating that the full model explained 61% of the observed variance in the number of chicks fledged from successful nests. The marginal R^2 of 0.24 shows that the fixed predictor variables are responsible for around a third of this explained variance, with the remaining two-thirds explained by one or more of the random effects. Inspection of these revealed that only nearest climate grid point has any associated variance – the number of chicks fledged from successful nests varied by 0.3 standard deviations across climate grid points. Of the variation explained by the fixed predictor variables, hierarchical partitioning indicated that the long-term maximum recorded temperature and the concurrent maximum recorded temperature were responsible for 43.8% and 48.3%, respectively. These were the only significant predictors in the model: on average, the higher the long-term maximum temperature, the greater the fledging success (0.33 ± 0.12, $F_{1,10}$ = 5.8, p = 0.04). However, at nests where the concurrent maximum recorded temperature was higher, the number of fledglings was lower (-0.35 ± 0.16, $F_{1,16.5}$ = 4.6, p = 0.05).

Nest tree selection, temperature and rainfall

Sap and living wood provide greater insulation than dead and more heavily cracked wood, while a hollow in dead cracked wood is likely to drain more quickly than a hollow in a live tree. While Gang-gangs have been recorded inspecting hollows in all months of the year, over 50% of the hollow sightings recorded via NatureMapr were in September and October, and it seems likely that hollow selection is made across these and perhaps the two immediately preceding months. Table 2 contains the number of dead and live tree hollows used in each season between 2017-18 and 2023-24 and the rainfall and temperatures recorded at Canberra Airport during the likely nest selection period of July-October. The first three years were relatively warm and dry while the next three years were cool and wet. Late winter to early spring of 2023-24 was again relatively hot and dry, but unlike the first three years, a cool and wet summer eventuated. Across the warm dry years of 2017-18, 2018-19, 2019-20 and 2023-24, one of 62 nests was in a dead tree, while during the three cool wet seasons from 2020-21 to 2022-23, there were nine nests in dead trees and 44 in live trees. This is a significant difference (χ^2 = 8.66, d.f. = 1, p = 0.003).

DISCUSSION

With 68 of the 85 observed nesting events occurring in the Canberra area, the fledging data is weighted towards one geographic area and climate profile, rather than spread evenly across the Gang-gang's distributional range. Fledging timing varied as much within the Canberra region as across the entire observed range. Nevertheless we detected a significant relationship between fledging date and altitude. We also found that fledging occurred earlier at sites with long-term higher rainfall and, to a lesser extent, long-term higher temperatures, both of which are more likely to be experienced at lower altitudes. Earlier fledging at lower altitudes means that chicks are more likely to have already fledged by the time the hottest temperatures and stormier weather of mid and late summer occur. Conversely, chicks fledging later at higher altitudes are more likely to experience the extremes of late summer climate and heightened bushfire risk before fledging. However, this

Table 2

Use of hollows in dead and live trees by nesting Gang-gangs in the Canberra region, and associated maximum temperatures and rainfall recorded at Canberra Airport during the hollow selection period, July - October (n = 116 nesting events)

	No. of dead tree hollows	No. of live tree hollows	Mean maximum temperature, July - October (°C)	Total monthly rainfall, July - October (mm)
2017-18	0	7	17	138.4
2018-19	0	9	17	89.2
2019-20	0	17	17.6	89.6
2020-21	5	9	16	313.2
2021-22	2	17	15.8	270
2022-23	2	18	15.3	370
2023-24	1	29	18.25	78.2

delay also means that chicks at higher altitude are less likely to experience early summer cool snaps and frosty conditions, which are more likely to occur here than at lower altitudes.

Although the number of chicks fledged at successful nests was similar across altitudes, across the study seasons those locations that experienced the hottest maximum temperature had fewer chicks fledged per nest than those that experienced the less extreme heat. An indication as to why breeding appears to be timed to avoid the likelihood of chicks experiencing extreme temperatures. Note, however, that our measure of the number of chicks fledged from successful nests is just one component of overall breeding success. For example, we could not analyse the relationship between temperature and the likelihood of successfully fledging any chicks, which may be different to its relationship with the number of chicks fledged.

Birds breeding later at higher altitudes appear to be common among Australian species. Gibbs *et al.* (2011) found that ten of the 16 species they studied bred later at higher altitudes, with delays of 1.5-5.8 days per 100 m increase in altitude. The Galah *Eolophus roseicapilla* was the only cockatoo among the species studied and its time of breeding was found to be significantly related to altitude. The study also found that across a 30-year period breeding in south-east Australia began earlier by 3.6 to 11.6 days per decade. McLean *et al*. (2022) analysed 60 common bird species of the United Kingdom and the Netherlands, and found that laying date was sensitive to mean temperature for 86% of the species while offspring number was temperature-sensitive for 31% of the species. The percentage of the overall trend in a trait attributed to warming differed substantially among species, with values ranging from 28 to 82% for laying date and from 17 to 71% for offspring number. The study did not include any parrot species but does raise the possibility that the difference in laying dates with altitude across the Gang-gang's range may have been heightened by a response to rising temperatures. Their study also cautions that warming is likely to be only part of an explanation, with other factors such as urbanisation also contributing to changes across time.

Heavy rains early in the 2022-23 season may have flooded active nests in the Campbelltown and Moruya areas, while heavy rain in late November 2023 resulted in chicks drowning in at least four nests in Canberra. The comparatively late fledging in Campbelltown during the 2022-23 season may have been the result of flooding and storm damage, which appears to have prevented nesting at two hollows at which strong nesting behaviour was observed in spring 2022, prior to heavy rains. Hollows on the main trunk and without lips or other structural features that divert water away are susceptible to water inflow. This water may drain away over time, but heavy, intense short-term rain can result in hollows flooding and chicks drowning. In addition, cooling of chicks could increase mortality. Concerningly, meteorological observations show an increase in the intensity of heavy rainfall events in Australia that occur on timescales of less than a day, and that this trend is predicted to increase as a result of climate change (CSIRO 2022).

There is evidence, from the Canberra observations, to suggest that while Gang-gangs may choose not to nest in poorly-insulated dead trees in relatively hot and dry years, they do utilise them when it is cool and wet, when their better drainage could provide an advantage. In addition, our analyses of fledge timing suggest the possibility that fledging may occur earlier at a given location if it is a wet season. The weak indication from our model that nests experiencing rainfall in a higher decile for their site appeared to have slightly earlier fledging times merits further investigation. Such flexibility in nesting behaviour may provide some resilience to the risk of nestlings drowning.

While a significant relationship between altitude and the timing of Gang-gang fledging was observed, it is a flexible trend rather than a fixed behaviour. Pairs were observed to breed later than expected due to various reasons, with most of the unusual early or late nesting behaviour occurring during the 2022-23 breeding season. The difference between this year and the other years of study may just reflect the relative paucity of nest data from outside the Canberra area. However, even within Canberra this year was unusual in relation to Gang-gang breeding. In 2022-23 a pair of chicks at a nest on Mt Ainslie, ACT, fledged 18 days earlier than any other Canberra nest during either the survey period or over seven years of observation. Eggs would have been laid in late September 2022. It was one of the mildest springs experienced, which may have influenced the early laying and survival of the chicks. The mean minimum temperatures for September and October in 2022 were 4.4°C and 8.4°C, respectively, compared to the long-term averages for these months of 3.2°C and 6.1°C. During these months in 2022 there were nine days below 2°C and six sub-zero days. The long-term averages are 16.7 and 7.8 days. The minimum record temperatures for the months were -2°C and 0.3°C, compared to long-term records of -6.8 and -3.3 (BOM Monthly climate statistics – Canberra Airport).

Although significant relationships between altitude and certain climate factors were found they only accounted for a minority of the variation in fledge dates observed, and other factors are at play, such as nest competition, predation, and their effects on parental provisioning. A Gang-gang pair that nested in a hollow at Plenty Gorge in 2021-22 was observed preparing to use this nest again the following season, but after a few weeks of nest activity was evicted by a pair of Sulphur-crested Cockatoos *Cacatua galerita*. They then established a nest in a hollow across the river and fledged a chick 27 days later than the previous year. A nesting pair at Hughes, among the last pairs to breed in Canberra, appeared to wait for Galahs to complete their breeding in the same hollow in each of the last two breeding seasons, moving into the hollow immediately after the Galah chicks fledged. A late breeding pair in 2021-22 used a hollow after it was vacated by another pair of Gang-gangs following predation of the first pair's egg(s). At a nest in Huskisson, NSW, the parents were first observed feeding at the hollow rim on 17 December 2023, with chicks first seen within the hollow entrance on 27 December. The female was not seen at this near-constantly watched nest after 22 December. She is suspected of being predated as both a Peregrine Falcon *Falco peregrinus* and a Square-tailed Kite *Lophoictinia isura* were in the close vicinity of the nest the previous day. Following the disappearance of the female, the male continued to feed two male chicks, which fledged on January 11 and 13. The chicks were first sighted at the hollow edge 24 days before the first one fledged, which is more than double the period recorded at any other hollow. The quantity of food fed late in the nestling stage has been found to delay fledging in other bird species. Lepcyk and Karasove (2000) found that House Sparrow *Passer domesticus* chicks restricted of food late in the nestling period had delayed growth in the eighth primary feather and a longer nestling period than those where food was unrestricted. Experimental food supplementation of breeding pairs of Canada Jays *Perisoreus canadensis* advanced the fledging date of young by 24% (5.5 d) compared to controls (Freeman *et al.* 2020).

We found that the timing of Gang-gang fledging varies with altitude, and with long-term rainfall and temperature variables associated with altitude, The differences in fledge timing across the Gang-gang's range appear to help avoid the nestling period coinciding with the riskiest weather extremes for chicks in different locations. Such adaptation across a climate gradient is expected to be threatened by climate change, as extreme weather events become more frequent and/or more unpredictable. Our finding that fewer chicks fledged from successful nests at the locations that recorded the highest maximum temperatures during the studied breeding season aligns with this prediction. Finally, our analyses suggest the possibility that Gang-gangs may adjust their nest hollow selection and the timing of breeding in relation to concurrent rainfall conditions. Whether such adjustments could help to buffer Gang-gang populations against the impacts of climate change must still be determined.

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Wildlife sighting online platform links

https://canberra.naturemapr.org/species/2201

https://inaturalist.ala.org.au/projects/gang-gang-nests-tree-hollows-search