Global Ecology and Conservation 20 (2019) e00703

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Original Research Article

Breeding home range movements of pre-fledged brolga chicks, *Antigone rubicunda* (Gruidae) in Victoria, Australia – Implications for wind farm planning and conservation

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A R T I C L E I N F O

Article history:
Received 6 January 2019
Received in revised form 1 July 2019
Accepted 1 July 2019

Keywords:
Wind turbine
Renewable energy
Buffer
GPS tracking
Waterbird conservation
Environmental impact

A B S T R A C T

Built infrastructure, such as wind farms and power lines, can impair wildlife movement. These barriers may displace individuals from important habitats due to direct mortality or disturbance. Understanding animal movement patterns can help avoid such impacts and manage population level effects. Avoiding impacts and implementing mitigation strategies is difficult when movement and home range information is lacking. Impact at breeding sites may negatively affect population recruitment. The number of wind farm developments is increasing in southern Australia within the core range of the south-eastern brolga (*Antigone rubicunda*) population. The main threats to this wetland bird include habitat loss, chick predation and collisions with power lines and fences. Wind farms may increase collision and mortality risk, and habitat displacement but the impact is difficult to assess or mitigate, as movement patterns and home range size are unknown. We deployed 11 GPS transmitters on pre-fledged brolga chicks at breeding sites in 2010–2012, including one at a wind farm, to investigate movement and home range use of brolga chicks. Brolga chicks moved 442 m on average, to and from night roost wetlands (range: 0 m–1964 m). The average breeding home range was 232 ha, estimated with a Brownian bridge movement model at 95% UD, but varied greatly between individuals (70 ha–523 ha). Brolgas used either single or multiple wetlands, and those using multiple wetlands either switched between them or relocated permanently. Information from this study can be used to design turbine–free buffers at brolga breeding sites and to manage breeding wetlands.

1. Introduction

Built infrastructure such as wind farms and transmission lines can impair bird movement (Erickson et al., 2005; Drewitt and Langston 2006, 2008). The number of wind farms is increasing across the world as countries invest in renewable energy sources to combat global greenhouse emissions and a warming world (Drewitt and Langston, 2006; Dahl et al., 2012; IPCC, 2013; Belaire et al., 2014; IPCC, 2014; Pearse et al., 2016). Wind farms are known to impact on

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https://doi.org/10.1016/j.gecco.2019.e00703

wildlife, and thus an increase in wind farms across landscapes is of conservation concern, especially if population viability, or threatened species, are affected (Drewitt and Langston, 2006). Some bird species are particularly vulnerable to wind farm related collision mortality, habitat displacement due to disturbance (Drewitt and Langston, 2006; Stewart et 2007; May, 2015), and barrier effects that influence movement patterns (Drewitt and Langston, 2006). The magnit of impacts varies greatly between species, life cycle stage (breeding, non-breeding, juvenile) and individual characteris of wind farms (Drewitt and Langston, 2006).

Knowledge of species' movements and habitat use is the key to avoiding and managing wind farm impacts on (Watson et al., 2014; Mojica et al., 2016; Pearse et al., 2016; Singh et al., 2016). Collecting detailed movement information to wind farm construction and operation is essential for three reasons. First, it can help in siting wind farms and turbines from movement routes and important habitats (Watson et al., 2014; Mojica et al., 2016). Second, buffers around important habitats can be incorporated into wind farm design (Watson et al., 2014). Finally, such knowledge can identify the effect of wind farms and form the basis for before-after-control-impact (BACI) studies (Dahl et al., 2012). Turbine- and powerline-free buffers at wind farms can mitigate against collision and disturbance effects. Disturbance effects of wind farms on some bird species are well documented and can result in displacement from important breeding habitats, akin to habitat loss (Drewitt and Langston, 2006; Pearce-Higgins et al., 2009; Dahl et al., 2012). From a conservation perspective, this can have negative population level impacts, particularly if breeding success is reduced. Pearce-Higgins et al. (2009), for example, found several species avoided suitable habitat and had reduced breeding density within 500 m of turbines. Similarly, displacement and mortality contributed to lower breeding success of white-tailed eagles (*Halieetus albicilla*) within 500 m of turbines (Dahl et al., 2012). Such post-operation and BACI studies increase our understanding of wind farm impacts at breeding sites. However, they do not necessarily provide detailed information on movements, which could inform conservation planning and impact mitigation at the pre-operation stage. Few such pre-operation studies exist (e.g. Watson et al., 2014; Singh et al., 2016).

Managing wind farm impacts is a global problem, and many countries have developed guidelines for assessing, monitoring and managing wind farm impacts on wildlife to aid conservation planning and avoid impacts on birds (e.g. WWF-UK, 2001; European Union, 2011; U.S. Fish and Wildlife Service, 2012; Central Local Government Region of South Australia, 2014). In Australia, the Victorian State environment department has developed guidelines to avoid cumulative and population level wind farm impacts on a threatened crane, the brolga (*Antigone rubicunda*) (DSE, 2011). The brolga is a large, long-lived bird, takes several years to reach reproductive maturity and has a low reproductive output. These characteristics make it vulnerable to population level impacts (Drewitt and Langston, 2006; McCarthy, 2008) and a priority species for assessing and avoiding potential wind farm effects (Desholm, 2009; Hill et al., 2011).

Although common in northern Australia, the southern brolga population has declined since the 1900s (White, 1987), is 'Vulnerable' and is listed under state legislation in Victoria, South Australia and New South Wales, (Bransbury, 1991; Bennett et al., 1998; Stanger et al., 1998; DuGuesclin, 2003). Threats to the population include ongoing habitat loss, due to agriculture and wetland drainage (Corrick, 1982; DuGuesclin, 2003), and collisions with fences and powerlines (DuGuesclin, 2003). The number of wind farms is increasing within the Victorian core range of brolgas in the state's south-west, with several already operating, under construction or in the planning stage (DELWP, 2018). Brolgas may collide with turbines or avoid wind farms, similarly to other cranes (sandhill crane (*Grus canadensis*): Navarrete (2011); Navarrete and Griffis-Kyle (2014); common crane (*G. grus*) Gerjets (2005)). Due to the current, and on-going threats, any wind farm-related habitat loss through displacement and increased mortality from collision are a concern for brolgas.

To manage cumulative impacts on the Victorian brolga population, guidelines recommend turbine-free buffers around breeding sites and breeding site enhancement or powerline marking to offset predicted mortality (DSE, 2011). However, brolga breeding site movements and requirements are poorly known, and no information exists on brolga's response to wind farms. Faced with this uncertainty, decision makers take a conservative approach and recommend turbine-free buffers around breeding sites (DSE, 2011).

The main challenge, however, is the lack of information that makes it difficult to determine buffer sizes and breeding site enhancement actions. Current home range estimates and buffer size recommendations are based on scant, unpublished, field-based sightings (Brett Lane and Associates, 2008; DSE, 2011; Venosta et al., 2011). Venosta et al. (2011) found brolgas with chicks remained within 0.5 km (95% of post-hatching movements) of nests and had home ranges of 41–53 ha but other studies suggest that in agricultural landscapes, breeding cranes move greater distances, 1.6–2 km, and have larger home ranges, 36–600 ha (Johnsgard, 1983; McMillen, 1988; Hereford et al., 2010; Månsson et al., 2013). If brolgas move further from nests than previous studies suggest, and have home ranges similar to other cranes, using current information to inform buffers and offsets may underestimate spatial and habitat requirements at breeding sites. Such buffers may not sufficiently protect breeding brolgas from potential wind farm impacts.

The motivation for our study was driven by the need for information on brolga breeding home ranges to inform buffer size and breeding site enhancement decisions. Our study had two main aims: 1) to define home range requirements, habitat use and selection; and 2) suggest conservation management actions to avoid potential wind farm impacts on breeding brolgas, based on these findings. Additionally, we discuss the broader relevance of our findings to conservation management of other crane species.

2. Methods

2.1. Study area

The study took place in south-west Victoria, Australia (Fig. 1), which is the stronghold of the southeast Australian brol population and supports 600–900 individuals (White, 1987; DuGuesclin, 2003; Sheldon, 2004; SWIFFT, 2018). The regioı landscape is characterised by volcanic plains, basalt and sedimentary rocky outcrops (Cochrane et al., 1995). The Victoı Volcanic Plains bioregion was historically dominated by grassland and woodland vegetation interspersed with wetlaı much of which have been cleared and/or drained for agriculture since European settlement (Corrick, 1982; Commonwealt Australia, 2011). A diversity of wetland types remains present throughout the region, including deep saline wetlands and shallow freshwater marshes and meadows (Corrick, 1982; Norman and Corrick, 1988). Brolgas prefer to nest in shallow, well-vegetated, seasonally inundated wetlands (Herring, 2001; Myers, 2001). South-west Victoria is one of the regions in Victoria where such wetlands are most abundant (Casanova and Casanova, 2016). However, 79% of shallow marshes and 14% of freshwater meadows of this habitat has been lost in parts of the brolgas' range (Corrick, 1982). The majority (81%–84%) of the remaining freshwater wetland habitat occurs on private land (Corrick, 1982; Papas and Moloney, 2012). The region also contains high wind resources, resulting in a rapid increase in wind farm development across the brolga's breeding and non-breeding range (Hill and Lane, 2008).

2.2. Capture methods and GPS transmitter deployment

We used GPS-tracking to study home range movements, habitat use and selection. We captured pre-fledged brolga chicks on agricultural land, used for cropping and grazing. One site was at a wind farm, and the chick was captured post-construction but before turbines began operating. We captured pre-fledged chicks, rather than adults for two reasons: 1) to avoid capture stress to adults during an important part of their lifecycle – brolgas have generally low breeding success (Herring, 2001;

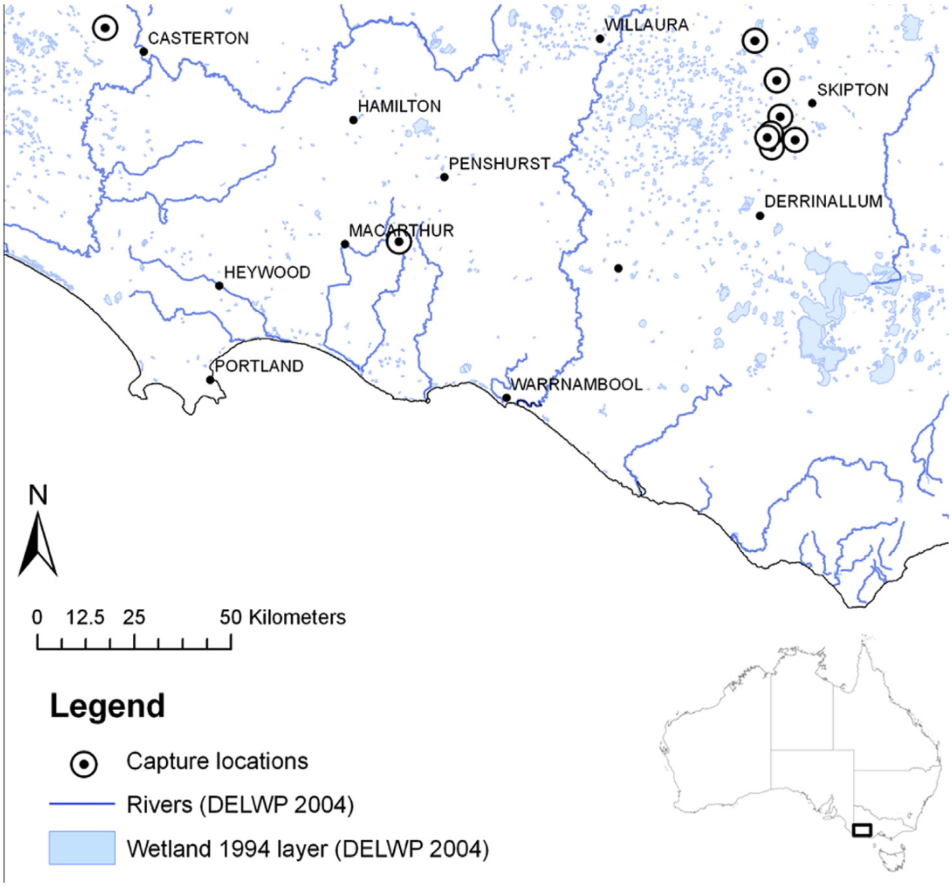


Fig. 1. Study area and capture sites in south-west Victoria, Australia, showing capture locations (nine in total). Inset shows Australia and the rectangle depicts the area of the current study.

Myers, 2001) – and to reduce potential impact to the breeding pair; 2) during 2009–2010 breeding season we banded eight pre-fledged chicks, which all survived to fledging, demonstrating this was a safe method. Brolga families roost and forage together (Marchant and Higgins, 1993), so the data were considered representative of the adult breeding pair and cl movements.

We captured eleven chicks, at nine breeding sites, using active pursuit (Blackman, 1973; Grant, 2008; Veltheim et al., 20 and fitted them with a 30 g leg-band-fitted solar GPS platform transmitter terminal (PTT) (North Star Science and Technol (North Star), USA) mounted onto a two-piece flanged band (Haggie engraving, USA). Capture sites were determined base landholder access and survival of chicks from hatching to capture age (Fig. 1). At two of the sites both chicks of the clutch captured and fitted with a GPS PTT. We took this approach because brolga chick survival is low (Herring, 2001; Myers, 2 and we did not expect all of them to survive to fledging. Ten chicks were fitted with GPS transmitters in 2010–2011, and one in 2012 (Table 1). A chick captured in 2012 at the Macarthur wind farm provided a unique opportunity to obtain data on a brolga family utilising a wind farm.

The leg-band mounted GPS PTT has previously been used on whooping crane (*G. americana*) chicks (Pearse et al., 2015) and was chosen for brolgas, due to their similar size and threatened status. The PTTs collected Doppler and GPS data, and we programmed them to maximise operational battery life and daily GPS fixes. Only the GPS data was used for analyses. The PTTs had a duty cycle of 8 h on/135 h off and acquired four GPS fixes per day: morning (8:00), midday (12:00), late afternoon (16:00) and evening (23:00). This schedule documented diurnal and nocturnal movement patterns and habitat use, including foraging and roosting areas. Accuracy of GPS fixes ranged from <26 m to 100 m, calculated by Argos (CLS, 2016).

2.3. GPS data

Data for each individual included the capture date and locations from pre- and post-fledging periods. Only data from the pre-fledging period were used for home range and habitat selection analyses. We determined the most likely fledging date using behavioural change point analysis (BCPA) (Gurarie et al., 2009) in R (R Core Team, 2013). The BCPA transforms step length and turning angle of the animal's location data into new variables – persistence velocity and turning velocity. A moving window shifts across a continuous autocorrelated series – the movement path – described by mean, variance and continuous autocorrelation, and identifies changes in behaviour (Gurarie et al., 2009).

The aim of the BCPA was to identify fledging date for all chicks. We used data from one individual (76437_2), which dispersed within known fledging period for brolga chicks, to determine the appropriate settings for window size and cluster width. The fledging time for this chick was obvious due to dispersal distance, which would be too great for an unfledged chick (27 km). We used the V*cos, window size of 30, K of 1 and cluster width of 1. We used the same settings for all consequent

Table 1
Summary of GPS data and home ranges estimated using Brownian Bridge movement model (BBMM % UD) (sig 2 = 50.6, see Methods section 2.4 'Home range analysis').

ID	Locality	Capture date	GPS data (# days)	Number of GPS fixes	Fix success rate (%)	BBMM 50% UD	BBMM 95% UD	Parameter sig1 (maximum likelihood estimate) (Calenge, 2006)
76387_1	Skipton	9/01/2011	11/01/2011–23/02/2011 (43)	82	48	29	156	1.78
76388[a]	Skipton	19/11/2010	21/11/2010–10/01/2011 (51)	124	61	26	125	1.46
76389	Casterton	21/11/2010	23/11/2010–14/12/2010 (22)	35	40	11	75	1.07
76434[c]	Skipton	22/11/2010	25/11/2010–6/01/2011 (53)	98	46	54	265	2.25
76436[a]	Skipton	19/11/2010	20/11/10–10/01/11 (52)	104	50	38	193	1.86
76437_2[d]	Gerrigerrup	21/10/2012	23/10/12–4/12/12 (43)	102	60	98	523	4.39
76438	Skipton	9/01/2011	11/01/11–15/02/11 (35)	65	46	8	70	1.0
76449[e]	Skipton	26/01/2011	28/01/11–18/02/11 (21)	47	56	29	263	1.68
76700[b]	Stoneleigh	26/01/2011	28/01/11–15/02/11 (18)	37	51	56	423	2.43
76827[b]	Stoneleigh	26/01/2011	28/01/11–15/02/11 (18)	35	47	28	243	1.88
76862	Skipton	27/02/2011	1/03/11–29/03/11 (29)	71	61	44	211	2.45

[a] Pair of chicks from the same clutch.
[b] Pair of chicks from the same clutch.
[c] Single chick captured from a 2-chick clutch where both fledged.
[d] Chick captured at a wind farm post-construction/pre-operation; both chicks captured from a 2-chick clutch where both fledged, one only fitted with a GPS PTT.
[e] Chick raised by a single male, after the female was trampled by cattle.

analyses to identify other chicks' fledging dates. If BCPA identified more than one change point, we took the first one, and assigned the date previous to this change point as the fledging date. Where we had deployed a PTT on more than one chick from the same clutch and BCPA identified different fledging dates for the paired chicks (pairs 76388 & 76436 and 76700 76827), we used the later fledging date for both as we assumed their movements would be restricted until both chic fledged. Crane chicks and parents move within a family unit at breeding sites (Johnsgard, 1983; Marchant and Higgins, 199 and would be unlikely to fly as a group until both chicks have fledged.

We compared the BCPA-estimated fledging dates with a) a subjective estimate of age at capture based on the s plumage, presence of down feathers and wing moult (determined from chicks of known age from 2009 to 2010 2010–2011 breeding season) and b) published information on the age of brolgas at fledging (11.5–14 weeks (Arnol et al., 19 Venosta et al., 2011) and c) maximum distances moved (1.6 km to over 2 km) prior to fledging based on information on crane chick movements (McMillen, 1988), to ensure fledging estimates were realistic. We additionally plotted the distance between fixes, which indicated a displacement and potential capture effect. We thus excluded the capture date and 1–3 days post-capture from analyses, to account for any disturbance effects due to capture and handling (Table 1).

2.4. Home range and buffer analysis

To understand spatial requirements within breeding home ranges, we used the Brownian bridge movement model (BBMM) to estimate brolga utilisation distributions (UDs) (Horne et al., 2007). We calculated 50%, 95% and 99% volume contours using adehabitatHR (Calenge, 2006), and mapped them in ArcGIS 10.3.1 to check the UDs were realistic. The function 'kernelbb', used to estimate BBMM UD, requires the standard deviation (∂^2) of telemetry error and Brownian motion variance ($\partial^2{}_m$) as smoothing parameters. To calculate telemetry error, we first classified Argos accuracy classes (<26 m; 26–50 m; 51–75 m; 76–100 m) to four integers: 26, 50, 75 and 100. We then calculated the mean, which was 50.6 ($n = 800$). We used the function 'liker', in the R package adehabitatHR, to estimate the Brownian motion variance for each individual (Table 1). We calculated the home range using the function 'kernel.area' and produced 50%, 95% and 99% contour surfaces using the 'getverticeshr' function. We used a grid size of 1500, which reduced the difference between the two estimates (to 0.02 ha on average).

To understand pre-fledged chick movement distances and habitat use within home ranges we calculated movement metrics using adehabitatLT (Calenge, 2006). We calculated the distance moved from the night roost (23:00) and the previous, or next, day fix. We based this on knowledge of daily habitat use – brolgas use night roosts and move out to forage during the day (Marchant and Higgins, 1993). As the GPS acquisition rate was imperfect, we chose the next day fix that was closest to the night-time fix (one of 8:00, 12:00 or 16:00). We overlaid GPS data on spatial layers in ArcGIS 10.3.1 to identify movement patterns and habitat use. To further understand wetland habitat use, to inform conservation management, we calculated the number and size of wetlands used within home ranges, and the distance between night roosts, using GME (Beyer, 2012) and ArcGIS 10.3.1.

To understand home range use at a wind farm, we examined the 95% UD of the chick at Macarthur wind farm before and after turbines begun operating. We used an equal number of locations ($n = 33$ before; $n = 33$ after) for this estimation.

To evaluate size of buffers that could be implemented at wind farms, and to inform policy guidelines (DSE, 2011), we investigated the proportion of 50%, 95% and 99% UD (produced using 'getverticeshr' function) incorporated within circular buffers with radii of 400, 800, 1200, 1600, 2000, 2400 and 2800 m, an approach used by Watson et al. (2014) for golden eagles (*Aquila chrysaetos*) to define buffer areas around nests. We used the centroid of the night roost minimum convex polygon as the starting point for radii, as the nest site was unknown for some individuals.

2.5. Factors influencing home range size

To evaluate drivers of home range size, we investigated the influence of the following factors: a) number of fixes on the 95% UD size; b) the number of chicks in a clutch; and c) wetland connectivity measured as distance to, and area of, wetlands, on home range size. We ran a linear regression to look at the correlation between the number of fixes and the 95% UD size. We compared the 95% UD size of single and two-chick clutches using a *t*-test.

To investigate the influence of connectivity on home range size, we first created centroids for wetland polygons and used the capture location wetland, or wetland nearest to capture location, as the focal wetland. From this point, we then calculated distance to, and area of, wetlands using the geospatial modelling environment (GME) (Beyer, 2012).

We calculated connectivity of wetlands within each home range by using an Incidence Function Model (IFM), which is a better measure of connectivity than the nearest neighbour distance to an occupied patch method (Moilanen and Nieminen, 2002):

$$\sum e^{-d_i/m},$$

where d_i is the distance to wetland and m is the mean distance moved by brolga chicks to, or from, night roosts (442 m). The maximum distance to wetlands (d_i) used was 2000 m, as $e^{-d_i/m}$ approaches zero with greater values of d_i (i.e. $e^{-2000/442} = 0.01$). We then modified the equation to investigate the potential combined influence of wetland area and distance:

$\sum area^{*}e^{-d_i/m}$.

For calculating both measures, we only included wetlands ≥0.6 ha, the smallest wetland that brolgas used in this stu

2.6. Habitat use, availability and selection

To understand what habitat should be incorporated, or avoided, when designing turbine-free buffers and ha enhancement sites, we investigated habitat selection at breeding sites. The 50% and the 95% UD was used to delineate habitat, and available habitat was determined by a 1370m radius of a minimum convex polygon around night roosts (Appendix A). We identified and digitised habitats within this radius. We chose this distance, as 95% of movement distances were within 1369 m of night roosts (Appendix B) and we rounded the distance up to 1370 m to delineate the available area. We used Landsat imagery to identify available wetland habitat (wetlands, creeks, rivers), and created a wetland layer with the actual extent of wetlands at the time brolgas were on breeding territories (Appendix C) (e.g. using December 2010 imagery for chicks that were on breeding territories in December 2010). We chose low cloud imagery and multiple images, particularly if Landsat 7 imagery bands obscured potential wetland habitats (Appendix C). We used known, inundated wetlands within brolga home ranges for ground truthing – matching the colour to identify all other inundated wetlands (Appendix C). We traced around the edges of inundated wetlands, and further checked aerial imagery (ArcMap 10.3.1, Google Earth) and the publicly available Victorian Department of Sustainability and Environment (DSE, 2013) Corporate Spatial Data Library wetland 1994 GIS layer (WET1994). We used aerial imagery and a Victorian land use GIS layer (South West Landuse) to identify non-wetland habitats, which included cropping, grazing, building, native woodland, plantation, fodder crop, roads, wind farm and unknown land use types. Additionally, we used landholder maps for ground truthing to identify land use at the time when brolgas used the habitats. We included major bitumen roads and minor gravel roads (including road reserves), but excluded internal farm roads. Due to the overall low number of buildings in the available habitat, we combined farmhouses and isolated sheds, though recognise that isolated sheds might have less human activity.

We calculated the proportion of wetland habitat used within the 50% UD, 95% UD and available wetland habitat within 1370 m of night roosts, and compared the means using a one-way ANOVA with a Tukey HSD (honest significance difference) post-hoc test. We also used GME (Beyer, 2012) to extract data on non-wetland habitat in ArcMap. We calculated the proportion of non-wetland habitat used within the 95% UD and the available area, by first excluding the wetlands from the land use layer in ArcMap. We then compared the proportion of used and available habitats using parametric compositional analysis (Aebischer et al., 1993) in adehabitatHS (Calenge, 2006). This method analyses proportional habitat use to availability by applying a MANOVA to log-ratios of the proportional use and availability values (Aebischer et al., 1993). Unused habitat, i.e. zero values, were replaced by 0.001, recommended by Aebischer et al. (1993), as log of zero cannot be calculated.

3. Results

3.1. GPS data and movement metrics summary

All 11 chicks survived to fledging. The total number of days prior to fledging ranged from 18 to 53 days and the number or GPS fixes depending on the chick age at capture (Table 1). The number of GPS fixes ranged from 35 to 124 and mean GPS fix acquisition success was 51% (range 40%–61%, se: 2%, n = 11) (fix acquisition rate is the number of fixes programmed, i.e. four, compared with actual fixes acquired by the transmitter, which ranged from 0 to 4 per day). Pre-fledged brolgas moved 442 m on average, between night roosts and day foraging areas (range: 0 m–1964 m, se: 20 m, n = 396) with 50% and 95% of movements within ≤315 m and ≤1369 m respectively (Appendix B).

3.2. Home range and buffer size

The home range of pre-fledged brolgas varied 7.5-fold from the smallest at 70 ha to the largest at 523 ha, at the 95% UD BBMM contour (mean: 232 ha, se: 40 ha, n = 11) (Table 1) and incorporated night and day roosts and day foraging areas (Fig. 2). The number of GPS fixes had no influence on the UD size (r = 0.04). The home range of the chick at a wind farm was larger after the turbines began operating (95% UD before: 423 ha; after: 698 ha) (Fig. 3).

The mean core home range at 50% UD was also variable (range: 8 ha–98 ha, mean: 38 ha, se: 7 ha, n = 11) and contained all night roost wetlands except in two cases (Fig. 2). Night roost wetlands excluded within the 50% UD were characterised by fewer GPS fixes (1–4) compared with night roost wetlands within the 50% UD (4–16), indicating less frequent use (Fig. 2). Two 95% UDs of breeding pairs overlapped (76449 and 76862).

Neither distance nor distance/area measures within the 50% UD and 95% UD had an influence on the home range sizes and we undertook no further analyses of these variables. Two chick clutches had larger home ranges on average (mean: 349 ha, se: 63 ha, n = 4) than single chick clutches (mean: 150 ha, se: 35 ha, n = 5), although the evidence was weak as the confidence intervals overlapped zero (t = –2.40; df = 4.71; CI: [–417.85, 18.45]).

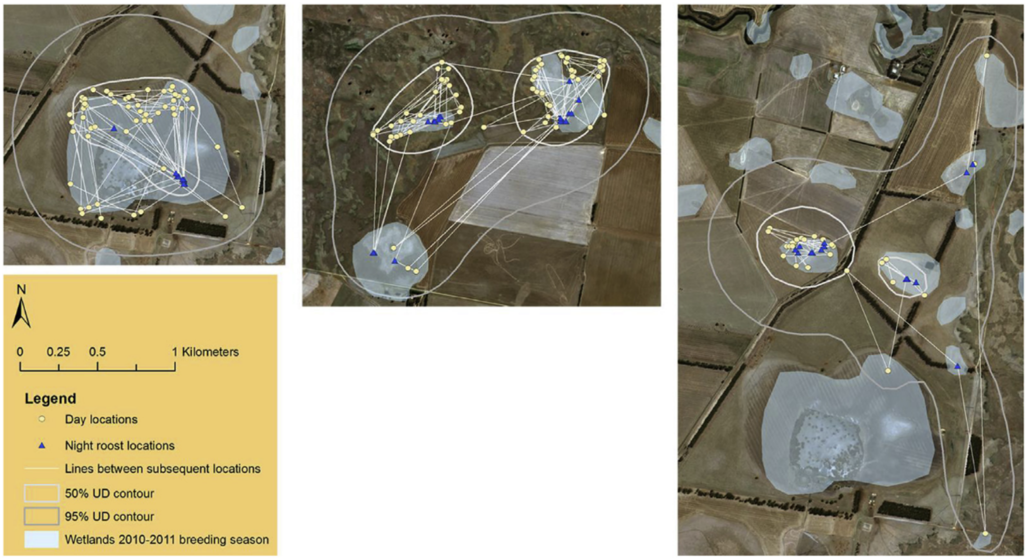


Fig. 2. Home ranges of pre-fledged brolga chicks, from capture to fledging, showing a) use of single night roost (76862); b) use of multiple night roosts, switching between wetlands (76434); c) use of multiple night roosts, relocating to a new wetland (76449). Aerial photography from World Imagery ArcGIS 10.3.1 (ESRI, 2015).

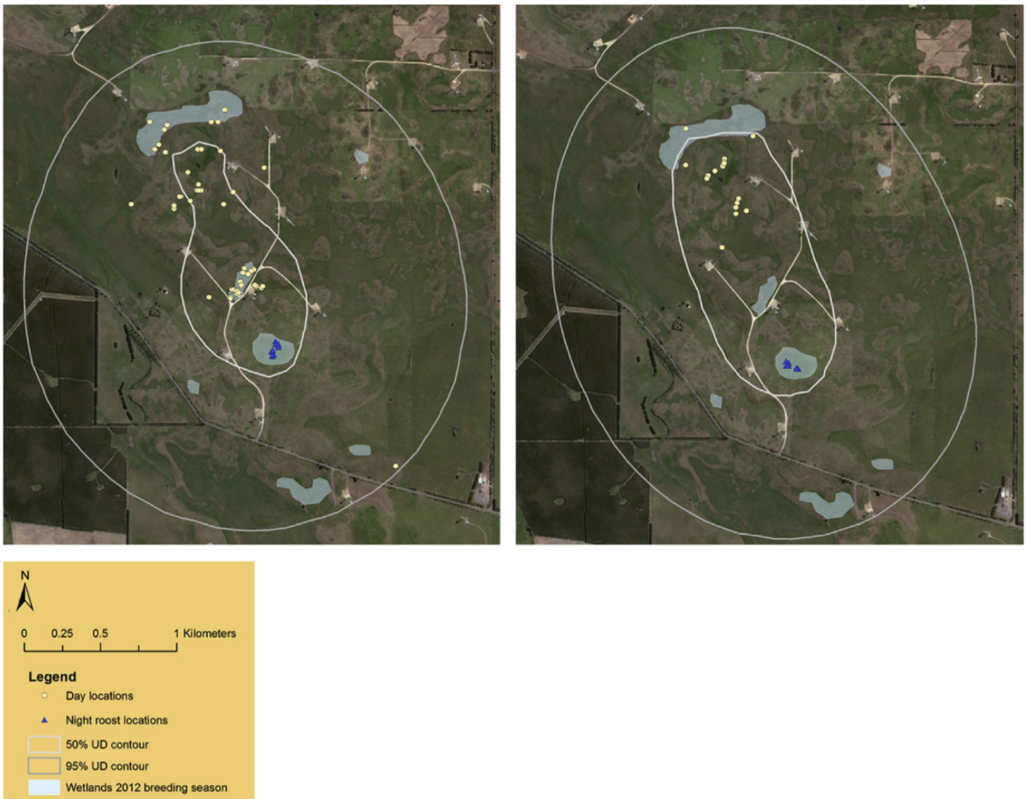


Fig. 3. Home range of 76437_2 pre- (left) and post-turbine (right) operation at the Macarthur wind farm, Victoria. The home range was larger after turbines begun operating (95% UD before: 423 ha; after: 698 ha), but the effect of the wind farm on the difference was inconclusive due to lack of replication (n = 1) and control sites. Habitats used, and direction of travel from night roost, were similar before and after except for the use of one wetland, which was drained and not used post-turbine operation. Aerial photography from World Imagegy ArcGIS 10.3.1 (ESRI, 2015).

Based on mean home range size values of all chicks, the 1200 m radii buffer encompassed 93% of the 50% UD, 88% of the 95% UD and 82% of the 99% UD. Close to 100% of the core home range of 50% UD was included within the 1600 m radius buffer (99%), whereas these radii were 2000 m for the 95% UD and 2400 m for the 99% UD (Fig. 4).

3.3. Habitat use and selection

Used wetlands comprised a higher mean proportion of the 50% UD (37.7%) compared with the 95% UD (8.5%) and available area within 1370 m of night roost MCP (12.6%). Brolgas selected wetland habitat within their 50% UD, using higher proportion than within the 95% UD (F: 9.85, df: 2, CI: [−45.90, −12.49], p: 0.00) and compared with the proportion available (F: 9.85, df: 2, CI: [4.14, 37.55], p: 0.01). Brolgas did not select wetland habitat within the 95% UD, as proportion used was not different to what was available (F: 9.85, df: 2, CI: [-25.05, 8.36], p: 0.44).

The mean number of wetland night roosts used prior to fledging was 2.09 (range:1–4, se: 0.34, n = 23) and the mean number of wetlands used overall (day and night) was 2.82 (range: 1–7, se: 0.58, n = 31) and most used wetlands were ≤15 ha in size (Appendix D; Appendix E). All night-time GPS fixes (23:00 EST) were in wetlands, whereas daytime fixes were in wetland and non-wetland habitat (Fig. 2). The average size of used night roost wetlands was 7.62 ha (range: 0.60–40.74 ha, se: 1.77 ha) and the size of all used wetlands was 8.38 ha (range: 0.60–40.74 ha, se: 1.72 ha). Wetlands within 1–10 ha were the most frequently used size class (Appendix E). The average size of five known nesting wetlands was 13.2 ha (range: 2.96–40.74 ha, se: 7.04 ha).

The main non-wetland habitats used by brolgas were cropping and grazing paddocks (Appendix F). We combined rocky and non-rocky knoll habitat in grazing and cropping land use context into two categories for analyses: “cropping” and “grazing”. Overall, an average of 81.0% of all non-wetland habitat consisted of cropping or grazing land, of which an average 48.8% was grazing and an average of 32.3% was cropping. Similar proportions of both habitats were available within the 95% UD (mean grazing: 53.3%, cropping: 37.4%). Overall, grazing habitat was preferred over cropping habitat, although this difference was small (Table 2).

The next highest proportion of non-wetland habitat within 95% UD of brolga chicks was blue gum (*Eucalyptus globulus*) plantation (mean: 5.5%, se: 4.8, range: 0.4%–19.8% n = 4) and major roads (mean: 1.9%, range: 1.6%–3.0%, se: 0.04, n = 6). Only one individual used plantation habitat (ID76389, Appendix 1), but it comprised a fifth (19.8%) of its 95% UD (Appendix F). Brolgas selected against buildings and watercourses within their home ranges (Table 2). We did not separate the potential effects of sheds and farmhouses, as they were only present within two home ranges and each consisted approximately half of the total proportion attributed to this habitat type. It is unlikely this affected our results or their interpretation, as buildings were absent in nine of the eleven home ranges and in proportions of one or less percent within the two remaining home ranges.

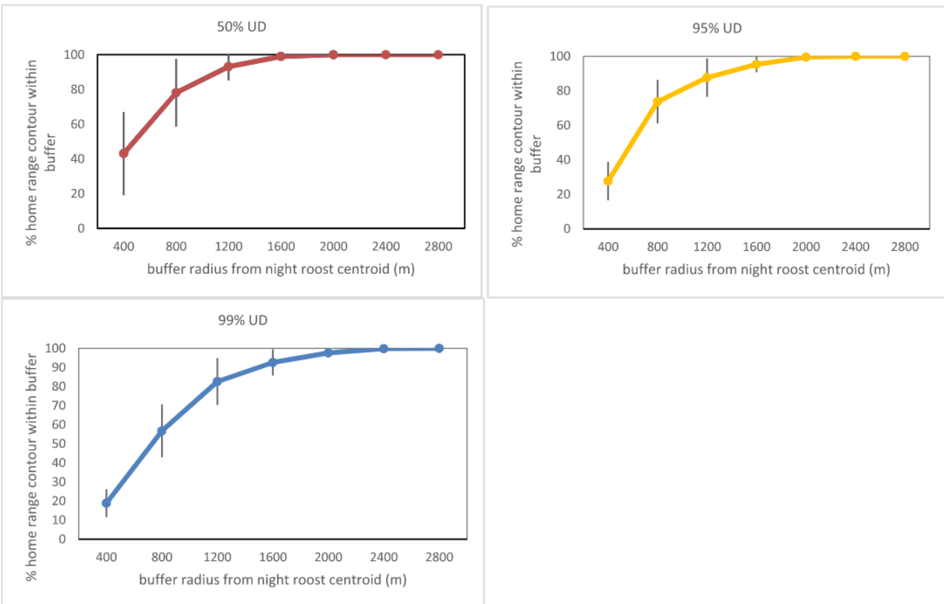


Fig. 4. Proportion of 50%, 95% and 99% UD contour within buffer of different radii from the night roost centroid. Solid circles denote mean, and vertical bars denote 95% confidence intervals. The findings indicate that 100% of the 50% UD, 95% and 99% would be incorporated within a radius of 1.6 km, 2 km and 2.4 km from the night roost centroid, respectively.

Table 2
Ranking matrix with t-values for pairwise comparisons of habitat types used by pre-fledged brolgas within the 95% BBMM UD. Significant differences are in bold, positive values denote habitat in row is used more than the habitat in the column.

		Habitat use									
		buildings	watercourse	native woodland	plantation	fodder crop	major road	minor road	wind farm	cropping	grazin
Habitat available	buildings										
	watercourse	**3.22**									
	native.woodland	**3.24**	**1.48**								
	plantation	**4.24**	**3.11**	**1.17**							
	fodder.crop	**2.68**	**1.29**	−0.09	−0.98						
	major.road	**2.66**	**0.66**	−0.61	−1.36	−0.45					
	minor.road	**2.23**	**0.91**	−0.20	−0.88	−0.19	**0.35**				
	wind.farm	**5.30**	**2.87**	1.01	−0.73	**1.01**	**1.26**	**0.85**			
	cropping	**1.46**	**0.50**	−0.50	−0.92	−0.49	**0.10**	−0.26	−0.92		
	grazing	**3.86**	**1.57**	−0.30	−1.33	−0.19	**0.62**	−0.03	−1.15	**0.18**	
	unknown	**2.90**	**1.24**	−0.01	−0.80	**−0.05**	**0.61**	**−0.13**	−0.57	**0.42**	**0.32**

4. Discussion

This study set out to address a conservation problem with wider global significance – how to avoid potential wind farm impacts on a species at risk, particularly when the species' spatial requirements are unknown. Studies of home range size and habitat requirements can identify important habitats and movement corridors. Siting wind farm infrastructure away from important habitat areas reduces wind farm-bird interactions, and can avoid potential collision and disturbance impacts. Informed planning and siting of wind farms based on movement studies is an important first step in the mitigation hierarchy, at early planning stages, and can avoid wind farm impacts on wildlife (Fielding et al., 2006).

This is the first study using GPS-tracking of brolgas at breeding sites and the only study that has tracked a crane chick at a wind farm. Prior to this study, no accurate information existed on brolga breeding home ranges or habitat selection. More importantly, no information exists on wind farm impacts on brolgas, or breeding cranes, so the Victorian environment department has taken a conservative approach, and has assumed that an impact from wind farm disturbance and collision will occur (DSE, 2011). The overlap of important breeding habitat and wind farms across brolga's core range is increasing, as a number of wind farms are currently under construction and in planning stages (DELWP, 2018). Proponents are required to implement turbine-free breeding home range buffers to avoid wind farm and brolga interactions and potential impacts from wind farm infrastructure. Our study on brolga breeding home range and habitat selection provides decision guidelines for such buffers and thus informs conservation management of this threatened species.

4.1. Home range size and movements

Understanding movements and home range requirements is important in conservation planning and home range studies are often applied to management of species at risk of potential wind farm impacts. Studies on similar species can provide insights that have wider global applications to their conservation management. Pre-fledged brolga chicks moved comparable distances and had similar home ranges to other crane species in studies where radio transmitters (McMillen, 1988; Hereford et al., 2010) or GPS telemetry (Månsson et al., 2013) have been used. Pre-fledged Mississippi sandhill and greater sandhill cranes (*G. c. pulla and G. c. tabida*) can move 1.6 km and more than 2 km (McMillen, 1988), respectively, from nest sites (Johnsgard, 1983; McMillen, 1988). Similarly, whooping crane families and black-crowned cranes (*Balearica pavonine*) forage 1.6–1.8 km from nests (Johnsgard, 1983). Ability to traverse long distances on foot could be important to chick survival if food in the nesting wetland is depleted or if the wetland dries out.

Such movement ability can produce large home ranges for cranes in agricultural landscapes, where the nesting wetland may not contain all the resources required from chick hatching to fledging. The home range size of pre-fledged brolgas was highly variable but comparable to other crane species despite different estimators used (brolgas 70–523 ha, this study; Mississippi sandhill crane 50–400 ha, Hereford et al., 2010; greater sandhill crane 36–388 ha, McMillen, 1988; common crane 116–600 ha Månsson et al., 2013). Variability in home range size is not surprising as it is common more generally across numerous bird (Schoener, 1968) and mammal taxa (McNab, 1963).

Time of the year, age and sex of tagged individuals, conspecific density (Johnsgard, 1983), body weight (McNab, 1963; Schoener, 1968), food density and habitat quality can influence home range size. Understanding the causes of brolga home range variation is difficult, as these factors were not measured. Year, age or sex of the individuals was unlikely to explain the variation, because all brolga chicks were followed up to fledging, chicks were similar age, 9 of the 11 chicks were female, and because brolgas move as a family unit at breeding territories. We expected high wetland connectivity and larger wetland area to result in smaller home ranges, but found no relationship between home range size and the connectivity measure. Brolgas possibly selected for wetland features not measured in this study and some wetlands within home ranges may have been unsuitable roosting and foraging habitat. Brolgas also used non-wetland habitat suggesting the proximity and spatial arrangement of different habitats may determine the size and shape of home ranges, as is the case for some mammal species (Martin and Martin, 2007; Di Stefano et al., 2011). There was some evidence that families with two chicks had larger hc ranges on average, compared with single chick families (349 ha vs. 150 ha). This may reflect faster food depletion rate: proximity to the nesting wetlands and the need to forage further over time to meet daily energetic requirements.

4.2. Habitat selection

Habitat selection studies can identify ecological requirements, or avoided habitat features, that may need to be consid in conservation planning. Brolga breeding sites occur in several land use contexts in Victoria, mainly cropping, grazing and plantation (Myers, 2001; this study). Habitat types surrounding brolga breeding wetlands more likely reflect dominant land use, rather than selection at the home range scale, which may explain why brolgas in our study did not select for any land use type. This is in contrast to suggestions that land use context around brolga nesting wetlands may influence wetland selection and breeding success (Myers 2001; Herring 2005). However, many other crane species in agricultural areas forage in open habitats away from breeding wetlands and show no selection for habitats at the broader home range scale, suggesting that cranes are similar in this aspect of their behaviour (Borad et al., 2001; Månsson et al., 2013; Van Schmidt et al., 2014). Indeed, sandhill and whooping cranes do not select habitat beyond 200 m of nests (Baker et al., 1995; Timoney, 1999). The evidence for wetland selection within 50% UD brolga breeding home ranges was weak, and illustrates that selection may in fact occur at the scale of the individual wetlands – possibly for dense vegetation, water depth or food, known to be important nesting site characteristics (Herring, 2001; Myers, 2001). Individual wetland condition and quality is thus most likely to be the most important habitat feature for brolga breeding success.

Brolgas were historically hunted and shot (White, 1987; Marchant and Higgins, 1993), and their eggs collected until the late 1960s (White, 1987). Frequent human activity characterises farmhouses and nearby sheds, and habitat selection away from buildings may therefore reflect sensitivity to disturbance. Brolgas are thus no different to other crane species, which choose to nest or roost away from humans and are sensitive to disturbance (Shenk and Ringelman, 1992; Meine and Archibald, 1996; Canadian Wildlife Service and U.S. Fish and Wildlife Service, 2007), though they may also become habituated to human presence if not threatened (Borad et al., 2001). Brolgas also seemed to select habitat away from creeks. Other breeding cranes also avoid watercourses, which are thought to pose a drowning risk or a movement barrier to chicks (McMillen, 1988).

4.3. Conservation and management implications

This study has greatly increased our understanding of brolga home range, habitat and ecological requirements at breeding sites and has implications for the species' conservation. The findings can be implemented at the wind farm planning, pre-operation and post-operation stages to reduce impacts on brolgas and to manage and create breeding wetlands. This is also the first study to document a crane species' breeding home range movements at a wind farm.

The Victorian brolga breeding site objective for avoiding and minimising wind farm impacts is to ensure no significant impact on breeding success (DSE, 2011). Avoiding impacts at breeding sites must therefore ensure fledging and recruitment of chicks is not adversely affected by the presence of wind farms. Land managers and conservation decision makers can use this study's results to make decisions on turbine-free areas around breeding sites to meet this objective, to manage breeding sites to improve breeding success, and to offset modelled collision mortality.

Single wetland management around a nest is unlikely to protect breeding brolgas from potential wind farm impacts. Brolga chicks in this study used multiple wetlands within their home ranges before fledging. Given that all chicks survived to fledging, this is the most important consideration for breeding site protection and enhancement at wind farms and in a broader conservation context. It is also likely to apply to conservation management of breeding cranes in agricultural landscapes, as home ranges, movement distances and use of multiple wetlands were comparable with other crane species (Kitagawa, 1982; Johnsgard, 1983; McMillen, 1988; Hereford et al., 2010; Månsson et al., 2013).

Single, large wetlands may also provide sufficient resources until brolga chicks fledge. However, the majority of brolga nests in south-west Victorian occur in small wetlands (<10 ha) (White, 1987; Myers, 2001; Sheldon, 2005; Appendix E). In comparison, brolgas in north-east Victoria nested in wetlands that were 115 ha in size on average (Herring, 2001). The large proportion of brolga nesting in small wetlands in south-west Victoria most likely reflects the size of wetlands remaining in the landscape, after large scale historical drainage and modification. The use of small wetlands (<10 ha) by breeding brolgas has further conservation implications. Small wetlands (<5 ha) are vulnerable to cropping – more so than larger wetlands (Casanova and Casanova, 2016) – and may be more prone to drying prior to chicks fledging. Protecting and managing multiple wetlands within breeding territories is therefore particularly important to improve breeding success. Conservation efforts should focus larger as well as small wetlands, to reduce risk of further breeding wetland losses from cropping.

Cranes are known to avoid wind farms (Gerjets, 2005; Navarrete and Griffis-Kyle, 2014) and caution should be applied to protect brolgas from impacts, particularly due to their threatened status (DuGuesclin, 2003) and generally low breeding success (Myers, 2001; Herring, 2005). Avoidance of turbines can result in increased movement distances (Drewitt a Langston, 2006), which in turn can increase energetic costs, predation risk (Johnsgard, 1983; McMillen, 1988) and pote tially, breeding success of cranes.

The large home range variation makes it challenging to apply a generic buffer, based on an average home range size movement ability of pre-fledged chicks. Designing turbine-free buffers should thus not be based on distances moved, or ho ranges, alone – particularly as they can vary greatly between sites (McMillen, 1988; Hereford et al., 2010; Månsson et al., 20 this study). It may be more appropriate to ensure habitat elements (breeding site, night roost, foraging areas), and poten movement corridors, are incorporated into buffers at each site, based on their spatial arrangement in the landscape. Turbines should be excluded from the 50% UD, which incorporates the breeding site, night roosts and surrounding foraging habitat, and the 95% UD, which includes movement corridors between them.

Our results indicate that brolgas need three wetlands within their 95% UD for successful fledging, based on the average number of wetlands chicks used prior to fledging. The availability of wetlands in addition to the nesting site is likely to influence breeding success and recruitment. Thus, breeding wetlands and non-wetland habitat within home ranges should be incorporated into turbine-free buffers and to allow barrier-free movement between wetlands and non-wetland foraging areas (e.g. Fig. 2). Turbine-free buffers of 1600 m are likely to protect all of the 50% UD core brolga breeding home range, which contains nesting and night roost wetlands (Fig. 4). Furthermore, 2000 m buffers would encompass additional foraging habitat and movement corridors within the 95% UD (Fig. 4), which are likely to be important in ensuring that brolga chicks fledge successfully. Managers could thus design turbine-free buffers based on the results of this study and additional recommendations detailed within the brolga wind farm management guidelines (DSE, 2011).

Current recommendations for protecting, creating and enhancing brolga breeding habitat focus on managing single wetlands (Arnol et al., 1984; Herring, 2001; DuGuesclin, 2003; DSE, 2011) whereas our results suggest that creating and restoring wetland complexes is more likely to improve breeding success. As crane chicks are at higher risk of predation when walking between habitats (Johnsgard, 1983; McMillen, 1988), wetlands should be as close to each other as possible. The mean distance walked by brolga chicks in this study (0.4 km) could be used as a guide when creating wetland habitats at breeding sites to reduce distances walked by chicks, thereby reducing predation risk and to increase breeding success.

This study was limited to pre-fledged chick movements at breeding sites. We recognise that breeding adults may range further to forage during nest building, incubation and chick rearing. Studies focusing on GPS telemetry of breeding adult pairs are recommended, to identify if larger buffers are required to avoid potential disturbance and mortality effects from turbines during the entire breeding season – from nest building and incubation, to chick fledging. Further GPS tracking studies at wind farms pre- and post-operation are warranted. The 95% UD of the brolga chick at Macarthur wind farm was larger after turbines began operating (423 ha vs. 698 ha), but the cause for this response is unknown. The increased movement distances may have been due to drainage of a wetland within the home range, or due to increasing home range as the chick gets older, rather than wind farm-related disturbance. Furthermore, lack of comparisons and replication at control sites for the same breeding season (2012), makes it impossible to generalise population level responses of breeding brolgas to wind farms. A before-after control-impact study tracking multiple individuals, within the same breeding season, should be undertaken to understand potential wind farm impacts to movement behaviour, habitat use and breeding success of brolgas.

Movements, home range size and habitat use of brolgas in south-western Victoria were similar to other crane species breeding in agricultural landscapes, such as sandhill cranes (McMillen, 1988; Hereford et al., 2010), common cranes (Månsson et al., 2013) and wattled cranes (*Bugeranus carunculatus*) (McCann and Benn, 2006). The general principles of habitat protection and enhancement suggested here for brolgas could be useful for managing other crane species at breeding sites, particularly in agricultural landscapes. Crane wetland preferences have common features, such as dense, emergent, wetland vegetation that provides nesting material and cover for chicks. Managing crane breeding territories by incorporating multiple wetlands within close proximity of each other is thus likely to increase breeding success of brolgas and other crane species inhabiting farmland.

Declarations of interest

None.

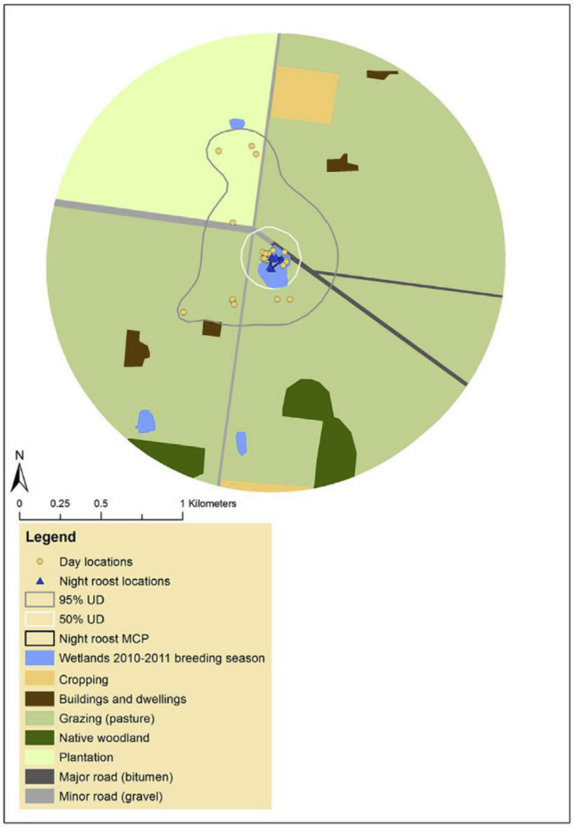
Acknowledgements

This study was funded by the Commonwealth Department of Environment, Victorian Department of Sustainability and Environment (DSE), Sustainability Victoria, Bird Observation and Conservation Australia (BOCA), Clean Energy Council, Origin Energy, Meridian Energy Wind Macarthur, Union Fenosa Wind Australia, Pacific Hydro, Biosis Research, Wind Prospect, TasHydro and a postgraduate scholarship to IV from Federation University Australia and DSE. Additional funding was provided by Holsworth Wildlife Research Endowment and Birds Australia Victoria research grant. The Australian Research

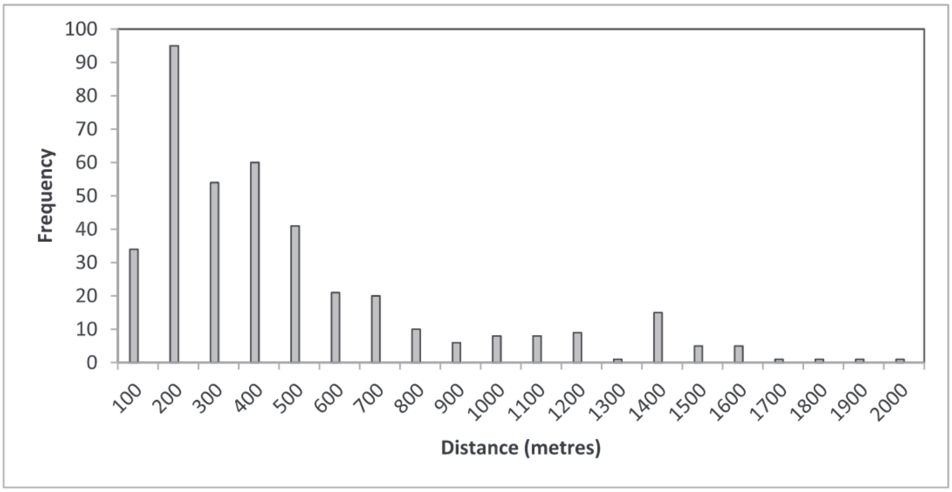
Council Centre of Excellence for Environmental Decisions provided additional support. We thank volunteers for field assistance and landholders for access, John McEvoy, Julian DiStefano and Bronwyn Hradsky for discussions about home range analyses, and Eli Gurarie for help with BCPA. We also thank Kylie Soanes and Birgita Hansen, and two reviewers for comme on the manuscript. The project was approved by the Federation University Australia Animal Ethics Committee, (08-0(Australian Bird and Bat Banding Scheme, approval and banding authority (2489); and was conducted under a scient permit, number 10004758 and 10006195 from DSE.

Appendices

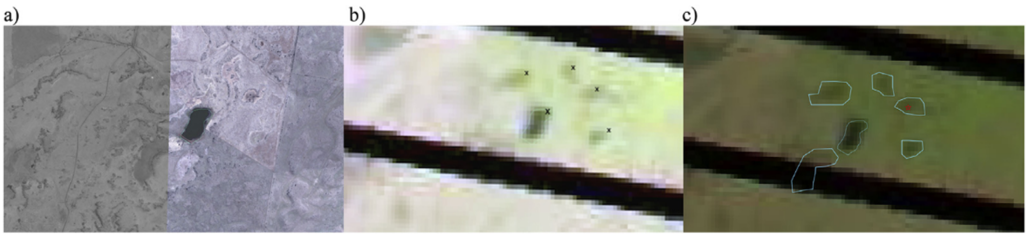
Appendix A. A 1370 m buffer around a night roost minimum convex polygon showing land use categories and wetlands from digitised ArcGIS layers, and the 95% UD and 50% UD, used to investigate habitat selection of brolgas within their home ranges.



Appendix B. Frequency distribution of distances moved by pre-fledged brolga chicks at breeding sites to and from night roosts (n = 396) – 50% of GPS fixes were within 315 m, 95% within 1369 m and the mean distance moved was 442 m.



Appendix C. Imagery used in creating a wetland layer for this study: a) shows an aerial photograph with the wetland 1994 DELWP GIS layer overlay (DSE, 2013); b) shows Landsat 7 imagery for the same area, used by one of the brolga chicks (76387_1), the x marks wetlands identified and used by brolgas, using GPS tracking; c) shows the resulting wetland GIS layer we created (the red star denotes capture location). Aerial photography from World Imagery ArcGIS 10.3.1 (ESRI, 2015).



Appendix D. Wetland use by brolga chicks within breeding home ranges. Multiple wetland use was evident at seven of the nine breeding home ranges (chicks 76388 & 76436 and 76700 & 76827 were two-clutch chicks – see Table 1).

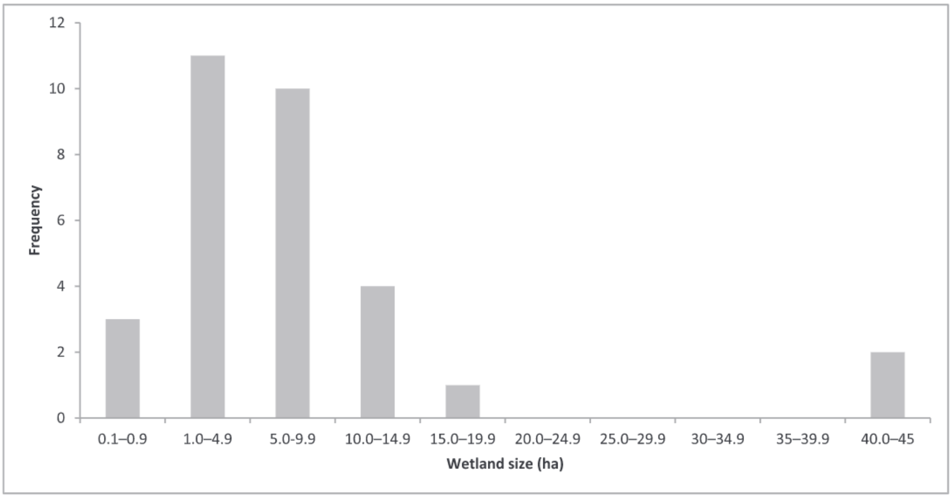
ID	Number of wetlands within 95% UD	Number of wetlands available within 1370 m night roost MCP buffer	Number of night roost wetlands used within 95% UD	Mean distance between night roosting locations (meters)	Total number of wetlands used within 95% UD	Minimum distance to nearest wetland within MCP Buffer
76387_1	11	28	4	167 (sd: 136, se: 30, range, 13–396)	6	215
76388	3	4	2	59 (sd: 173, se: 31, range: 0–1016)	2	581
76389	2	1	1	29 (sd: 31, se: 11, range: 0–70)	1	915
76434	3	11	3	211 (sd: 411, se: 79, range: 0–1405)	3	920
76436	3	5	2	52 (sd: 161, se: 26.2, range: 0–1010)	2	581
76437_2	3	7	1	25 (sd: 20, se: 4, range: 0 –70)	3	492

(continued on next page)

(*continued*)

ID	Number of wetlands within 95% UD	Number of wetlands available within 1370 m night roost MCP buffer	Number of night roost wetlands used within 95% UD	Mean distance between night roosting locations (meters)	Total number of wetlands used within 95% UD	Minimum distance to nearest wetland withi MCP Buffer
76438	2	5	1	48 (sd: 52, se: 13, range: 0–87)	2	736
76449	7	16 (1 unknown status in band)	4	223 (sd: 376, se: 94, range: 0–1233)	7	331
76700	16	67	2	906 (sd: 1333, se: 421, range: 0–2860)	2	518
76827	13	45	2	336 (sd: 857, se: 271, range: 0–2773)	2	518
76862	1	2	1	108 (sd: 182, se: 50, range: 0–519)	1	1068

Appendix E. Size of wetlands used by breeding brolga chicks prior to fledging, in south-west Victoria. Most frequently used wetlands were less than 10 ha, comparable to other studies' findings in south-west Victoria (White, 1987; Myers, 2001; Sheldon, 2005).



Appendix F. The proportion of each habitat type within 95% UD brolga chick home ranges ("USED") and available within 1370 m radius of night roost MCPs ("AVAILABLE").

USED											
Habitat type	76387_1	76388	76389	76434	76436	76437_2	76438	76449	76700	76827	76862
Cropping (non-rocky)	0.00	21.47	0.00	11.34	22.90	0.00	76.20	30.11	0.00	0.00	5.43
Building/dwellings	0.00	0.00	0.06	0.11	0.00	1.11	0.00	0.00	0.00	0.00	0.00
Unknown (cropping/hay/pasture)	0.00	5.52	0.00	1.61	5.10	0.00	0.00	0.00	0.00	0.00	0.00
Pasture/stock (non-rocky)	0.00	0.00	68.52	20.42	0.00	12.44	0.00	35.25	0.00	0.00	54.57
Creek/river	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.43	0.01	0.00
Remnant native woodland	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plantation	0.00	0.00	19.76	0.00	0.00	1.13	0.00	0.00	0.46	0.41	0.00
Fodder crop (including silage and hay)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Major road (bitumen)	0.00	1.88	1.99	0.00	1.85	1.87	0.00	1.75	0.00	0.00	2.02
Unknown/undefined (paddocks next to dwellings, internal roads, riparian areas)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary roads (not bitumen)	0.00	0.00	4.95	0.12	0.00	0.00	2.75	0.00	0.00	0.00	0.00
Wind farm infrastructure	0.00	0.00	0.00	0.00	0.00	1.28	0.00	0.00	0.00	0.00	0.00
Rocky knoll grazing	100.00	54.12	0.00	52.99	52.24	58.04	0.00	17.95	6.03	1.76	2.07
Rocky knoll cropping	0.00	5.17	0.00	0.00	5.28	0.00	0.00	0.00	86.28	86.28	4.48

(*continued*)

USED											
Habitat type	76387_1	76388	76389	76434	76436	76437_2	76438	76449	76700	76827	7686
AVAILABLE											
Habitat type	76387_1	76388	76389	76434	76436	76437_2	76438	76449	76700	76827	7686
Cropping (non-rocky)	0.60	39.59	2.38	24.40	39.59	0.00	75.46	30.65	0.00	0.00	23.2
Building/dwellings	0.00	2.84	0.97	1.03	2.84	0.99	1.06	1.75	0.87	0.87	1.71
Unknown (cropping/hay/pasture)	0.00	7.88	0.00	1.73	7.88	0.00	0.00	0.00	0.00	0.00	0.00
Pasture/stock (non-rocky)	3.67	0.95	73.12	11.76	0.95	23.95	9.99	25.66	0.00	0.00	32.52
Creek/river	0.00	0.47	0.00	0.00	0.47	2.17	0.77	0.21	1.03	1.03	0.00
Remnant native woodland	0.00	0.00	3.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plantation	0.00	0.00	17.32	0.00	0.00	5.62	0.00	0.00	0.00	0.00	0.00
Fodder crop (including silage and hay)	0.00	0.00	0.00	0.00	0.00	0.00	11.41	0.00	0.00	0.00	0.00
Major road (bitumen)	0.00	3.11	1.05	0.63	3.11	1.96	0.00	1.47	2.29	2.29	1.70
Unknown/undefined (paddocks next to dwellings, internal roads, riparian areas)	0.00	0.36	0.00	0.00	0.36	0.00	0.00	1.67	0.00	0.00	0.00
Secondary roads (not bitumen)	0.00	0.00	1.78	0.59	0.00	0.00	1.32	0.00	0.37	0.37	0.00
Wind farm infrastructure	0.00	0.00	0.00	0.00	0.00	1.17	0.00	0.00	0.00	0.00	0.00
Rocky knoll grazing	95.73	35.60	0.00	59.86	35.60	64.14	0.00	38.59	16.64	16.64	40.82
Rocky knoll cropping	0.00	9.20	0.00	0.00	9.20	0.00	0.00	0.00	78.81	78.81	0.00

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