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Movements and habitat use of the night parrot *Pezoporus occidentalis* in south-western Queensland

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Abstract The nocturnal, cryptic and geographically remote nature of night parrots, combined with their apparent rapid decline, means that very little is known of their biology or ecology. The discovery of a resident population in south-western Queensland in 2013 provides the first opportunity to undertake detailed studies on this most enigmatic of birds. We attached a radio tag to a bird for 20 days in April 2015 and a GPS tag to another bird for 5 days in May 2016 to study movement patterns and habitat use. Both birds displayed similar behaviour but the GPS-tagging provided a much finer resolution of spatial data. They called at dusk from their diurnal roosts amongst spinifex hummocks and then flew to more floristically diverse habitats dominated by large-seeded species to feed. We conducted floristic surveys to describe the feeding grounds of the GPS-tagged bird and make dietary inferences. This individual spent most of its time in highly diverse but ephemeral habitats, including seasonally inundated plains and depressions associated with the outer Diamantina floodplain and gilgais on ironstone plains. Prolifically seeding ephemeral species, most notably the annual grass *Uranthoecium truncatum*, dominate these feeding grounds. This work suggests that the habitat mosaic containing roost sites in close proximity to feeding grounds with key seed-producing species is an important factor, rather than an association with spinifex or samphire alone. Further work is needed to examine movement patterns and habitat use in more typical dry seasons and the impact of cattle grazing on night parrot feeding areas, particularly with regard to seed production. The information presented here is vital for both *in situ* conservation of the Pullen-Pullen-Mt Windsor-Diamantina population and for setting future research and survey priorities.

Key words: arid zone, diet, endangered bird, granivory, roosting, telemetry.

INTRODUCTION

Night parrots (*Pezoporus occidentalis*) are cryptic, nocturnal and endemic to Australia's arid interior. Until the late 19th century they were widespread and relatively easily found at least at some locations. For instance, 14 of the 25 museum skins in existence came from the Gawler Ranges in South Australia between 1871 and 1881 (Andrews 1883; Black 2012). The last night parrot collected intentionally was in Western Australia in 1912 (Wilson 1937). Then followed 78 years of unconfirmed reports spanning all mainland states and the Northern Territory, until in 1990 a desiccated body was found by a roadside in western Queensland (Boles *et al.* 1994). In 2006, another body was discovered by a national parks ranger 200 km to the south-east of the 1990 specimen (McDougall *et al.* 2009). In 2013, the first photographs of a living night parrot were captured close to the site of the 2006 specimen (Dooley 2013). Due to its apparent decline the species is listed as Endangered under the federal *Environment Protection and Biodiversity Conservation Act* 1999, and included on all mainland state and territory threatened species schedules (Australian Government 2016).

Their cryptic nature, remote distribution and apparently rapid decline mean that there is scant ecological information about night parrots. This includes information about habitat use and movements, which, from a conservation management perspective presents an especially acute problem. Information which does exist is based on incidental, anecdotal and/or unconfirmed encounters, or observations by early naturalists who were both focused on obtaining specimens rather than collecting ecological information and hampered by the limited technologies available to them (Andrews 1883;

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Howe & Tregellas 1914). Night parrots have been associated with habitats containing one or more species of the widespread grass genus *Triodia*, used for roosting, breeding and feeding (Andrews 1883; Whitlock 1924; McGilp 1931; Wilson 1937). There have also been numerous sightings and at least five specimens collected in or near habitats featuring species of Chenopodiaceae (Austin 1855; Andrews 1883; McGilp 1931; Powell 1970; Forshaw *et al.* 1976; Ellis 1982; Boles *et al.* 1994; McDougall *et al.* 2009).

There is even less information about the movements of night parrots. Andrews (1883, p. 30) stated that they 'come and go according to the nature of the season' and that if *Triodia* does not set seed due to dry conditions '... no birds are to be seen.' This suggests that night parrots undertake large-scale, rainfall-driven movements, which is also reflected in comments from Aboriginal people who reported that night parrots disappear during dry spells (Cleland 1930; Wilson 1937). Parker (1980) suggested that night parrots may occupy habitats dominated by *Triodia* spp. during wet periods and move into chenopod habitats during dry periods (Parker 1980) but there is no evidence for this. At smaller scales or over shorter periods, there is also very little known about night parrot movements. Andrews (1883, p. 29) stated that he had 'known them to fly a distance of four or five miles' to visit water.

The site in western Queensland where the first photographs were taken in 2013 presented the first opportunity to conduct systematic research on key aspects of night parrot biology and ecology. Here we report on the results from radio and GPS tracking of two individuals – the first night parrots trapped and released for scientific study – that were followed for 20 and 5 days, respectively, to gain insights into habitat use and movements. Sample sizes are necessarily limited due to sensitivities about invasive research techniques on a population that is suspected to be small. Our objectives were to (i) describe short term movements of night parrots; (ii) describe the habitats used by night parrots in terms of landscape position, vegetation structure and composition; (iii) attempt to interpret the activities of the individual in each habitat; (iv) describe the roosts made by night parrots; (v) infer diet based on field measurements and plant biology, and; (vi) suggest directions for further research. The findings will inform conservation management of the known population, and assist in locating additional populations.

METHODS

Study site

This study was undertaken on Pullen-Pullen Reserve and neighbouring Mount Windsor Station in south-western Queensland. Pullen-Pullen is 56 000 ha and was part of Brighton Downs beef cattle station prior to its subdivision in early 2016. The reserve sits within the Goneaway Tableland subregion of the Channel Country biogeographical region (Thackway & Cresswell 1995). Due to potential illegal collecting activity, precise location information, including locations of bird movements, are not provided here.

The region is hot and arid with approximate mean maximum temperatures of 39°C in January and 23°C in July. Annual rainfall is highly unpredictable with dry periods punctuated by occasional wet years. Median annual rainfall at Brighton Downs is 240 mm and on average 65% of the rainfall occurs between December and March (Bureau of Meteorology 2017). Rainfall was collected at the study site using a tipping bucket gauge between 12 November 2013 and 27 April 2016 (Fig. 1). These data demonstrated that 2013 and 2015, during which the radio tracking of the first bird was conducted, were very dry years. Rainfall in 2014 was slightly above average due to large rain events in February and December (Fig. 1). At the end of 2015 after a three-year period of low rainfall the whole of western Queensland was 'drought declared' by the Queensland Government (https://www.longpaddock.qld.gov.au/queenslanddroughtmonitor/queenslanddroughtreport/2015/dec1.pdf). Drought-breaking rains occurred through much of 2016, including 155 mm in March, shortly before the capture and tracking of the second night parrot.

Radio tracking, April 2015

To minimize potential risks associated with attaching relatively large tracking units on a species about which we knew so little (including at the time, a live weight), for the first telemetry attempt we opted for very small VHF unit (0.42 g, LB-2N, Holohil Systems Ltd., Canada). The signal pulse rate was 60 pulses per minute and pulse length of

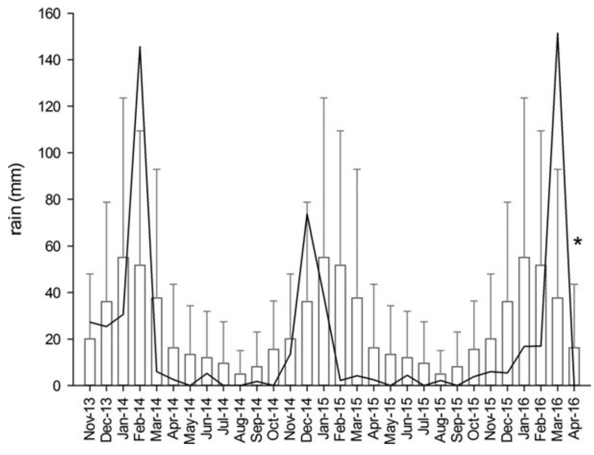

Figure 1. Rainfall at the site November 2013 to April 2016 (line) compared to long-term mean and standard deviation for that month at nearby Brighton Downs (columns and bars; values repeated for comparison; data: Bureau of Meteorology). Asterisks indicate the two tracking periods.

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20 ms, giving a nominal operating life of 21 days. It was attached to trimmed feathers on the back just above the hips using a cyanoacrylate glue so that it would be shed without harm to the bird when it next moulted, if not before. A single individual, weighing 104 g, was captured within an 11 ha area of *Triodia* at 19.00 hours on 4 April 2015, in a 38 mm 18 m polyester mist net, without the use of call-playback. In addition to fitting the transmitter, while in the hand we recorded the bird's weight using a 300 g spring balance and sampled a growing contour feather for molecular sex determination. The time from mist-net extraction to release was less than 20 min.

Tracking of the bird, using an *Australis 26K* receiving unit (*Titley*, Australia) and hand-held three-element antennae was achieved using a combination of ground (by foot, 4 × 4 vehicle and 4 × 4 motorbike) and aerial searches (*Robinson R-22* helicopter). Aerial searches were done at varying heights from 100 to 800 m above ground, which testing using the same model transmitter showed gave us a range of approximately 2 km by holding the antennae outside of the fuselage. The aerial search paths were a combination of a systematic transects spaced approximately 1 km apart covering all habitats and targeted examination of all *Triodia* patches. Locations where signals were detected were logged using a handheld GPS unit and the signal bearing was estimated using a compass. Precise locations of the bird could not be obtained. Sunset/sunrise during the radio tracking period ranged from 1831/0642 on 4 April to 1813/0650 on 24 April.

GPS tracking, May 2016

With lessons learned through the 2015 radio-tracking session, a larger GPS tracking device was used for a second round of telemetry. A second night parrot weighing 102 g was captured (6 km from the 2015 location) at 18.30 hours on 6 May, again without call-playback but this time in a 60 mm 18 m nylon mist-nest. The tag incorporated a GPS unit (*PinPoint 10*) and VHF radio transmitter (*PicoPip Ag379*) with 20 ms pulse length and 33 ppm pulse rate, for a nominal life of 34 days (*Biotrack*, U.K.). A small gauze patch was also fitted to the underside of the tag to aid adherence to the bird, using the same attachment method as described above. Total tag weight was 1.8 g. Handling time was approximately 15 min.

The tag was programmed to acquire GPS fixes in two 'series' per night for five nights using the schedule outlined in Appendix S1. The first GPS fixes were programmed to occur the night after capture to allow the bird to settle. For all or part of the series on three evenings, we increased the fix interval in the first hour to every 5 min in an attempt to detect drinking behaviour, because it was hypothesized that night parrots would be more likely to drink during this time. Sunset/sunrise during the GPS-tracking period ranged from 1804/0656 on 7 May to 1802/0658 on 11 May.

At the time of sampling, there were no field-tested GPS tags of suitable weight with remote data download function. To retrieve the tag the bird was recaptured using call-playback in a mist-net on 23 May, 5.6 km from its original capture point, where it was located using a helicopter to detect the VHF signal in the manner described above.

Tag positional error was estimated by deploying the tag (prior to attachment) at three points over two nights using a similar schedule to that described above. The mean and standard deviation of distances between the position of the tag (as determined by handheld GPS) and the tag's fixes were then calculated, and these statistics helped when inspecting and interpreting the locations where the individual was later recorded, including in the design and placement of subsequent vegetation survey plots.

Several of the bird's locations were represented by a single fix, and it was possible these may have been logged while the bird was flying. We examined this using the procedure outlined in Appendix S2. To calculate the time spent by the bird at each location, it was important to consider where the fixes at each location occurred in the programmed series. If a location included the first and/or last fixes in a series ('end points'), we could only know the *minimum* time the bird spent at that location based on the number of fixes and fix interval. If fixes were recorded at a location with fixes from other locations either side in the same series ('nested points'), then it was possible to calculate the *maximum* time spent at that location. For locations with single fixes, we applied the same logic; if it was a nested point, the maximum time spent there was less than twice the fix interval, whereas if it was an end point, the minimum time spent there was the time it took to get a fix, which we nominally annotate at 1+ min.

Descriptive statistics were calculated: (i) mean, maximum and minimum distances moved within a series and between fixes; (ii) maximum, minimum and mean cumulative distances moved in a night, and; (iii) nightly and total minimum convex polygons (MCPs). Cumulative measurements included movements to and from the roost (which VHF tracking showed was stable during the GPS tracking period), and movements between series within a night. Given there were long periods each night when the GPS tag did not acquire fixes, cumulative distances are minimum values. All spatial calculations were done using *ArcMap 10.0* (*Environmental System Research Institute*, USA).

Molecular sex determination

Full details of sexing methods are given in Appendix S3.

Vegetation surveys, June 2016

Between 12 and 17 June, we visited all fixes where the GPS-tagged night parrot had been recorded 1 month earlier. As discussed below, some sites were apparent feeding grounds where the bird was recorded two or more times in succession, whereas some sites involved repeated visits over extended periods. Others were apparently fly-overs or very brief stops, with only single GPS fixes taken at some distance from the preceding and following fixes. All sites were visited, but more detailed surveys were done at sites where the bird had spent longer periods of time. Sites were assigned to various 'broad land types', comprised of a landform category combined with common vegetation structural characteristics, and 'habitats', which we described floristically.

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Each site comprised between one and 35 GPS fixes. Where there was a single fix in a homogenous habitat, four floristic quadrats were placed within 30 m of the fix; this distance was based on estimates of GPS fix accuracy (see Results). Where there were multiple fixes, a site encompassing all of them was marked using steel droppers and quadrat selection was stratified by habitat type, with each type represented by at least three quadrats. Quadrat selection within a site was biased towards GPS fixes. Where vegetation was patchy (i.e. small vegetated areas on stony pavements), quadrats were placed within vegetated areas. Most sites were separated from each other by more than one kilometre, but four clusters of fixes located within a square kilometre were treated as discrete sites (labelled Nardoo, Lumpy, Succulent Flat and Mitchell Grass Flat – see Appendix S6) due to habitat differences. The total number of quadrats at each site increased with the time spent there by the parrot and the heterogeneity of the habitat.

Each 2 × 7 m quadrat was split into four sub-plots of increasing size. Plant species present in the first 0.3 × 2 m sub-plot were assigned an abundance score of 4, new species present in the next 0.7 × 2 m sub-plot an abundance of 3, new species in the next 2 × 2 m sub-plot an abundance of 2, and the final 2 × 4 m sub-plot an abundance of 1. This method, involving unrepeated scoring of species presence, has been demonstrated to provide the best return (robust measure of rank abundance) for effort (no more time than presence-absence scores), thereby allowing for a relatively large quadrat size (Morrison *et al.* 1995). Voucher specimens of species have been lodged at the Queensland Herbarium. Nomenclature follows Bostock and Holland (2007). The data were analyzed using the R package (R Core Development Team 2016), and ordinated using non-metric multidimensional scaling package 'vegan' (Oksanen *et al.* 2017).

Lifeforms were assigned based on the above-ground parts of the plant, thus species with perennial rootstock but annual stems were classified as annual for this study. Short-lived species which can be biennial in higher-rainfall areas, or in consecutive high-rainfall years, were classified as annuals, as field observations, expert knowledge and examination of herbarium specimen labels suggested they are short-lived in the study area. Rain (10.6 mm) was recorded in the month between the last GPS fix and our flora surveys. Where field observations suggested that plants were more or less abundant at the time of the parrot's visit, this was noted. In particular, short-lived summer-growing grasses were probably more common, but they were still detected in quadrats as seed heads and litter lying on the ground.

RESULTS

Radio-tracking

We had difficulty locating the 2015 radio-tagged bird, which molecular sexing showed was a female. Apart from detecting it within *Triodia* 200 m from the capture point 5 h after release, ground-based searches failed to locate the bird for 3 days (until 7 April) when it was located 7 km to the north-east. We inspected this location on foot shortly after discovery, but the bird was inadvertently flushed at 18.35 hours from a roost in an isolated *Triodia* hummock measuring 9.8 × 5.3 m across by 0.5 m high. The roost was a 25 cm long, horizontal tunnel, 8 cm in diameter (at entrance), constructed 8 cm above ground, with the entrance facing inwards towards the bare centre of the ring-shaped hummock. The tunnel was evidently constructed by a combination of chewing some leaves to length, and pushing and shaping others (the majority). There was no chamber at the end. A camera-trap trained on the roost for 108 days after discovery showed that the bird did not return after being disturbed.

Triodia in the vicinity of the new roost was sparse, covering only 6.8% of a 25 ha sample area around the roost (based on high resolution satellite imagery), the rest being an ironstone pavement dominated by sparse *Sclerolaena longicuspsis* (a habitat similar to the broad land type 'Stony Rise', described below). Following flushing, we did not detect a signal for 12 days, despite approximately 1200 km of aerial and 250 km of ground searching over 450 km^2 of suitable roosting habitat, up to 50 km from the 7 April roost. The bird was relocated by air on 19 April only 1.1 km away. *Triodia* cover within 25 ha around the 19 April roost area was 1.9% and again, hummocks were embedded in a matrix of ironstone and sparse *S. longicuspsis*.

The tag stayed attached to the bird for the life of the battery. Between 19 and 24 April (when the battery failed), we detected the tagged bird 16 times from six locations, always in the early evening or just before sunrise. After a bout of calling involving one or two conspecifics, the tagged bird left the roost area each evening about 20–30 min after sunset and returned to the roost area about 40–60 min before sunrise. On most mornings, one or two calls were heard as the bird settled. We failed to detect the bird outside of these twilight periods despite approximately 380 km of vehicle-based searching. The times, detection positions (in relation to 19 April roost), bearings, signal strength (which is a proxy for distance between receiver and tagged bird) and our interpretation of the bird's activity are shown in Appendix S4. Despite the small number of detections, we were able to conclude that the female was moving considerable distances (at least 5 km and possibly greater than 10 km) away from her roost into habitats that included floodplains and non-*Triodia* grasslands.

GPS-tracking

The mean positional error of the GPS tag was 12.8 m (SD = 11.2 m; min. = 0.18 m; max. = 36.9 m;

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$n = 48$ fixes at three locations). Despite expectations, we were unable to determine from metadata if a fix was taken on the wing or not (see Appendix S2).

Based on molecular sexing, the GPS-tagged bird was a male. The tag remained attached to the bird until recapture on 23 May, when it fell off while the bird was being extracted from the mist net. The tag logged 127 fixes clustered into 18 sites. Excluding series one on night one (the night after capture, when the bird was still settling from capture) and series nine and ten (which were less than 2 h), the mean distance moved within the remaining seven-two-hour series was 8.9 km (SD = 5.3 km; max. = 17.62 km; min. = 1.3 km). The maximum distance between fixes within a series was 6.3 km between two locations that were logged 10 min apart, which indicates a minimum flight speed capability of ca. 38 km per hour.

The mean minimum cumulative distance moved per night was 29.9 km (SD = 9.6 km; max. = 41.18 km; min. = 17.82 km; $n = 4$). The maximum straight-line distance the bird was recorded away from the roost was 9.4 km at 04.10 hours on 12 May. The nightly mean MCP area was 783 ha (SD = 605 ha; max. = 1821 ha; min. = 305 ha). The total MCP area for all points was 3344 ha.

Four of the sites – Uranth Flat, Despair Flat, Osteo and Stony Flat – appeared to be the favoured feeding grounds during the tracking period, with a minimum of one hour spent at each (Appendix S6). The bird stayed for at least 20 min at a further three sites (Mitchell Edge, Succulent Flat and Nardoo, the latter being visited four times over three nights, including two possible fly-overs). The bird spent an extended period at the roost area early in the night after capture and, given movement patterns over the subsequent four nights, we consider this anomalous behaviour related to capture stress. Nine sites were single points and possible fly-overs. A single point was logged at an artificial water point for stock.

Broad land types and site-based descriptions

The roost site of the GPS-tagged night parrot was located in *Triodia longiceps* at the base of a low sandstone range. Based on high resolution sub-1 m *DigitalGlobe* (www.digitalglobe.com) satellite imagery, *Triodia* cover within a 25 ha area (centred on the roost) was approximately 10%, but this was inflated due to the 25 ha area extending towards the plateau margin where *Triodia* cover was more extensive. The GPS fix at water was at the corner of an artificial stock 'tank' (earthen reservoir) that was approximately 60 m wide. The remaining 16 sites encompassed six broad land types, (with some sites comprising more than one land type; Figure 2). Three sites were situated on a floodplain which is periodically inundated by waters from the Diamantina River: an extensive plain dominated by ephemeral species (Uranth Flat, in the broad land type 'floodplain') and two small patches of *Astrebla* grassland ('Mitchell grassland') on the edge of the floodplain, one of which graded into ephemeral herbfield (Mitchell Edge). One site was located within a broad depression fed by local run-off from nearby hills (Despair Flat). One was on stony rises close to a sandstone mesa dotted with gilgais, one was in an ephemeral herbfield, four contained herbfields and gilgais on ironstone, while the remaining six sites were situated on undulating ironstone plains dotted with vegetated patches (gilgais and small drainage channels) of varying sizes.

Floristic diversity was concentrated in the ephemeral floodplain and depression land types, which had the highest average species richness (22.5 and 23 species per 14 m^2 respectively), comprised primarily of annual forbs (Fig. 3). On ironstone plains, diversity and biomass were mostly restricted to gilgais and small drainage channels, with average species richness per quadrat of 13.8, compared to 9.3 on ephemeral herbfields which sometimes occur adjacent to them. No quadrats were located on ironstone plains themselves, which generally support no plants except occasional small annuals *Eriachne pulchella* and/or *Trianthema triquetra*. The gilgai land type as a whole supported a slightly higher richness and abundance of annual grasses than other land types, including the floodplain and depression (Fig. 3).

The Mitchell grassland quadrats unsurprisingly had the highest perennial grass frequency and rank abundance, but were otherwise quite similar to ironstone gilgais in floristic diversity and lifeform composition. Herbfields tended to occur adjacent to gilgais or close to small drainage lines, and were dominated by ephemeral flora with isolated perennial chenopods and/or *Astrebla* tussocks and had the lowest overall species richness. The stony rise quadrats were also floristically similar to gilgais, but with lower annual grass frequency and abundance (Fig. 3).

Annuals (including geophytic species with annual stems) comprised 70% of the flora, including 59 herb, 22 grass and three sedge species. Annual herbs were the most frequent and abundant lifeform in all land types, with the exception of gilgais where they were slightly eclipsed by both perennial herbs and annual grasses. Twenty-six perennial herbs, seven perennial grasses, three shrubs and two trees were recorded. Apart from sedges (three species recorded at three sites), perennial grasses had by far the lowest richness and abundance across all land types, with richness only greater than one species per 14 m^2 in three land types (Depression,

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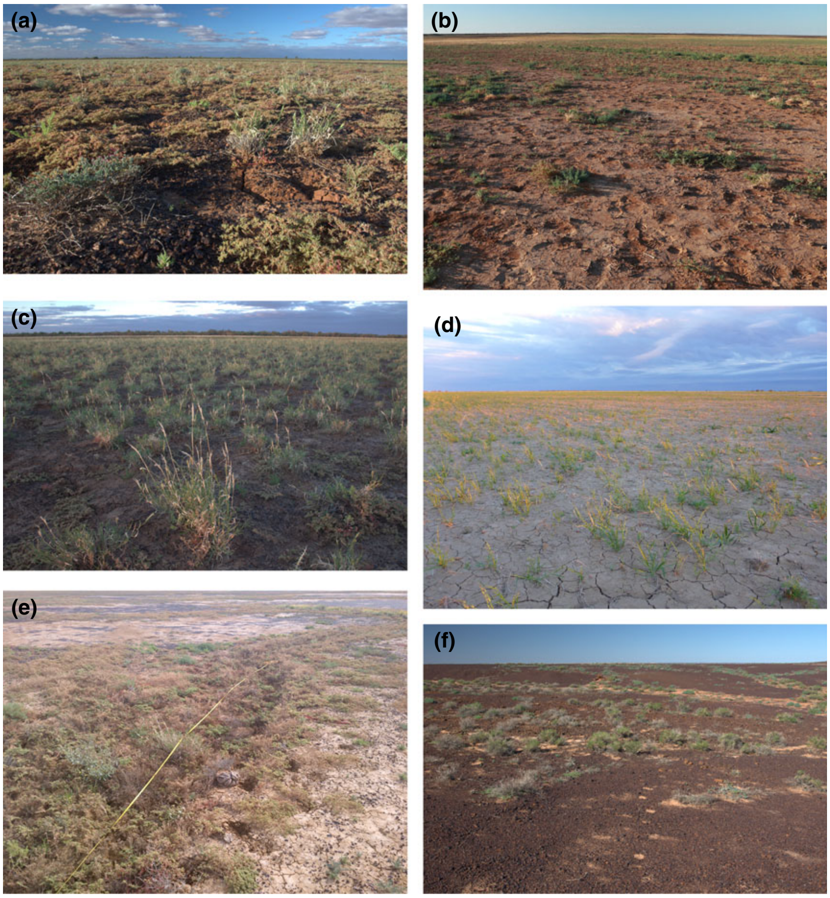

Figure 2. Examples of the six main broad land types. (a) Herbfield ('Lumpy' site); (b) Depression (local runoff; 'Despair Flat' site); (c) Mitchell grassland ('Mitchell Grass Flat' site); (d) Floodplain ('Uranth Flat' site); (e) Gilgai on ironstone ('Rattlepod' site); (f) Stony Rises ('Stony Rise' site). All photos taken at time of vegetation surveys (approximately 30 days after visits by the GPS-tagged night parrot), except for (d) which was taken 13 days after the parrot visited the site.

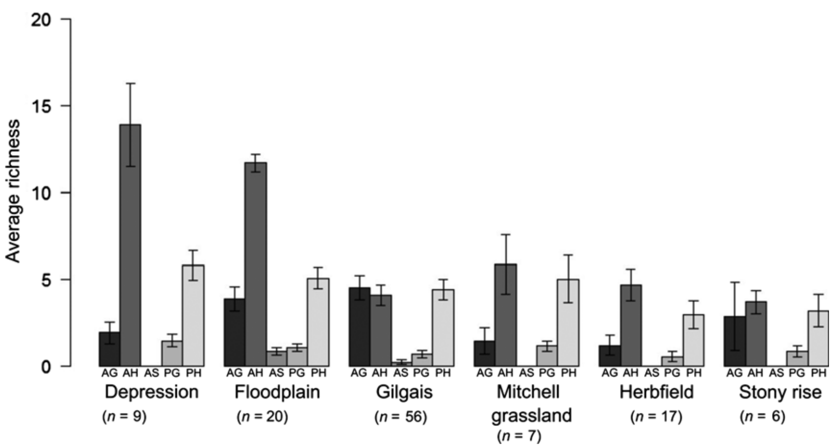

Figure 3. Average species richness by lifeform per 14 m^2 quadrat in six broad land types, with standard error bars, for each land type visited by the night parrot. AG, annual grass; AH, annual herb; AS, annual sedge; PG, perennial grass; PH, perennial herb; *n*, number of quadrats in each land type.

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Floodplain and Mitchell Grassland). With the exception of Mitchell grasslands, perennial grasses were sparse and patchy, and only occurred in gilgais and small drainage channels. Appendix S5 shows the frequency and abundance of species that were recorded in all quadrats.

Four sites were apparently favoured feeding grounds during the tracking period (Appendix S6). Two are low-lying, periodically inundated plains: an outer floodplain (Uranth Flat), where the bird spent at least 4 h over four nights, and a broad, shallow depression fed from local run-off (Despair Flat; a single visit for at least one hour). These sites were the sole representative of the floodplain and depression land types respectively (Appendix S6). Soils at both sites are strongly self-mulching clays, and both are intersected by small drainage channels less than 0.5 m deep. Despite their different hydrology, both sites occur on fertile cracking clay soils and are characterized by a diverse ephemeral flora, having the highest species richness across all sites and comprised primarily of annual herbs (Appendix S7). Perennial forbs were the next most frequent and abundant lifeform at both sites, while annual grasses made a substantial contribution at Uranth Flat (Appendix S7). There were occasional shrubs (*Acacia farnesiana* and *Eremophila polyclada*) at Despair Flat, but no trees or shrubs at Uranth Flat.

The two other main sites visited by the bird, Osteo and Stony Flat, were located on ironstone plains dotted with vegetated gilgais of varying size and floristic composition (gilgais on ironstone land type). Samphire (*Tecticornia* spp.) was dominant in the wetter areas of Stony Flat, while deeper gilgais supported scattered perennial grasses, mostly *Astrebla pectinata* and *Eragrostis xerophila*. Apart from the Nardoo site, all other ironstone gilgai sites appeared to be short visits or fly-overs. Although overall species richness was lower than at inundated sites, these sites had the highest annual grass richness and abundance of all sites (Appendix S7).

Analysis of dispersion (ANDOSIP) using species abundance scores across all sites revealed that quadrats within Nardoo, Hoofprint and Stony Rise sites were significantly more variable than other sites because they spanned multiple land types. Uranth and Despair Flats were clear outliers in the floristic ordination, although the quadrats from deeper gilgais at Nardoo had some overlap with the former (Fig. 4). Stony Flat and Osteo overlapped with each other, but were mostly separate from the other sites in the ordination space, having some overlap with Stony Rise. Although Analysis of Similarity (ANOSIM) revealed that differences in plant composition between sites were not significant, numerous species occurred only at the main feeding sites.

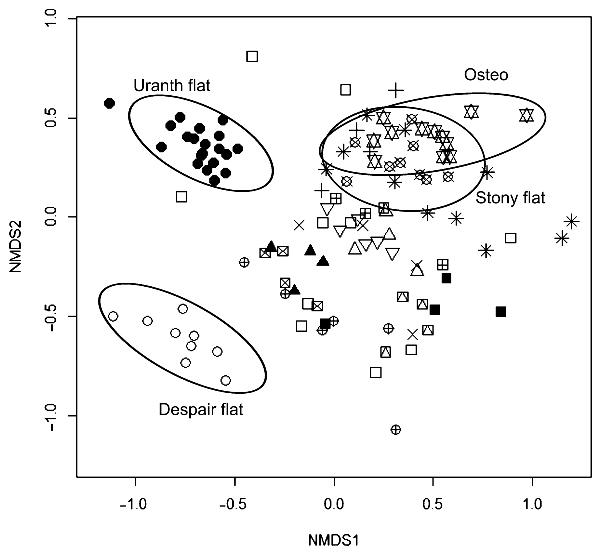

Figure 4. Two dimensional non-metric multidimensional scaling (NMDS) ordination diagram of untransformed floristic frequency data from 115 quadrats where the GPS-tagged night parrot spent time. Stress = 0.205. Key feeding sites identified as follows: black circles, Uranth Flat; hollow circles, Despair Flat; stars, Osteo; crossed circles, Stony flat. Other sites as follows: hollow squares, Nardoo; triangles inside squares, Succulent Flat; upside-down triangles, Mitchell Edge.; triangles, Flowering Lignum flat; crosses, Hoofprint; Grove, plus sign; black triangles, Lumpy; crossed squares, Mitchell grass flat; asterisks, Stony rise; circles with + sign, Rattlepod Gully; crossed squares, Sandy Blight; black squares, Unlikely Plains. Ninety-five percent confidence ellipses are placed around the favoured feeding site clusters of Uranth Flat, Despair Flat, Stony Flat and Osteo quadrats.

Diet inferences

Although it is impossible to determine with certainty what the bird was eating without direct observation, or scat or crop analyses, the floristic data provide some insights into what drew the bird repeatedly and/or for lengthier periods to the four main sites, and a further three where it spent at least 20 min during a single visit (here grouped as feeding sites). Fifty-five species were frequent (occurred in >50% of quadrats) at one or more of these seven feeding sites (Appendix S8). Twenty of these were widespread and abundant across the majority of the 16 sites. These include prolifically seeding short-lived herbs (notably *Portulaca oleracea*, *T. triquetra* and *Boerhavia schomburgkiana*) and grasses (including *A. pectinata*, *Dactyloctenium radulans*, *Enneapogon polyphyllus*, *Iseilema vaginiflorum* and *Tripogon lolliiformis*), which are potential food sources but could be found throughout the landscape. A further nine species are mostly restricted to one or two land types, but locally abundant within them at both feeding and non-feeding sites (Appendix S8).

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Eleven species occurred across numerous sites but were only frequent and abundant at one or more of the feeding sites, while fifteen occurred only at the feeding sites. Of particular note are four prolifically seeding, large-seeded annual grasses (*U. truncatum*, *Xerochloa barbata*, *Brachyachne prostrata* and *Tragus australiense*; the three former being locally restricted to the mid-reaches of the Diamantina; Queensland Herbarium records). Similarly, numerous large-seeded and prolific annual forbs were also found commonly at one or more feedings sites, including *Ptilotus murrayi*, two *Portulaca* species, two Curcurbitaceae vines and *Alternanthera denticulata*.

DISCUSSION

Understanding species' movements, habitat use and key resources within habitats is vital for conservation management. The discovery of a night parrot population in south-western Queensland in 2013 (Dooley 2013), coupled with advances in the miniaturization of tracking devices, has allowed us to provide the first detailed information about night parrot habitat use and movements. Our small sample size necessitates caution in interpreting the data, but knowledge gathered in this study is unique and will underpin both the management of the known populations and searches for additional ones. It will also provide the basis for further research, which is necessary given only two individuals were studied at a single location.

Activity patterns and movements

Both tagged birds displayed similar behaviour in terms of a brief period of vocal socialization for about 30 min after sunset and upon returning to their roosts within an hour of sunrise. Both birds also moved similar (known maximum) distances away from the roost (ca. 8 and 9.4 km for the female and male respectively). The value of GPS tag technology was demonstrated by the increased resolution it provided, showing greater than expected movement including a total of at least 41 km travelled in a single night. This scale of nightly movement contrasts starkly with that known for the congeneric eastern ground parrot (*Pezoporus wallicus*). For example, the mean home range for 12 radio-tagged eastern ground parrots was 9.2 ha, compared to over 3000 ha for our GPS-tagged night parrot (McFarland 1991). We suggest the differences may be related to the more widely dispersed resources used by night parrots in their arid environment compared to mesic, coastal habitats of eastern ground parrots. Night parrot roosting and foraging habitats were widely separated in our study, whereas the heathlands and sedgelands occupied by eastern ground parrots fulfil both roosting and feeding needs (McFarland 1991).

At a broader scale we found no evidence of nomadic behaviour; both tracked birds were captured approximately 7 km apart in consecutive years (one dry, one wet) and moved within the same relatively small area (~70 km^2). Furthermore, the species has continuously occupied the same area for 4 years based on acoustic monitoring (S. Murphy, unpublished data), and we assume that at least some individuals have been resident through the entire period. Indeed the population may have been resident for a much longer time given the close proximity of the 2006 specimen location (McDougall *et al.* 2009). This contrasts with previous assumptions of nomadism (Reid & Fleming 1992; Higgins 1999) that may have arisen because of Andrews' (1883) observations cited earlier. An important implication of the night parrot being more sedentary than previously assumed is that all localities where the species was recorded historically should become the focus of renewed, intensive survey.

On 9 May 2016 (day two of the tracking period), 38.2 mm of rain fell, and this may explain why the bird was only detected visiting a watering point once (Appendix S6). While it is possible that the bird visited this site (or other permanent water points) on other nights given the intermittent tracking schedule, ephemeral water was abundant during the tracking period. Although we cannot conclude with certainty that the bird actually drank while at water on night two, it seems reasonable to assume that it did, and so this corroborates earlier assertions that night parrots fly to water, sometimes over considerable distances (Andrews 1883; McGilp 1931).

Use of regular roost sites to which our tagged night parrots returned before dawn each night confirms earlier accounts (Andrews 1883; McGilp 1931). However, both birds were absent at times from their respective roosting areas. The male relocated 5.6 km and the female apparently relocated to an unknown location for 12 days. Both movements may have been in response to capture stress (for the female), or disturbance while recapture attempts were being made (in the case of the male). Further studies are required to determine if night parrots preferentially use a single roost or can use multiple roosts within a large home range, perhaps depending on the proximity to feeding areas which we suspect will shift through time and space.

Habitats

Both tagged birds roosted in long-unburnt *Triodia* hummocks, which is consistent with the established association between *Triodia* and night parrots (Andrews 1883; Whitlock 1924; McGilp 1931; Wilson 1937). However, the total extent of *Triodia*

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patches at these sites was not large; one roosting area had only 1.9% *Triodia* cover on a sparsely vegetated ironstone plain.

From *Triodia* roosts, both birds travelled relatively large distances into non-*Triodia* habitats. The GPS data clearly show the bird making use of fertile, diverse but ephemeral parts of the landscape: floodplains, run-on areas and gilgais. The two sites with the highest plant species richness appeared to be favoured feeding grounds, as were the sites with the highest diversity and abundance of prolifically seeding annual grasses, most notably *U. truncatum*, and herbs (Fig. 3; Appendix S7).

It is important to note that, despite floristic similarity, variation exists within broad land types and this may explain why some sites were visited more frequently or for longer. Some ironstone sites, notably Osteo, Stony Flat and Nardoo, had more extensive gilgai development and therefore more total seed production than others. The geographical context of favoured sites also appeared important, with Stony Flat and Osteo being closest to the roost site. The spatial configuration of habitat types is likely to be important in determining optimal landscapes for sustaining night parrot populations.

The GPS tracking was done on one bird in an exceptionally wet season. Many of the plant species recorded only persist for a brief period (weeks). However, we suggest that seeds from these ephemeral species might be available to night parrots well into dry spells, based on movements of the radio-tagged bird, which we detected in these same areas during a dry period. Further anecdotal support is provided by the long-term occupancy of the general area by night parrots through the 2013–2015 drought (S. Murphy, unpublished data). Despite the high effort, cost and risk involved, we strongly recommend more tracking data be obtained during dry periods. This information will be critical to informing conservation management.

Apart from feeding, another reason for the GPS-tagged night parrot to visit ironstone plains frequently could be for ingesting gastroliths – small stones swallowed to aid food comminution (Wings 2007). Autopsies revealed similar grit in the gizzards of two night parrot specimens (Murie 1868; McDougall *et al.* 2009).

Habitat comparisons with other night parrot localities

There are broad similarities in habitat and floristics between most published sightings of night parrots and the study area. Most had areas of *Triodia* spp. on stony/hilly terrain juxtaposed with more fertile plains supporting vegetation dominated by chenopod and/or grass species (e.g. Black 2012; J. Reid & S. Murphy, unpubl. data, 2015; Paton 1970; Forshaw *et al.* 1976; Higgins 1999; McDougall *et al.* 2009). This includes the 1990 Boulia specimen locality, which was characterized by gilgais on an ironstone plains and patches of *Triodia* nearby (*contra* Boles *et al.* 1994). A similar range of landforms (alluvial plains and hillslopes) and vegetation types (*Triodia* and mixed herb-grasslands) were recorded in the Selwyn Ranges (north-western Queensland) around the seven locations where night parrots were reported in 1992–1993 (Garnett *et al.* 1993). The sighting of two night parrots at water at Fortescue Marsh in Western Australia in 2005 occurred close to extensive plains of samphire (a chenopod) alongside expanses of *Triodia* (Davis & Metcalf 2008), while the March 2017 confirmed sighting in Western Australia was from a spinifex plain adjacent to an open chenopod shrubland dotted with a chain of ephemeral pools fringed by samphire (*Tecticornia* spp.; N. Jackett and B. Greatwich, in litt. 8 April 2017).

There are regions where night parrots occurred historically which have no *Triodia* or limited amounts in the general area of the observations. In these areas, shrubby samphire or lignum may have provided roosting sites (Andrews 1883). We concur with Garnett *et al.* (1993) that night parrots can be found in a wide range of habitats, but highlight here for the first time the importance of feeding areas in proximity to dense ground layer vegetation for roosting and nesting (Murphy *et al.* 2017). It is likely that the species needs access to free-standing water, at least during hot conditions (Kearney *et al.* 2016).

Conservation implications and future research directions

Available evidence strongly suggests that this population is resident rather than nomadic, but ranges across a far greater area (>3000 ha over five nights) than previously known. In particular, we have revealed extensive use by night parrots of habitats that are distant, and structurally and floristically distinct, from their roost sites. These are the focus of the grazing industry in the region (Phelps *et al.* 2007), but the impact of cattle grazing on the habitats used by the night parrot, particularly on seed production of key species, is unknown. Previous studies have shown minimal impacts of grazing on floristic composition in the Channel Country floodplains and dunefields (Phelps *et al.* 2007; Silcock & Fensham 2012) and in Mitchell grasslands (Fensham *et al.* 2014). However, floodplain grazing exclosures have demonstrated significant reductions in vegetation biomass and groundcover at typical levels of commercial cattle grazing (Phelps *et al.* 2007).

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Studies in other areas have shown negative impacts of livestock on seed production of grasses and herbs (Friedel & James 1995; Crowley & Garnett 2001). The impacts of reduced biomass on seed production and availability in the study area require further investigation, using grazing exclosures and repeated measurements across different seasons.

Further night parrot surveys in similar habitat are also required, and our initial tracking results and habitat descriptions provide a good basis for identifying potentially suitable habitat: that is, *T. longiceps* ranges abutting areas containing an abundance of large-seeded, prolific species, particularly floodplains and ironstone plains with drainage lines and/or gilgais. Mapping of spinifex and flooded areas is currently being undertaken using remote sensing and ground validation. This habitat model will identify high-priority areas to survey, using acoustic monitoring and targeted searching for nest/roost sites. We anticipate that additional night parrot populations will be located in the region broadly circumscribed by Cloncurry, Boulia, Winton and Jundah, due to the similarities in landscapes and vegetation with our study area, and also because of the number of night parrot sightings in the region over the past 25 years (Boles *et al.* 1994; S. Murphy unpublished data, 2017; Garnett *et al.* 1993).

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Acquisition schedule for GPS tag.
Appendix S2. Interpreting night parrot behaviour at single GPS fixes.
Appendix S3. Molecular sex determination methods.
Appendix S4. Summary of signal detections for the 2015 radio tagged night parrot.
Appendix S5. Species frequency (% of quadrats occurring in) and abundance (average abundance score per quadrat) for each broad land type where the GPS-tagged night parrot was recorded.
Appendix S6. Details of the locations visited by the GPS-tagged night parrot, and inferred type of activity at each.
Appendix S7. Average species and lifeform richness (per 14 m^2 quadrat) and abundance at night parrot habitat sites.
Appendix S8. Frequent species (defined as occurring in >50% of quadrats at any one site) at seven night parrot feeding sites.

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