Threatened Species Recovery Hub

National Environmental Science Programme

Strategic planning for the Far Eastern Curlew

Final Report

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Charles Darwin University Australia · The University of Queensland Australia · Darwin Port · Larrakia Nation · In partnership with Northern Territory Government

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Cover image: Damien Stanioch and Amanda Lilleyman fitting a GPS to a Far Eastern Curlew in Darwin. Image: Gavin O'Brien

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Executive summary

Globally, shorebirds are doing poorly with population declines of multiple species occurring throughout the world's flyways (Piersma et al. 2016, Munro 2017, Studds et al. 2017). Of the world's shorebirds, species from the Numeniini tribe are most highly threatened with seven species of conservation concern (Pearce-Higgins et al. 2017). One of the world's largest shorebirds, the Far Eastern Curlew (*Numenius madagascariensis*) belongs to the Numeniini tribe, is endemic to the East Asian-Australasian Flyway and is considered globally endangered (BirdLife International 2017). The species has suffered population declines of up to 80% in three generations (Department of the Environment and Energy 2015). It is listed as Critically Endangered under the *Environment Protection Biodiversity Conservation Act 1999* in Australia because numbers were thought to be rapidly declining. Population declines of multiple shorebird species in the EAAF have been linked to reclamation and land conversion activities in the Yellow Sea region causing a loss of suitable habitat for shorebirds (Studds et al. 2017). Threats to shorebirds are not limited to staging area bottlenecks, but also to non-breeding areas where shorebirds face pressures from coastal development and anthropogenic disturbance (Harding et al. 2007).

Recent research has highlighted the importance of high-quality non-breeding habitat to migratory shorebirds, but it has been difficult to provide strategic guidance to developers and decision-makers because too little was known regarding the ecological requirements of the Far Eastern Curlew, particularly their feeding and roosting habitats. In the current study we investigate the habitat use of the critically endangered Far Eastern Curlew on the non-breeding grounds in Australia and present results of local movements of GPS-tagged birds from four regions across Australia – Darwin Harbour in Northern Territory (NT), Roebuck Bay in Western Australia (WA), Western Port Bay in Victoria (VIC) and Moreton Bay in Queensland (QLD). Such knowledge is needed to develop strategic guidelines for Far Eastern Curlew conservation.

We discovered that tagged individual curlews repeatedly used familiar roosting and feeding sites, although the home range size varied markedly among the four study regions. Home range was largest for individuals in QLD and then WA, VIC and smallest in NT. We found considerable overlap of the home ranges of curlews within each region with birds moving daily from regular roost sites to regular feeding areas. The mean maximum daily distance travelled was greatest in the VIC curlews (8.4 km, range 0 – 74.4 km) and least in NT curlews (2.8 km, range 0.01 – 6.9 km).

The curlews showed a strong preference for intertidal habitats with a soft substrate. The average core area used at both feeding and roosting sites was relatively small in NT curlews but larger in all other regions and both feeding and roosting were used repeatedly by each individual over multiple seasons (average KUD 50%: NT = 2 km^2; WA = 22.3 km^2; QLD = 39.6 km^2; VIC = 32.4 km^2). The curlew rarely fed outside their usual feeding home range.

The regularity of habitat used by individuals benefits planning because the areas occupied by curlews when roosting and feeding in one survey are likely to be those required by the species at all times. Both foraging and roosting habitat types need protection, but the species does not require areas outside these two contexts.

Roost sites that curlew use during spring tides are particularly valuable and all roost sites within 30 km of the home ranges identified by our study should be managed for shorebirds Given that curlew have been shown to use artificial roost sites (though relative abundance at artificial sites varies widely by region), degradation or loss of natural roosting habitat could potentially be offset by creation of alternative roost sites that could be used at all tide states and are as close to feeding areas as existing roost sites and have similar properties in terms of protection from disturbance and in allowing curlews the visibility they need to detect potential predators. Offsetting by protection of potential sites not currently used by curlew is not recommended unless the reasons they are not used are determined and mitigated and there is evidence that the curlews will then find such sites suitable.

Feeding areas are less readily offset. Potentially soft sediments currently unused because of excessive disturbance could be protected from that disturbance, allowing their use. Given the strong philopatry of curlew to existing feeding areas, the efficacy of augmented protection of sites that are currently unused could only be determined over multiple seasons to provide curlew time to find and use such areas. At this stage, while it is known that curlew eat crustaceans and other relatively large invertebrates living within soft sediments, the minimum density of such prey required is not known so establishing new feeding habitat to replace any rendered unsuitable by development would require additional research. Ideally any areas used regularly by feeding curlew should be avoided in development. Surveys of habitat to detect the presence of feeding curlew should be undertaken at least three times over the non-breeding period of September to March to assess the numbers and limits to the home ranges of any curlews using a site. Surveys also need to determine the location of likely roost sites that also need protection, potentially by assessing direction of travel of any curlew departing feeding areas as the tide rises.

Background to the Far Eastern Curlew

Understanding the habitat use and distribution of individuals across a landscape and resources used by the population is fundamental to conserving threatened species (Piersma 2006). Many populations of migratory shorebirds on non-breeding grounds face direct conflict with humans and anthropogenic activities, which can change how birds use resources in the landscapes (Piersma 2006). The primary driver of shorebird movement in coastal landscapes is to search for food for survival (Piersma 2006). The habitats that shorebirds use can provide information on the quality of the area and birds can be used as sentinels for environmental change (Piersma and Lindström 2004). The Far Eastern Curlew is the largest of the annual migrant shorebirds that travel along the East Asian-Australasian Flyway (hereafter the EAAF), to which it is endemic (Higgins and Davies 1996). It is found along the coastline of Australia where it uses sheltered coasts, estuaries, harbours, inlets, coastal lagoons, with intertidal mud- and sand-flats available for birds to forage (Higgins and Davies 1996).

Currently listed as Vulnerable on the IUCN Red List, the Far Eastern Curlew is highly threatened within its range, facing the most challenges at critical staging sites in the Yellow Sea region. Habitat destruction and reclamation of tidal mudflats are the biggest threats to this and many other migrant species dependent on these staging grounds, but the species is also threatened by hunting, pollution, changes to water regimes, disturbance, and climate change impacts on breeding grounds (Harding et al. 2007). The cumulative interaction of these threats within the Flyway and the dramatic decline in Far Eastern Curlew numbers has led to the uplisting of Far Eastern Curlew from Endangered to Critically Endangered in Australia under the Commonwealth Government's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

The Far Eastern Curlew is found all around Australia and population trends for the species have varied across its range despite suitable habitat occurring along most of the Australian coastline (Figure 1). The most severe population declines for this species have occurred in the south-east of the continent (Clemens et al. 2016). The last thirty years has seen an increase in the reported rate of decline of the Flyway population of Far Eastern Curlew with projections that the species will continue declining at 30-49 % over the next thirty years (Garnett et al. 2011). Once a common visitor to Tasmania, the Far Eastern Curlew population has declined by 65% since the 1950s and a continuing decline at this rate would see the few remaining individuals extirpated from the area within the next 30 years (Reid and Park 2003). Similar trends have been reported for areas in South Australia, Victoria, New South Wales, northern Western Australia and Queensland (Close and Newman 1984, Gosbell and Clemens 2006, Rogers et al. 2009, Hansen et al. 2011, Wilson et al. 2011, Minton et al. 2012). Frequently cited potential causes leading to the species declines are habitat loss and reclamation of tidal flats in the core staging sites in the Yellow Sea region. Despite the severe declines in some areas, Far Eastern Curlew numbers have been reported as increasing or stable in two regions in the north of Australia (Lilleyman et al. 2016b, Rogers 2019, Lilleyman et al. 2020).

Recent research has highlighted the importance of high-quality non-breeding habitat to migratory shorebirds, but it has been difficult to provide strategic guidance to developers and decision-makers because too little was known regarding the ecological requirements of the Far Eastern Curlew, particularly their feeding and roosting habitats. Such knowledge is needed to develop strategic guidelines for Far Eastern Curlew conservation. The problem is that very little is known about the exact habitat requirements of Far Eastern Curlew at non-breeding sites. This makes it extremely difficult to provide appropriate guidance on proposals to develop coastal Far Eastern Curlew habitat to avoid having a significant impact on the species. Additionally, as coastal development most often occurs at a small scale, individual developments are unlikely to have a major effect on their own. However, effects can become significant when several small-scale developments are combined (cumulative impacts).

This research project aims to analyse Far Eastern Curlew feeding and roosting habitat, and the relationship between these habitats. This research will be used to inform and develop strategic guidelines for the Department to inform Far Eastern Curlew conservation that will provide more certainty to developers, planners and regulators. It is also anticipated that such strategic planning for Eastern Curlew will also benefit other EPBC Act listed threatened migratory shorebird species.

This project aims to:

1. Understand the local movements of Far Eastern Curlew across the Australian non-breeding grounds by GPS tracking of individuals.
2. Determine the types of habitat that individual curlews use during the non-breeding season through spatial mapping.
3. Examine the availability of intertidal habitat across study regions on the non-breeding grounds by calculating tidal exposure and extent and availability of intertidal zone.
4. Engage with and train local Indigenous rangers to monitor migratory shorebirds in an industrial harbour.

Tracking the Far Eastern Curlew

AIM 1 Understand the local movements of Far Eastern Curlew across the Australian non-breeding grounds by GPS tracking of individuals.

The goals of tracking the Far Eastern Curlew are to understand the local movements made by individuals, and to compare these movements across four different regions. Collecting data from multiple study regions will help us to inform management for the species by understanding habitat use across 1) different habitat types, 2) different climatic zones, and 3) by identifying land tenure and appropriate managers and landowners.

This study focused on for Far Eastern Curlew at four regions on the non-breeding grounds of Australia: Darwin Harbour on Larrakia country, Northern Territory, Roebuck Bay on Yawuru country, Western Australia, Moreton Bay on Quandamooka country, Queensland, and Western Port on Boon Wurrung country, Victoria (Figure 1). Maximum counts of Far Eastern Curlew for the years 2017 – 2020 were: 292 individuals in Darwin Harbour, Northern Territory; 693 individuals in Moreton Bay, Queensland; 200 individuals in Western Port, Victoria; and 568 individuals in Roebuck Bay, Western Australia. Maximum counts per year for Moreton Bay and Roebuck Bay exceeded the 1% EPBC Act threshold and these sites are considered internationally important. Maximum counts at Darwin Harbour and Western Port met the 0.1% EPBC Act threshold and are considered nationally important.

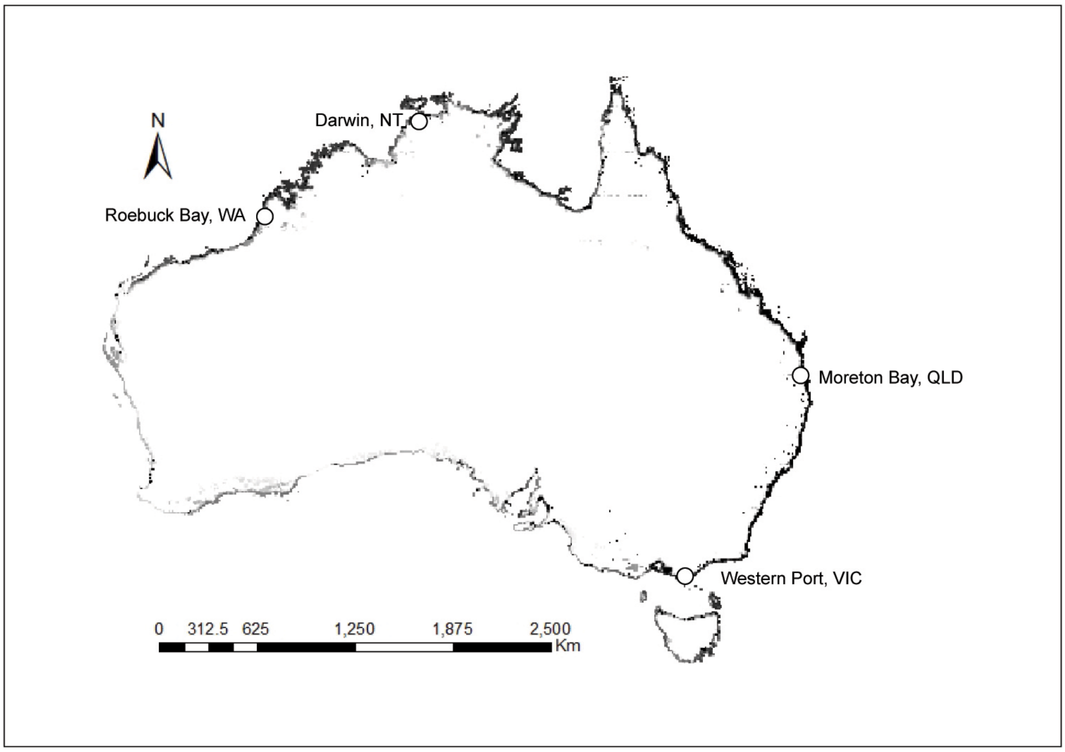

Figure 1. *Map showing the likelihood of occurrence of the Far Eastern Curlew across the non-breeding grounds of Australia and the four study sites selected for this project. Darker areas show a higher likelihood of occurrence. Derived from species distribution models from Pintor et al. (2018) - the Australian Government's National Environmental Science Program (NESP) as part of the Northern Australia Environmental Resources Hub.*

Bird capture methods

We captured 22 Curlew (nine female and 13 male) at four regions (Darwin, Northern Territory, Broome, Western Australia, Moreton bay, Queensland, Western Port, Victoria) across Australia during 2017, 2018, 2019 (Table 1) using cannon nets (day-time catches) or mist nets (night-time catches) depending on the site and conditions for catching. All birds were captured at high tide roosts or when birds were arriving at the site during high tide. All birds were measured and individually marked with a metal band and leg flags with a unique combination code used to identify the bird in the field. Birds were aged on the basis of plumage and wing-moult characteristics (Higgins and Davies 1996) and weighed to the nearest 1 g. All birds caught were aged as either sub-adult or adult birds (Table 1). The following linear measurements were taken: wing length (maximum chord, to the nearest mm); head-bill, and bill (exposed culmen) to the nearest 0.1 mm. Bill length was used to sex the bird (following summaries listed in Higgins and Davies (1996)). Primary moult was recorded in all birds, with the wear and stage of growth of each primary classified.

We used a combination of Argos tags and 15 or 20 g GSM GPS tags (Ornitela, Lithuania) (tag weights were within the 5% rule) and attached tags to the lower back of the bird using a leg-loop harness made up of Teflon ribbon (4.7 mm wide, Bally Ribbon Mills, USA) and held together with aluminium fishing crimps. Birds were kept in a holding cage for at least 30 minutes after attaching the tag to ensure that they were not affected by it and they were then released at the site of capture.

The PTT devices were programmed using the on/off feature to record fixes on a duty cycle of 10 hours on and 48 hours off. The GPS-GSM devices were programmed to record two locational fixes every 2 – 6 hours. If a PTT device stopped transmitting fixes mid migration, it was assumed that the cause was either a broken harness, a malfunctioning device, or the bird died.

Bird position estimates were downloaded from Argos. A correlated random walk state-space model was used to regularise daily positions using the FoieGras package in R v 4.0.2 (Jonsen et al. 2020, R Core Team 2020). Ornitela GPS tracking data were downloaded from the Glosendas data acquisition system (http://www.glosendas.net).

Table 1. *Summary of catching and satellite tracking information of Far Eastern Curlew in Australia from 2017 - 2019. Age codes are 2- = sub-adult, 2+ = adult, 3+ adult.*

Engraved leg Flag ID	Catch date	Age	Sex	State	Region	Device type
00	21/11/2017	2+	M	NT	Darwin	Ornitrack
01	4/12/2017	2+	M	NT	Darwin	Ornitrack
03	9/11/2018	2+	M	NT	Darwin	Ornitrack
16	18/02/2019	3+	F	WA	Broome	Ornitrack
W2	18/02/2019	3+	M	WA	Broome	Ornitrack
17	21/02/2019	3+	F	WA	Broome	Ornitrack
43	18/02/2019	3+	M	WA	Broome	Ornitrack
18	21/02/2019	3+	F	WA	Broome	Ornitrack
26	21/02/2019	3+	F	WA	Broome	Ornitrack
13	21/02/2019	3+	F	WA	Broome	Ornitrack
19	21/02/2019	3+	F	WA	Broome	Ornitrack
AFA	16/11/2017	2+	M	QLD	Moreton Bay	Argos
AAD	26/11/2017	2+	F	QLD	Moreton Bay	Argos
AAH	3/03/2018	2+	F	QLD	Moreton Bay	Ornitrack
AAJ	3/03/2018	2-	F	QLD	Moreton Bay	Argos
AAK	3/03/2018	2+	M	QLD	Moreton Bay	Argos
AAL	13/01/2019	2-	M	QLD	Moreton Bay	Argos
AAN	13/01/2019	2-	M	QLD	Moreton Bay	Ornitrack
AAP	13/01/2019	2+	M	QLD	Moreton Bay	Ornitrack
50	13/01/2019	2+	M	VIC	Western Port	Ornitrack
51	13/01/2019	2+	M	VIC	Western Port	Ornitrack
49	13/01/2019	2+	F	VIC	Western Port	Ornitrack

Tracking birds on migration

Our tracking study gave us an opportunity to contextualise our local work, highlighting the migration of individuals from across the non-breeding grounds along their migration pathway in the EAAF. The use of tracking devices on migratory shorebirds has uncovered key ecological information about threatened species (Gill et al. 2009) and revealed previously unknown stopover sites of a globally endangered species (Chan et al. 2019). Satellite tracking of wildlife can provide continuous, fine-scale insights in species habitat and space use requirements. At the same time, tracking can help to resolve the migration routes and population connectivity of Far Eastern Curlew from across Australia (Driscoll and Ueta 2002, Minton et al. 2011). Here, we present an overall map showing the migration tracks of the 22 Far Eastern Curlew tagged in our study.

Of the 22 birds tagged, 13 individuals (59%) were tracked to the breeding grounds, and complete round-trip migrations between Australia and the breeding grounds or northern Yellow Sea were recorded for 9 individuals (41%) (Figure 2). A tenth individual completed a round trip migration between Australia and the northern Yellow Sea/China's Liaoning province. We recorded partial northward migrations for 6 of the remaining eight individuals, with final location fixes occurring in China (n = 3), Okinawa (n = 2), Taiwan (n = 1). Two individuals did not migrate out of Australia; the tag for one individual stopped transmitting several days after deployment and the other migrated overland from Victoria to the Northern Territory coast only to then return to Victoria via Australia's east coast.

The only previous study to track Far Eastern Curlew from the Australian non-breeding grounds was conducted in the late 1990s (Driscoll and Ueta 2002). A total of 37 individuals were equipped with tracking devices in Moreton Bay (Queensland) and Western Port (Victoria), but a majority of individuals either aborted migration over the South Pacific Islands and returned to Australia or never flew beyond Australia's borders, and only five individuals (13.5%) were successfully tracked to the breeding grounds. By comparison, 59% of individuals were tracked to the breeding grounds; 45% recorded round-trip migrations to and from the breeding grounds or northern Yellow Sea; and northward migration tracks ending no farther south than Taiwan were recorded for 91% of individuals.

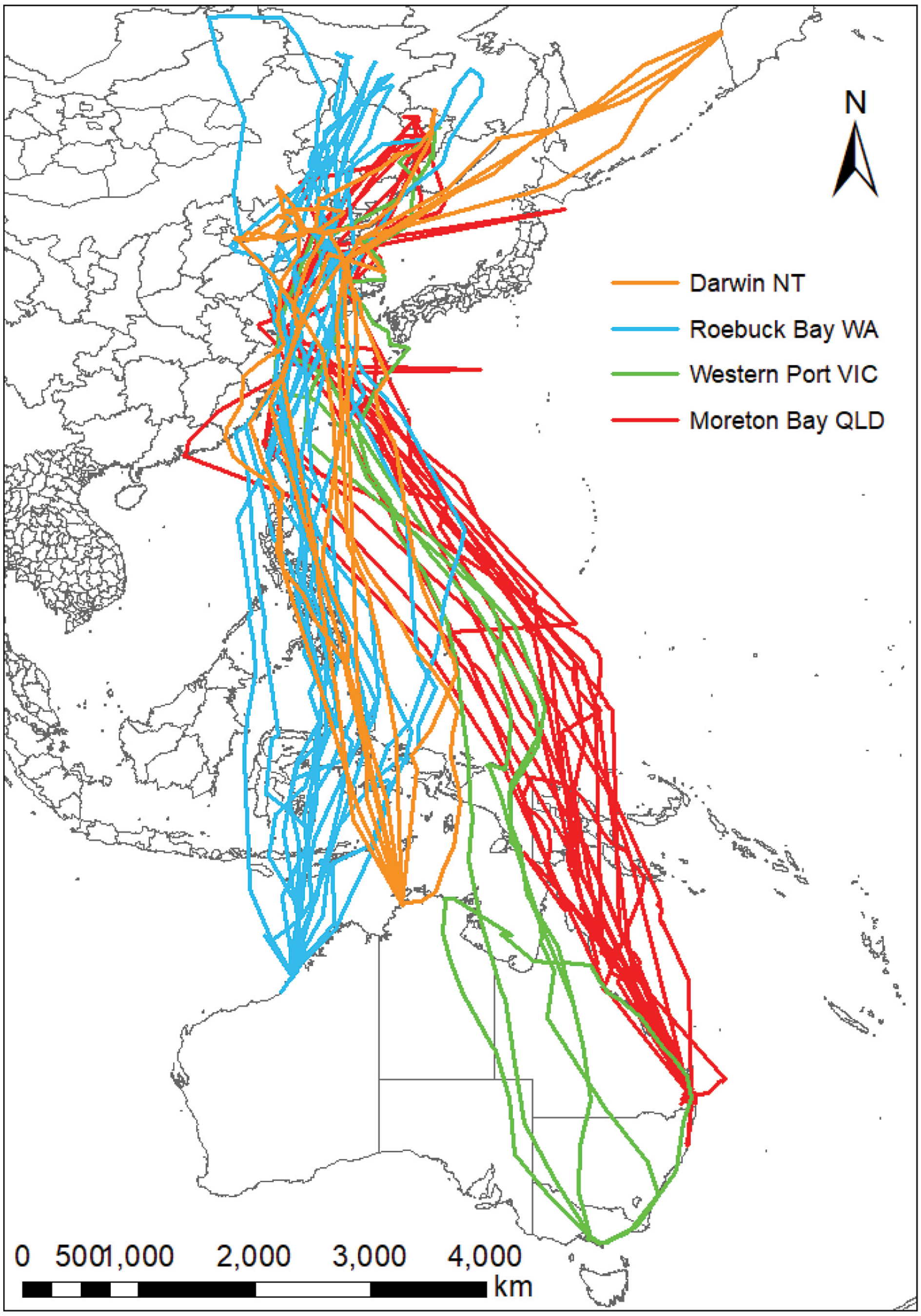

Figure 2. Migration tracks of all tagged Far Eastern Curlew from four regions in Australia and their annual movements within the East Asian-Australasian Flyway.

Tracking birds on the non-breeding grounds

Data filtering

The Ornitela GPS-GSM movement data were first filtered to exclude entries that were duplicates, before start, and after end dates of GPS tracking, within first 24 hours of tracking (re: potential changes in behaviour), with satellite count ≤3, with improbable: speed (max set at = 70 km/h), distance, angle (Freitas et al. 2008, Douglas et al. 2012). Data were then further filtered to exclude detections outside of study areas (i.e., exclude migration data) and then we visually inspected tracks to identify potential location errors.

For all movement data, we converted dates & times from UTC to the local corresponding time zones and assigned tidal periods based on lunar phases (data from Bureau of Meteorology). The assigned tide start times were: spring = 5 days after 1st quarter, neap = 5 days after full moon, spring = 5 days after 3rd quarter, neap = 5 days after new moon (based on animation on: http://home.hiwaay.net/~krcool/Astro/moon/moontides/). The number of days of a tide cycle was approximately 7 days. We then matched the tide cycles with GPS detections based on local dates and times. We used bird-season combinations for calculations of seasonal metrics.

Calculations of movement metrics

We examined the fine-scale movement of individuals within each region for each austral summer season to determine the distance that curlews moved between roosting and feeding sites and if this varied between the study regions. This information can be used to understand the interconnectedness of curlews and the coastal environment as the distances travelled will inform us how far birds have to go to feed and to roost. By understanding how much area individuals occupy we can determine how territorial birds are and examine why there might be differences in the space that curlews occupy.

All calculations of movement metrics were performed per region using local time zones and projections and all spatial processing was performed in R package *sp* (Pebesma and Bivand 2005) and R package *rgdal* (Bivand et al. 2020).

We first calculated the daily distance, defined as the cumulative distance among all detections along a trajectory for a given day and filtered the data by excluding bird-days with <2 GPS detections and then calculated individual trajectories using the R package *adehabitatLT* (Calenge 2006) and the functions *as.ltraj* (generates trajectory) and *ld()* (gets summary data from trajectory). Understanding cumulative daily distance travelled can be useful for estimating energy expenditure. Next, we calculated the maximum daily displacement, defined as the maximum distance among any two GPS locations for a given day. This metric allows us to understand the maximum extent of where curlews will go to feed or roost. This information complements the home range estimates used to determine core habitat used by birds. We filtered the data by excluding bird-days with <2 GPS detections and then created a matrix between each detection and extracted the maximum value per day.

Home range estimators are an essential spatial tool used to understand population dynamics and to inform spatial planning and management strategies for species. It is important to understand wildlife habitat use in urban environments to inform appropriate conservation management. To define the home range estimates of Far Eastern Curlews across the four study regions in this study, we used the GPS data to estimate total feeding and roosting home range size for individuals on the non-breeding grounds using minimum convex polygon (MCP) (Mohr 1947), utilisation distribution using the kernel density estimator (KUD) (Worton 1989), and the Brownian Bridge Movement Model (BBMM) (Horne et al. 2007) per bird, bird-season, and bird-month. We used the MCP to capture the full area utilised by curlews during a time period and calculated these to create a 100% MCP encompassing all detections using R package *adehabitatHR* (Calenge 2006) using the function *mcp()* (generates polygons). We then excluded some outliers and capture areas of use (95%) and high use (50%). We used the KUD to summarise the seasonal distribution of curlews and estimated the 95% and 50% utilisation distributions (UDs) using the functions *kernelUD()* (estimates UDs), and for the kernel smoothing parameter (h) we used *href, getverticeshr()* (produces 95% and 50% contour surfaces), *kernel.area()* (estimated UDs area) in the R package *adehabitatHR* (Calenge 2006). We used the BBMM to summarise the seasonal distribution of curlews and estimated the 95% and 50% utilisation distributions (UDs) using the functions kernelbb() (estimates UDs), we estimated the movement variance parameter (sig1) using liker function, while location uncertainty was set as 7.3 m as evaluated by (Ripperger et al. 2020), and used *getverticeshr()* (produces 95% and 50% contour surfaces), *kernel.area()* (estimated UDs area).

Resulting MCPs, KUDs, and BBMMs were exported as shapefiles and plotted in ArcGIS (version 10.4.1). The best home range estimator to fit the GPS data was the KUD and we present the home range estimates for this model here. The BBMM performed so poorly with a wide fit that was unrealistic given the data points, so the results of the BBMM are not presented.

In addition to the home range estimates, we calculated the maximum daily distance of birds within each region (Table 2). Maximum daily displacement was greatest in WA and QLD birds and shortest in NT and VIC birds (Table 3).

Table 2. *Summary statistics and home range estimates for daily movements of Far Eastern Curlews over three seasons (2017–2020) in the Northern Territory (NT), Western Australia (WA), Queensland (QLD), and Victoria (VIC), Australia. Alphanumerical codes for bird ID represent state of release and individual identifier. Home ranges were estimated using Minimum Convex Polygons (MCP) and Kernel Density Estimators (KUD). *the estimate for this individual is over a very large area because of time spent on the north coast away from the site of capture and initial tagging.*

						Daily movements (km)				
		MCP (km^2)		KDE (km^2)		Daily distance		Maximum daily displacement		
Bird ID	100%	95%	50%	95%	50%	Mean	SD	Mean	SD	*n* (Days)
NT17004	15.7	14.6	7.1	20.8	4.7	5.5	4.4	3.5	2.1	250
NT17007	18.4	4.5	1.3	5.9	0.8	3.8	3.6	2.0	1.4	208
NT182228	6.2	5.6	0.1	3.9	0.5	2.2	1.7	1.6	1.1	6
WA17006	37.0	21.1	2.4	40.6	6.4	4.3	2.4	3.4	1.9	42
WA17008	21.6	13.5	1.2	23.3	2.6	3.8	2.3	3.1	1.7	38
WA180111	339.5	184.0	2.5	142.2	14.7	7.4	9.4	5.9	7.2	192
WA180112	17.6	14.2	1.1	19.6	3.7	3.4	2.3	2.9	1.9	39
WA180113	321.9	104.5	4.2	131.0	12.2	7.2	9.3	6.2	8.0	261
WA180114	326.7	244.8	4.9	184.6	17.2	8.5	10.9	7.1	8.5	238
WA180115	349.7	338.2	247.2	554.2	120.2	5.4	6.6	4.7	5.8	260
WA182226	59.5	22.4	1.0	42.6	5.0	4.2	2.6	3.2	1.8	40
QLD171323	32.6	31.7	28.1	178.2	37.9	53.2	17.1	16.9	0.2	13
*QLD171324	13076.0	5835.9	13.7	432326.1	74569.0	8.2	8.3	4.1	5.4	61
QLD171332	16.5	7.5	1.4	67.6	15.1	3.9	3.8	2.9	2.9	2
QLD40961	6.7	4.5	3.0	24.6	5.6	3.2	2.6	2.4	2.0	30
QLD40963	42.0	13.2	0.4	12.0	0.8	2.2	2.1	1.4	1.4	231
QLD40964	1035.4	608.1	203.3	567.7	128.6	7.8	7.2	5.8	5.4	339
QLD40965	368.7	98.0	42.4	126.4	23.3	8.5	7.8	6.8	6.5	203
VIC182225	72.4	28.6	9.9	124.3	23.3	24.0	14.5	11.1	5.2	59
VIC182227	4327.1	85.5	39.1	318.2	38.2	13.0	12.7	7.6	7.1	210
VIC182229	3749.5	106.5	48.8	297.0	35.6	13.4	11.9	8.5	7.4	382

Table 3. *Summary statistics for seasonal ranges and daily movements of Far Eastern Curlews over three seasons (2017–2020) in the Northern Territory (NT), Western Australia (WA), Queensland (QLD), and Victoria (VIC), Australia. Bird-seasons identify state of individual release, numerical device identifier, and the last two digits of tracking season years (preceded by 'S'). Seasonal ranges were estimated using Minimum Convex Polygons (MCP) and Kernel Density Estimators (KUD). *as above in Table 2.*

						Daily movements (km)				
		MCP (km²)		KDE (km²)		Daily distance		Maximum daily displacement		
Bird Season	100%	95%	50%	95%	50%	Mean	SD	Mean	SD	*n* (Days)
NT17004_S17_18	13.3	6.7	0.0	9.7	1.3	5.2	3.1	2.3	2.2	9
NT17004_S18_19	10.2	9.9	4.5	20.9	4.5	6.6	4.8	3.8	2.0	123
NT17004_S19_20	9.3	8.0	1.3	18.0	3.3	4.4	3.8	3.2	2.2	118
NT17007_S17_18	5.1	4.7	1.3	6.0	0.9	6.1	4.1	2.4	1.2	84
NT17007_S18_19	16.7	3.9	0.8	7.8	1.2	2.2	2.0	1.7	1.5	124
NT182228_S18_19	6.2	5.6	0.1	3.9	0.5	2.2	1.7	1.6	1.1	6
WA17006_S18_19	37.0	21.1	2.4	40.6	6.4	4.3	2.4	3.4	1.9	42
WA17008_S18_19	21.6	13.5	1.2	23.3	2.6	3.8	2.3	3.1	1.7	38
WA180111_S18_19	20.8	11.6	0.6	20.9	2.9	3.4	1.8	2.9	1.4	33
WA180111_S19_20	329.8	240.9	2.3	177.7	18.2	8.3	10.1	6.5	7.8	159
WA180112_S18_19	17.6	14.2	1.1	19.6	3.7	3.4	2.3	2.9	1.9	39
WA180113_S18_19	43.6	11.6	0.8	21.9	2.9	3.3	2.1	2.7	1.6	38
WA180113_S19_20	321.5	170.2	4.6	151.8	14.5	7.9	9.9	6.7	8.5	223
WA180114_S18_19	36.5	8.3	0.6	27.4	3.6	3.7	2.1	3.3	2.0	26
WA180114_S19_20	285.0	220.5	4.9	202.7	19.8	9.0	11.4	7.6	8.9	212
WA180115_S18_19	276.6	255.1	8.1	264.9	51.3	4.6	5.3	4.1	5.2	38
WA180115_S19_20	293.9	276.9	212.5	580.9	125.1	5.6	6.8	4.8	5.9	222
WA182226_S18_19	59.5	22.4	1.0	42.6	5.0	4.2	2.6	3.2	1.8	40
QLD171323_S17_18	32.6	31.7	28.1	178.2	37.9	53.2	17.1	16.9	0.2	13
*QLD171324_S18_19	13076.0	5835.9	13.7	432326.1	74569.0	8.2	8.3	4.1	5.4	61
QLD171332_S18_19	16.5	7.5	1.4	67.6	15.1	3.9	3.8	2.9	2.9	2
QLD40961_S18_19	6.7	4.5	3.0	24.6	5.6	3.2	2.6	2.4	2.0	30
QLD40963_S17_18	37.4	21.5	0.6	23.0	2.1	3.6	2.4	2.4	1.7	45
QLD40963_S18_19	10.2	7.3	0.3	6.5	0.6	0.8	0.8	0.7	0.7	96
QLD40963_S19_20	26.1	12.4	0.4	12.7	1.1	3.0	2.1	1.8	1.3	90
QLD40964_S17_18	348.0	235.8	95.5	425.0	96.9	12.6	8.5	9.0	5.6	40
QLD40964_S18_19	602.4	251.5	55.9	381.2	66.7	6.0	5.8	5.1	4.9	160
QLD40964_S19_20	830.1	505.7	300.7	579.2	105.0	8.5	7.5	5.7	5.5	139
QLD40965_S18_19	67.2	63.8	29.3	123.3	23.4	6.4	6.6	5.7	6.0	106
QLD40965_S19_20	368.7	96.5	45.6	160.4	31.0	10.8	8.5	8.1	6.9	97
VIC182225_S18_19	72.4	28.6	9.9	124.3	23.3	24.0	14.5	11.1	5.2	59
VIC182227_S18_19	86.5	59.5	5.7	143.1	25.8	23.5	12.8	11.1	5.0	59
VIC182227_S19_20	4246.1	42.0	27.4	444.6	68.7	8.8	10.1	6.3	7.3	151
VIC182229_S18_19	3699.5	108.5	56.1	961.1	176.2	18.8	13.9	10.9	8.9	99
VIC182229_S19_20	413.5	79.4	45.4	138.1	27.9	11.5	10.4	7.7	6.6	283

Habitat use across the non-breeding grounds

This section meets the goals of AIM 1 of the study, to:

Understand the local movements of Far Eastern Curlew across the Australian non-breeding grounds by GPS tracking of individuals.

The goals of tracking the Far Eastern Curlew are to understand the local movements made by individuals, and to compare these movements across four different regions. Collecting data from multiple study regions will help us to inform management for the species by understanding habitat use across 1) different habitat types, 2) different climatic zones, and 3) by identifying land tenure and appropriate managers and landowners.

Examining habitat use at multiple sites across a continent can help species' management producing a more comprehensive understanding of individual preferences and variation across the study regions. This is a case study that is applicable to many other settings around Australia, and can inform decision-making around approvals, conditions and offsetting. In some places, shorebirds are using working landscapes and require management that is integrated with industrial operations, such as ports. It is typical of shorebirds in coastal areas to be found in natural and modified environments (Jackson et al. 2020, Lilleyman et al. 2020). At two of our study regions, we found that the home range estimates for curlews included working port operations (Darwin Port in the Northern Territory and Brisbane Port in Queensland).

We argue that this study is a useful comparative exercise where we can compare and contrast movement patterns and habitat use of the Far Eastern Curlew in different environmental settings.

Habitat use in Darwin Harbour, Northern Territory

Study area

Darwin Harbour is a tropical macrotidal estuary with a tidal range of 0.1 - 8.1 m, where spring high tides occur close to sunrise and sunset. The region is tropical with an average temperature that ranges between 25°C and 32°C (Bureau of Meteorology 2019). Most rainfall occurs between October and April. The harbour intertidal area is bordered by mangroves and saltpans and the region is considered to be in pristine condition (Munksgaard et al. 2018). Far Eastern Curlews were caught at the artificial East Arm Wharf site. East Arm Wharf (an area managed by Darwin Port) is the main point of departure for exports from Darwin and is surrounded by industrial infrastructure. The wharf was established in 2000 and the pond system is estimated to be 15 years old. The site contains four artificial ponds used to store stormwater runoff and to settle dredge spoil from Darwin Harbour. Some of these ponds have changed over time based on port operations and each pond is a different age. Two ponds at the site have become more attractive to shorebirds over time. One is flushed by the tide and always has water. The other three are freshwater and tend to be dry by September but start filling during the wet season to the point where little water shallow enough for shorebirds is available by February. Human access is only allowed by permit, and the site is rarely disturbed by people. Shorebirds that roost at East Arm Wharf feed on intertidal mudflats nearby when the tide recedes.

Home range estimates

The home range size of the three Far Eastern Curlew from Darwin Harbour did not vary a great deal, with the three individuals overlapping in their roosting habitat use at the 95% KUD contour at the East Arm Wharf ponds (where two individuals were caught) (Figure 3). All three birds overlapped in their roosting and feeding habitat use in a saltpan within Charles Darwin National Park, at the 95% KUD contour. Further to this, two of those birds overlapped within that saltpan at the 50% KUD contour.

The core home range for all three individuals at 50% KUD ranged between 0.5 and 4.7 km^2. Key roosting areas for these birds in Darwin Harbour were the East Arm Wharf ponds and the saltpan in Charles Darwin National Park. Key feeding areas were the intertidal mudflats adjacent to East Arm Wharf, the mangrove areas of Charles Darwin National Park, and the modified intertidal mudflat next to Fisherman's Wharf and the Darwin Central Business District. Feeding areas ranged in distance from the roosting areas from 1 to 5 kms. The mean maximum daily displacement distance travelled in NT curlews was 2.8 km (range 0.01 – 6.9 km).

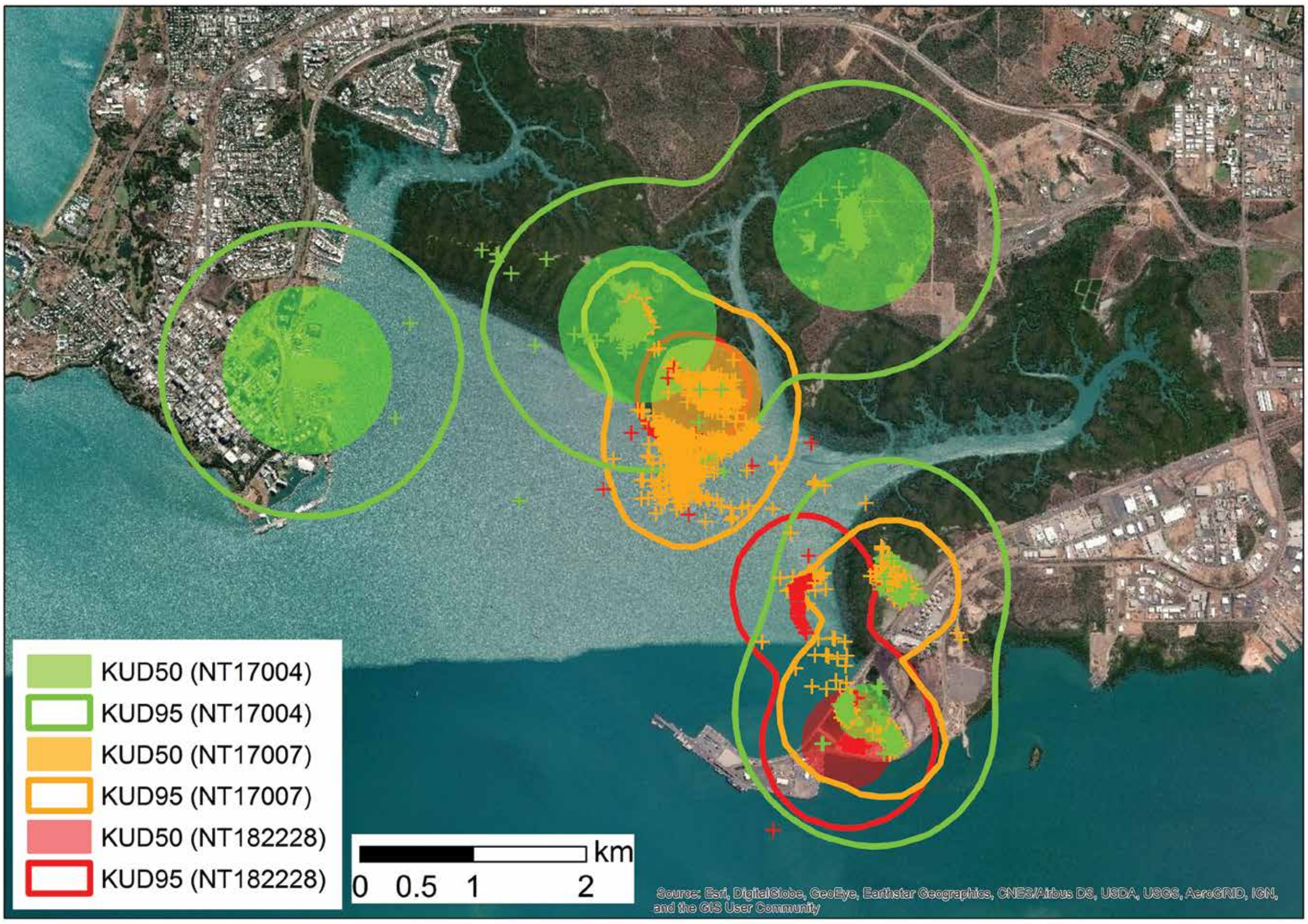

Figure 3. Home range estimates and GPS tracking points for three tagged Far Eastern Curlew in Darwin Harbour, Northern Territory for tracking years 2017 – 2020. Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individuals.

Habitat use in Roebuck Bay, Western Australia

Study area

Roebuck Bay is in the north of Western Australia. Roebuck Bay is a tropical macrotidal bay with a tidal range up to 10.5 m. The climate is tropical and characterised by wet-dry seasons. Maximum temperature in the region reaches 35°C, and most rainfall occurs in January, February and March. Roebuck Bay is a RAMSAR site as it is a wetland of international importance. It is one of the most important shorebird sites in the southern hemisphere. The area is jointly managed by Yawuru People and Parks and Wildlife and the Conservation and Parks Commission. The study area sits fully within the Yawuru Nagulagun / Roebuck Bay Marine Park, the Roebuck Bay intertidal reserve and the Yawuru Conservation estate. The Port of Broome is situated at the northern end of Roebuck Bay and is a major port servicing the Kimberley region.

Home range estimates

All tagged birds were recorded using the protected areas within the Yawuru conservation estate within the Yawuru Nagulagun / Roebuck Bay Marine Park. All eight tagged Far Eastern Curlew overlapped in their 50% and 95% KUD contour within Roebuck Bay near Crab Creek (Figure 4 and Figure 5). Further to this, four individuals overlapped in their 95% KUD contour on feeding and roosting habitat at Bush Point, the most southern part of Roebuck Bay.

The core home range for all eight individuals at 50% KUD ranged between 2.8 and 120.2 km^2. Key roosting areas for these birds in Roebuck Bay were the intertidal saltpans on the landward side of the mangroves, and at Bush Point for the four birds that spent time feeding in that area. The key feeding sites were the mudflats connected to Crab Creek; and the mudflats adjacent to the stretch of beach known as Minton's Straight, and further south at Bush Point. Distances from roosting to feeding areas ranged from 1 to 20 kms. The mean maximum daily displacement distance travelled in WA curlews was 5.5 km (range 0.04 – 31.4 km).

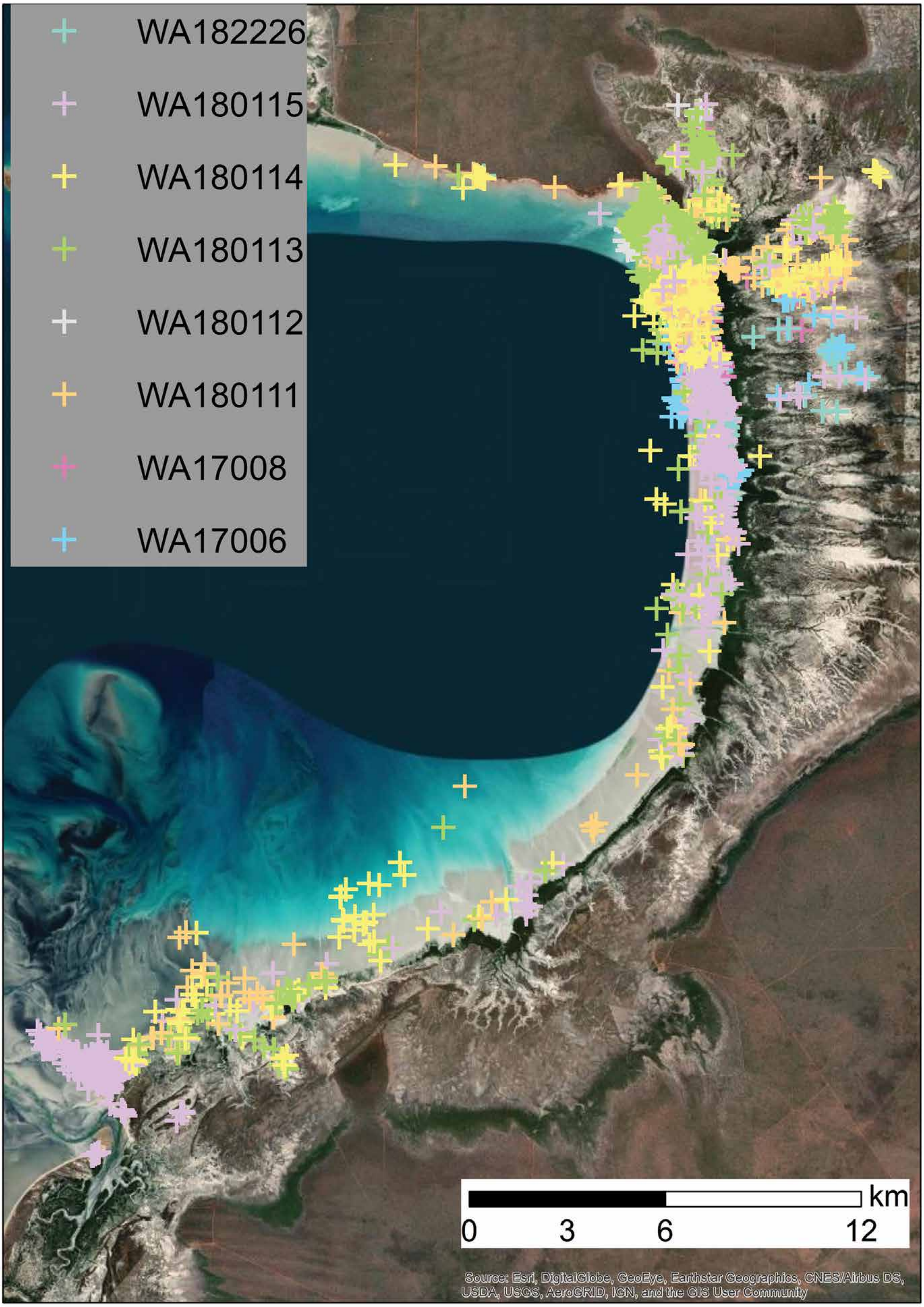

Figure 4. GPS tracking points for eight tagged Far Eastern Curlew in Roebuck Bay, Western Australia for tracking years 2019 – 2020. References

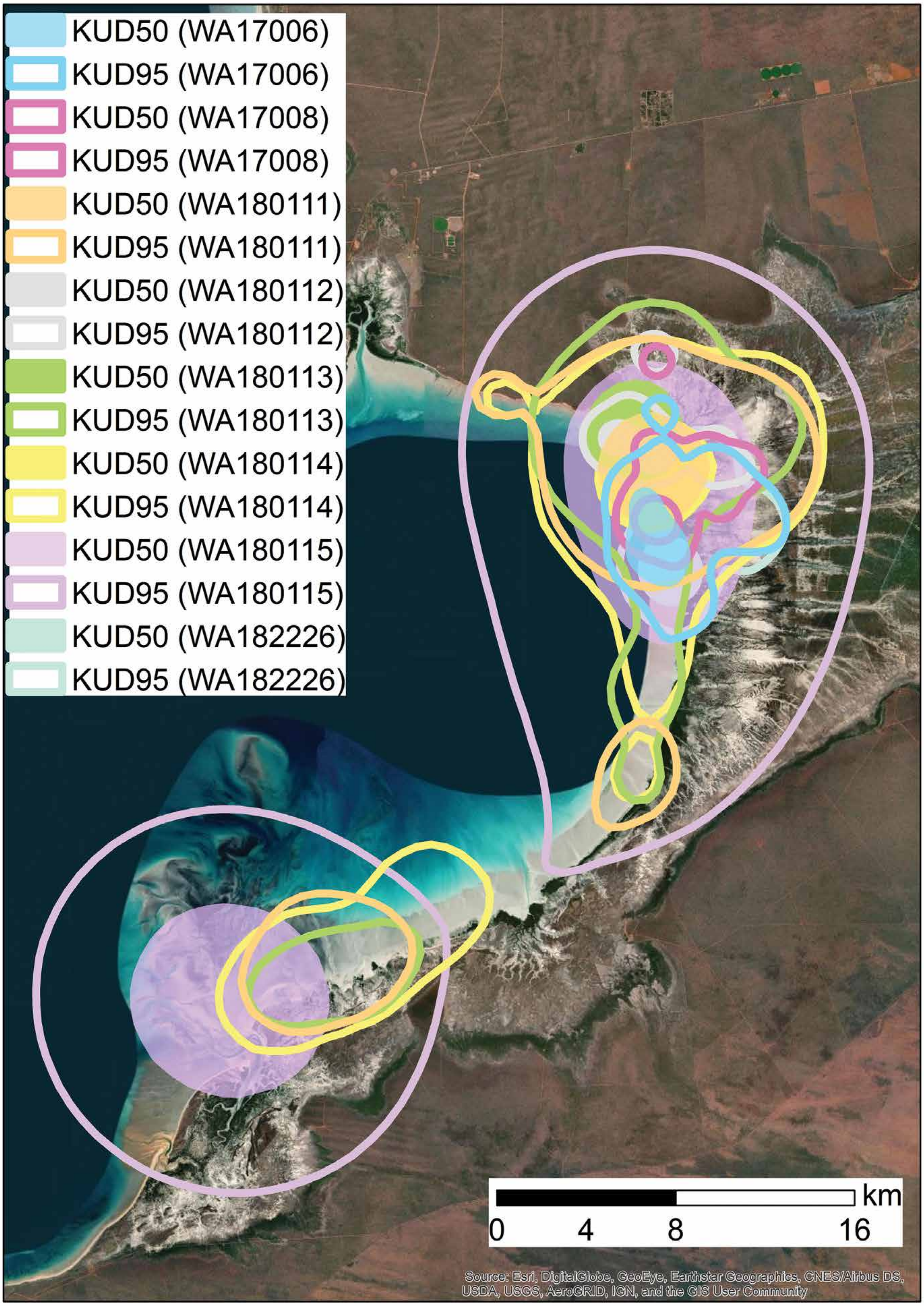

Figure 5. Home range estimates for eight tagged Far Eastern Curlew in Roebuck Bay, Western Australia for tracking years 2019 – 2020. Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individuals.

Habitat use in Moreton Bay, Queensland

Study area

Moreton Bay is located in south-eastern Queensland and is a large estuarine bay made up of extensive intertidal mudflats, seagrass, mangroves and saltmarsh. The region has a sub-tropical climate with a mean daily maximum temperature of 29°C. The tidal range reaches a maximum of 2.5 m in the region. A large majority of Moreton Bay is classified as a RAMSAR site of international importance. The area is also protected by the Moreton Bay Marine Park and Marine National Parks. Despite this, the area is heavily populated and industrialised. The Port of Brisbane is located on the coast, east of Brisbane city and is the largest capital city port in Australia.

Home range estimates

All tagged birds were recorded within the protected areas of the Moreton Bay Marine Park (Figure 6 – Figure 8). Of the eight birds that were tagged in Moreton Bay, one of the birds spent time (March and April 2019) around coastal wetlands in Townsville in northern Queensland, which meant the home range estimator generously overestimated the 50% and 95% KUD contours to include hundreds of kilometres of land and sea, so these are not presented in the final maps. Four of the tagged birds in Moreton Bay overlapped with other individuals at the 95% KUD contour. The only curlew tagged in Pumicestone Passage near Bribie Island (area marked as Conservation Park) did not overlap with the home range estimates of other birds in this study that were tagged in the central part of Moreton Bay.

The core home range for all individuals (excluding QLD171324) at 50% KUD ranged between 0.8 and 128.6 km^2. Key roosting areas were coastal areas near Lytton and the Port of Brisbane, the Toorbul roosting area, Geoff Skinner Wetland, Manly Wader roost, and Dunwich on North Stradbroke Island. Distances from roosting to feeding areas ranged from 1 to 20 kms. The mean maximum daily displacement distance travelled in QLD curlews was 4.7 km (range 0 – 26.5 km).

Mangroves in Darwin Harbour. Image: Amanda Lilleyman

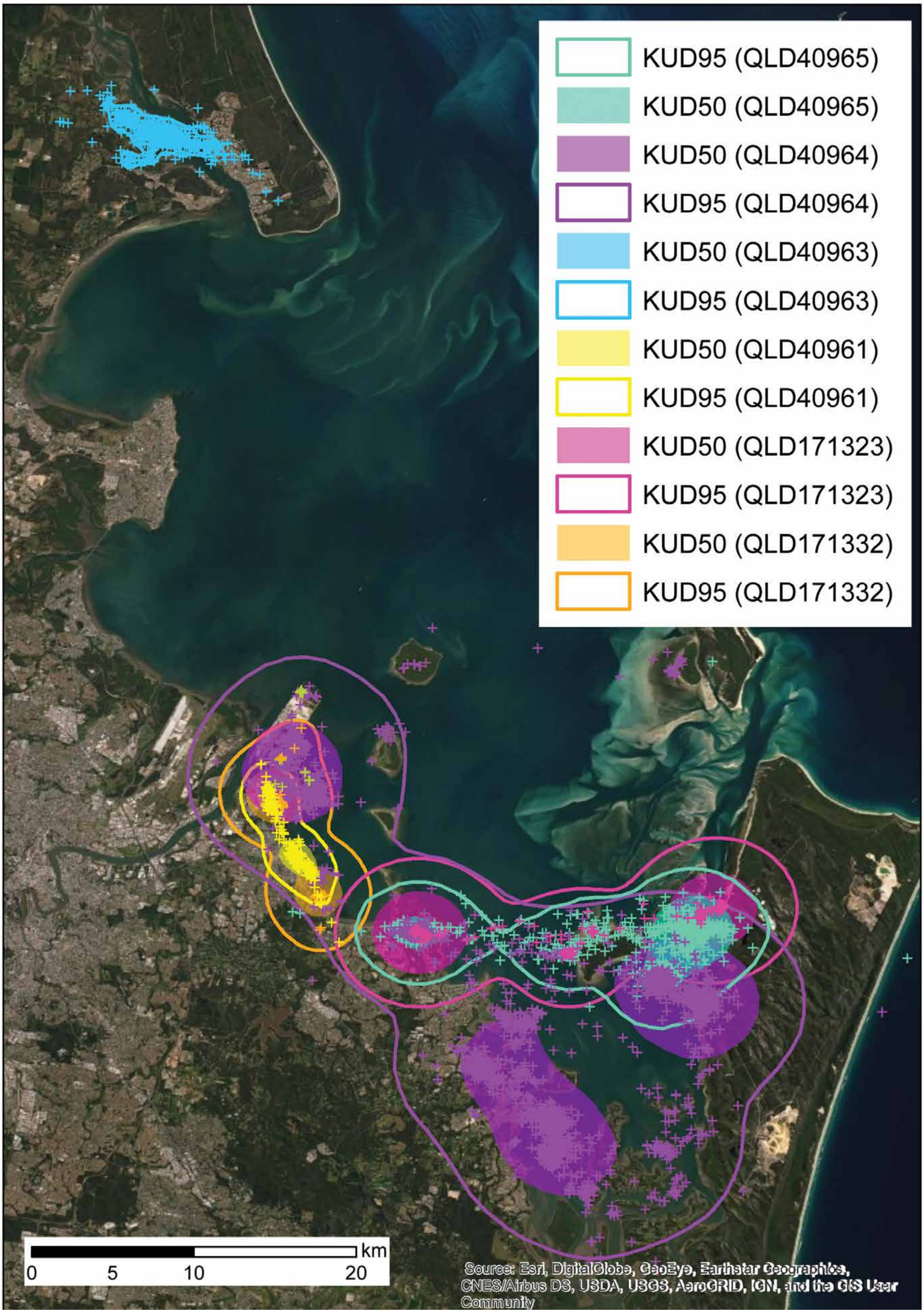

Figure 6. Home range estimates and GPS tracking points for six tagged Far Eastern Curlew in Moreton Bay, Queensland for tracking years 2017 – 2020. Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individuals.

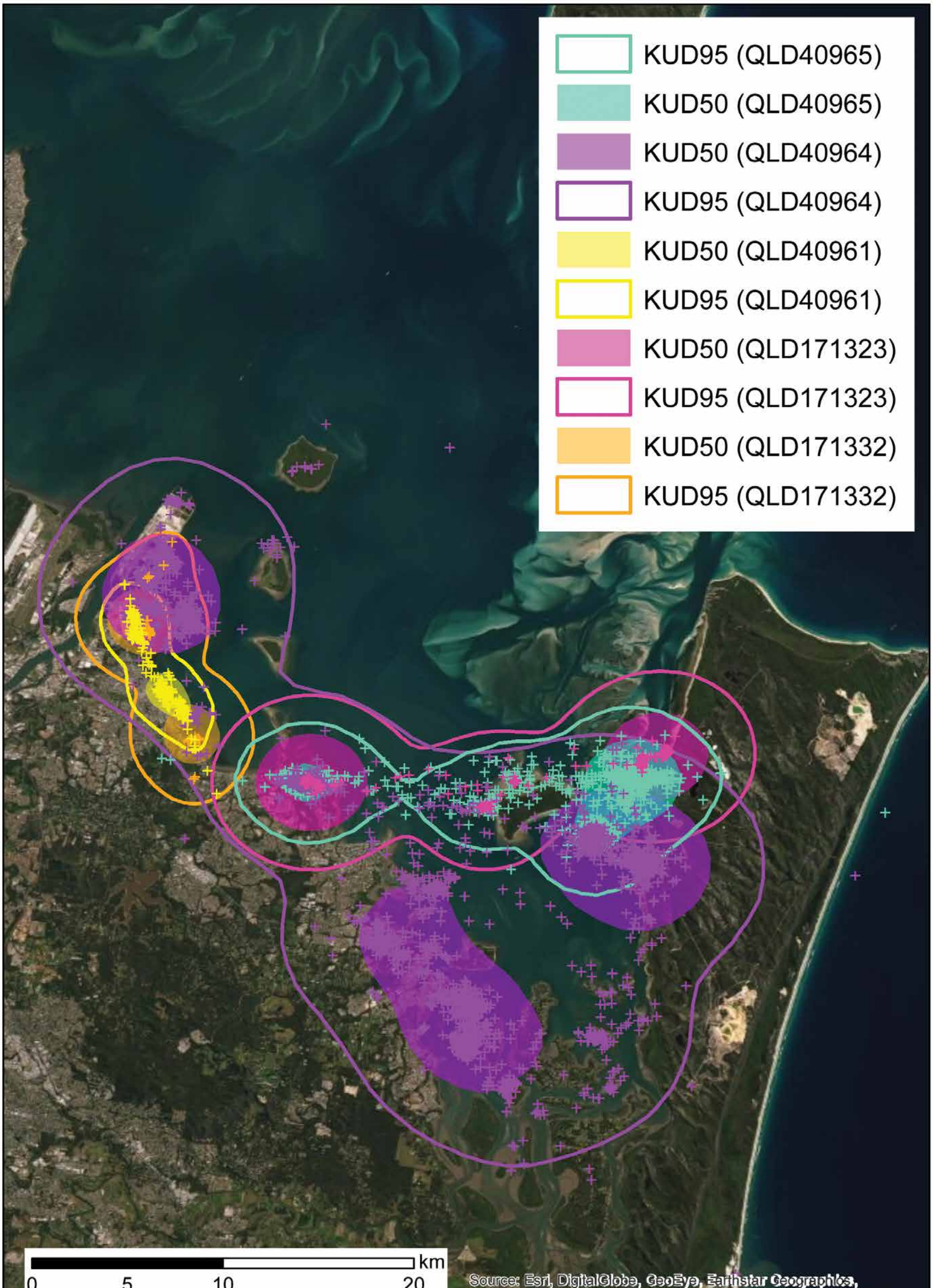

Figure 7. *Home range estimates and GPS tracking points for five tagged Far Eastern Curlew in Moreton Bay, Queensland for tracking years 2017 – 2020 (zoomed in view). Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individuals.*

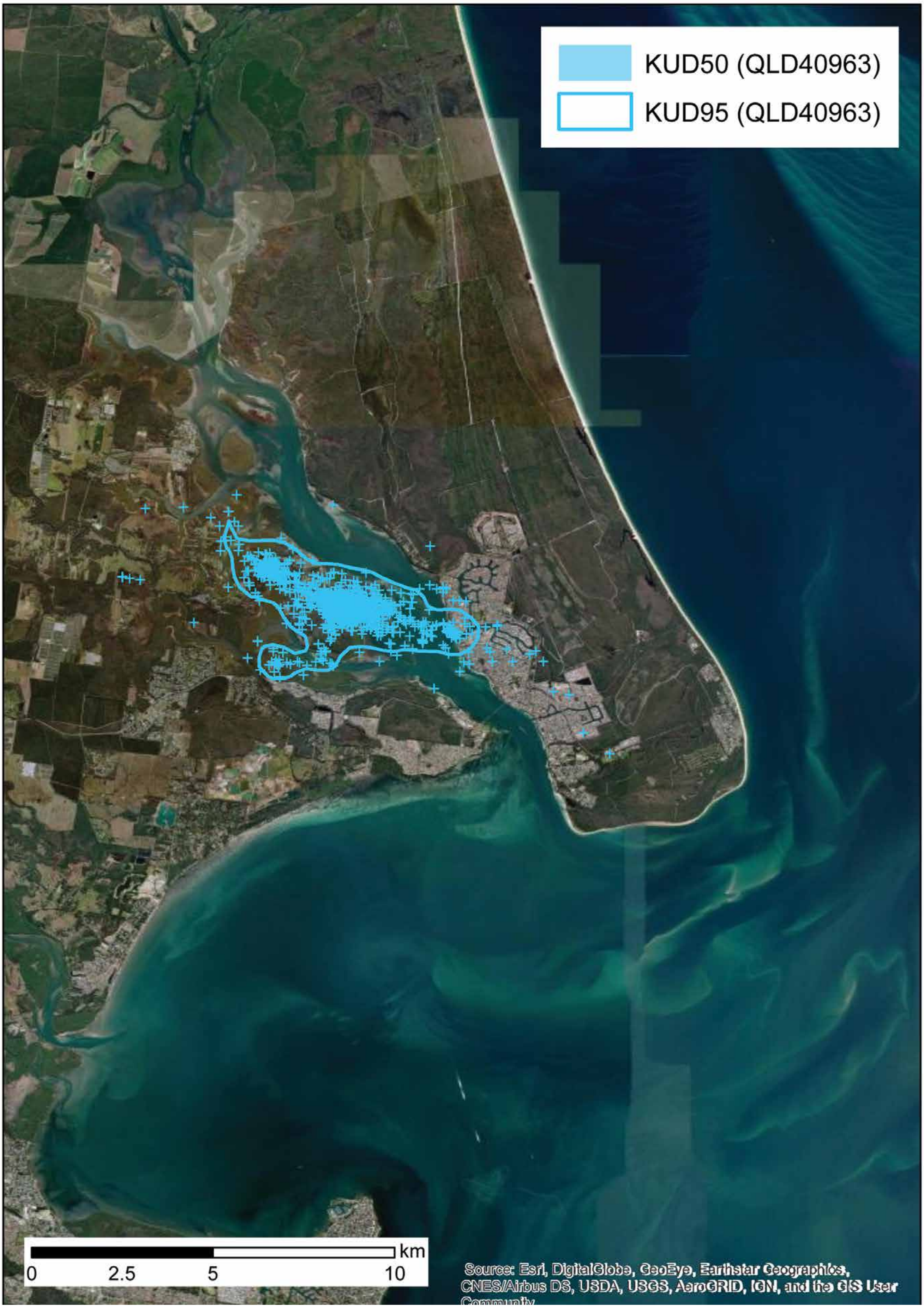

Figure 8. *Home range estimates and GPS tracking points for one tagged Far Eastern Curlew in Moreton Bay, Queensland for tracking years 2017 – 2020 (zoomed in view). Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individual.*

Habitat use in Western Port, Victoria

Study area

Western Port is located in Victoria in southern Australia. It is a large tidal bay with two islands located within the bay: French Island and Phillip Island. Western Port has large intertidal mudflats and a tidal range of 3.5 m. The region has a temperate climate with a mean maximum daily temperature of 20.5°C. Western Port bay is classified as a RAMSAR site of international importance and parts of the marine environment are protected within the French Island Marine National Park and Yaringa Marine National Park. Surrounding land uses are mostly for agriculture and wineries.

Home range estimates

All three individuals overlapped in their home ranges at 50% and 95% KUD contour in Western Port (Figure 9). Birds primarily moved between the roosting area of Yallock Creek and the bay near The Gurdies, approximately 15 km away (straight line distance). One individual made some exploratory flights to roosting and feeding habitat on French Island, but this area did not fall within the 50% KUD contour. The eastern most tip of French Island fell within the 95% KUD contour for all three birds.

The core home range for all three individuals at 50% KUD ranged between 23.4 and 38.2 km^2. Key roosting areas were the beaches and saltmarsh areas of Yallock Creek. Key feeding areas were the intertidal mudflats and beach between Jam Jerrup and The Gurdies, within the Western Port Intertidal Reserve. The mean maximum daily displacement distance travelled in VIC curlews was 8.4 km (range 0 – 74.4 km).

Crocodile Islands Rangers conducting migratory shorebird survey during a ranger exchange program with the Larrakia Rangers. Image: Amanda Lilleyman

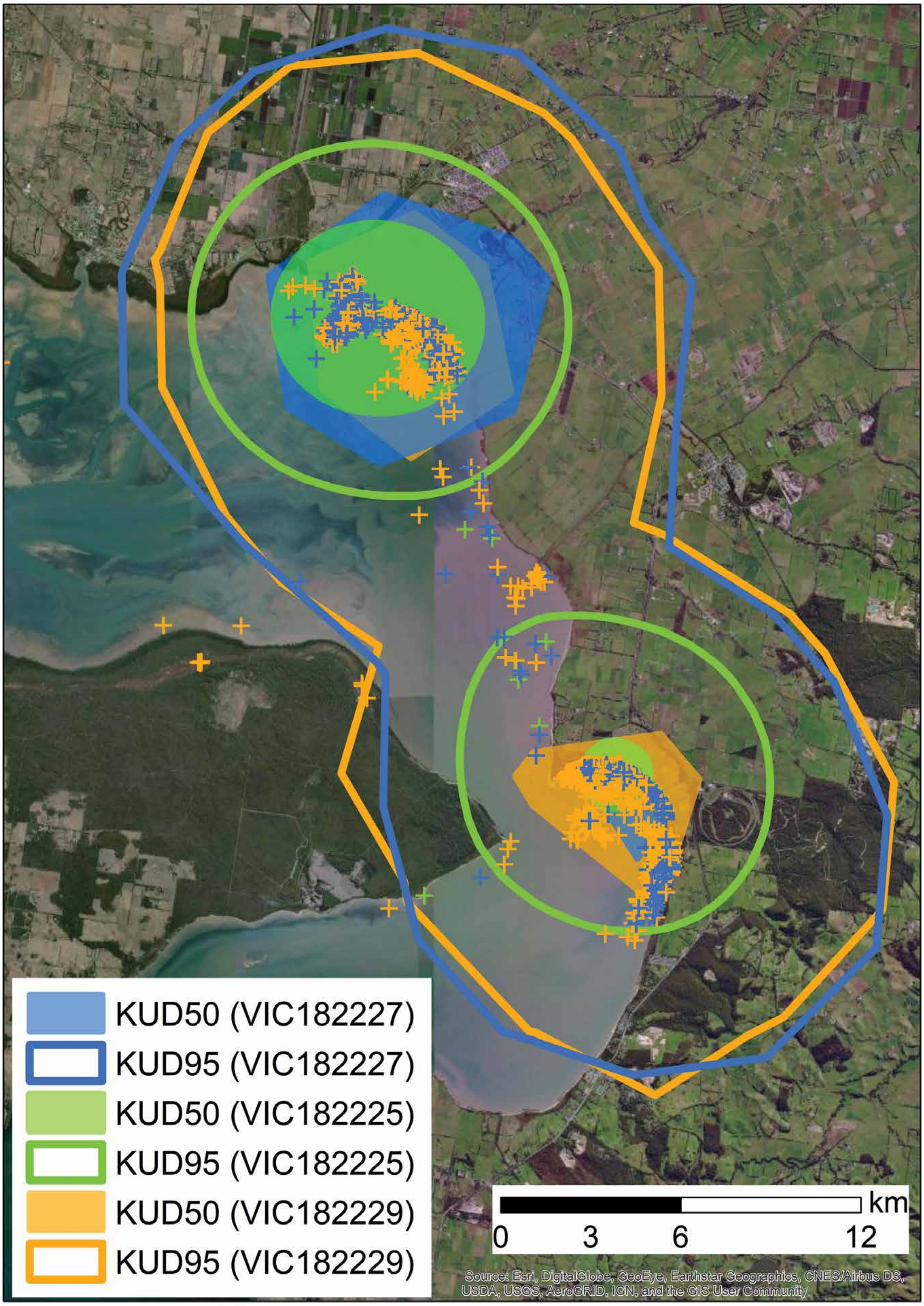

Figure 9. Home range estimates and GPS tracking points for three tagged Far Eastern Curlew in Western Port, Victoria for tracking years 2019 – 2020 (zoomed in view). Home range estimator used is the kernel utilisation distribution representing 50% and 95% of core habitat used by the tagged individuals.

Intertidal distribution and exposure

This section meets the goals of AIM 2 of the study, to:

AIM 2 Determine the types of habitat that individual curlews use during the non-breeding season through spatial mapping.

The goals of mapping the habitat that Far Eastern Curlew use are to understand if there are commonalities or differences in the preferred environmental characteristics chosen by the birds. Collecting data from multiple study regions will help us to inform management for the species by understanding habitat use across 1) different habitat types, 2) different climatic zones, and 3) by identifying land tenure and appropriate managers and landowners.

Coastal shorebirds depend on the intertidal zone of the coastal and marine regions where there is soft sediment available for birds to feed. The Far Eastern Curlew captures prey almost entirely by probing in soft sediment where its long bill can detect the movement of its preferred prey, crustaceans. Finn et al. (2008) found that substrate resistance was a greater determinant of where Curlews were found rather than the density of prey influencing habitat use. Therefore, we decided to look at the extent of soft substrate available across the intertidal zone within each study region.

Species distribution models (SDMs) are currently the main tools to derive spatially explicit predictions of environmental suitability for species and this modelling technique has been done to describe the suitable habitat available for the Far Eastern Curlew across Australia (see Pintor et al. 2018). This modelling approach is beneficial for a coarse examination of habitat use but does not tell planners or decision-makers about the finer-scale habitat use of the species and how developments and the like might interfere with important habitat for threatened species.

In this study, we used our GPS tracking data to examine the habitat types where the tagged Far Eastern Curlew were found across the four regions on the non-breeding grounds. We then examined the frequency that the habitat was available for the birds as curlews and other shorebirds use the intertidal zone and the timing and extent of tidal coverage will affect how birds use this system.

Mapping

The spatial extent of the intertidal zone was primarily determined using the Intertidal Extents Model (ITEM) 25m v2.0.0 product (Commonwealth of Australia 2017, Sagar et al. 2017), a national dataset derived from Landsat observations between 1986 and 2016. Within the ITEM product, the Relative Extents Model (REL) relates the extent of exposed intertidal zone with tidal information, attributed to each Landsat observation based on location and image acquisition time. The extent of intertidal zone exposed at differing tidal heights and stages are presented at percentile intervals of the observed tidal range (Table 4). For each study site, tidal heights were assigned to each REL interval using the waterline contours data from the National Intertidal Digital Elevation Model (NIDEM) 25m v1.0.0 product (Bishop-Taylor et al. 2018). This allowed us to determine at what tidal height each REL interval is exposed or inundated and deduce intertidal zone availability for the Far Eastern Curlew.

Table 4. *The Relative Extents Model (REL) presents the extent of intertidal zone exposed at differing tidal heights and stages presented at percentile intervals of the observed tidal range.*

REL interval (grid-code)	Description
0	Always water
1	Exposed at lowest 0-10% of the observed tidal range
2	Exposed at lowest 10-20% of the observed tidal range
3	Exposed at lowest 20-30% of the observed tidal range
4	Exposed at lowest 30-40% of the observed tidal range
5	Exposed at lowest 40-50% of the observed tidal range
6	Exposed at lowest 50-60% of the observed tidal range
7	Exposed at lowest 60-70% of the observed tidal range
8	Exposed at lowest 70-80% of the observed tidal range
9	Exposed at lowest 80-100% of the observed tidal range (land)

The ITEM and NIDEM products consider the exposed intertidal zone (e.g. areas of sandy beaches and shores, tidal flats and rocky shores and reefs) but exclude intertidal vegetation communities such as mangroves and saltmarshes. Furthermore, the upper limit of the intertidal zone is not delineated by REL because it includes terrestrial hinterland areas. To classify habitat for the Far Eastern Curlew within the intertidal zone, we sourced geospatial data for benthic communities (e.g. coral reefs, seagrass meadows), substrates (e.g. soft and hard substrates) and coastal vegetation associated with each of the study areas.

For Darwin Harbour, vegetation communities of the intertidal zone were mapped by Brocklehurst and Edmeades (2018). The Broad Vegetation Form attribute was used as a basis to classify mangrove and saltmarsh (including areas of salt flat and samphire) communities. Soft and hard substrate within the harbour was mapped by N. Smit (pers. comm.) using high resolution aerial photography captured during low tide. Although not intertidal, areas of East Arm Wharf where curlews are known to inhabit were delineated by A. Lilleyman based on high-resolution aerial photography and classified as REL interval 9.

For Roebuck Bay, mangrove communities were mapped based on delineation from (Brocx and Semeniuk 2016) and the wetland communities were determined using the Roebuck Plains System polygon (Department of Biodiversity 2020). Hard substrate was delineated by A. Lilleyman based on high-resolution image data and the remainder of the intertidal zone was assumed to be soft substrate.

For Moreton Bay, vegetation communities of the intertidal zone were mapped by (Accad et al. 2016) and classified as mangrove and saltmarsh communities. Marine benthos and substrates mapped by Roelfsema et al. (2017) and Healthy Land and Water (2020) were classified as hard or soft substrate. Remaining areas of the intertidal zone that were mapped as free-standing water – saline/brackish by (Accad et al. 2016) were assumed to be soft substrate.

For Western Port, habitat data of the intertidal zone and marine benthos and substrates were compiled by (Flynn et al. 2016). Based on habitat (SM_HAB_CLS) and substrate (subst) attributes of the data, we classified the upper intertidal vegetation communities as mangroves or saltmarsh communities and the remainder of the intertidal zone was classified as hard or soft substrate.

To create a final intertidal zone layer attributed with habitat classes, we intersected REL and habitat data. The final extent of the intertidal zone included the full extent of REL intervals 1-8 and any areas of REL interval 9 with intertidal vegetation communities including mangroves, saltmarshes and wetlands. All spatial data were projected and analysed using appropriate coordinates systems for area calculations (Table 5), and processing was performed using ArcGIS (version 10.6).

Table 5. *Coordinate systems used for each study area*

State	Study area	Coordinate system
NT	Darwin Harbour	GDA 1994 MGA Zone 52
WA	Roebuck Bay	GDA 1994 MGA Zone 52
QLD	Moreton Bay	GDA 1994 MGA Zone 56
VIC	Western Port	GDA 1994 MGA Zone 55

Habitat availability

This section meets the goals of AIM 3 of the study, to:

AIM 3 Examine the availability of intertidal habitat across study regions on the non-breeding grounds by calculating tidal exposure and extent and availability of intertidal zone.

The goals of examining intertidal exposure are to understand how the dynamic intertidal system might influence habitat use of Far Eastern Curlew across the non-breeding grounds.

To determine habitat availability, we calculated the number of hours each REL interval was exposed per month using six-minute interval tide prediction models from the Bureau of Meteorology for the years 2017-2020 (Bureau of Meteorology 2020). Tides were predicted at Darwin, Broome, Brisbane Bar, and Stony Point tide gauges for Darwin Harbour, Roebuck Bay, Moreton Bay, and Western Port, respectively.

Limitations of mapping

- ITEM derived from 30+ years of data, so areas of recent land use change (e.g. due to land reclamation) may have been mapped as intertidal.
- Some areas mapped as intertidal, according to ITEM, do not have overlapping habitat classification data. For some sites (e.g. Moreton Bay) assumptions were made on their nature (e.g. that they are soft sediment).
- Because Landsat satellites are sun-synchronous, observations do not capture the full tidal range of any location but rather what is referred to as the observed tidal range.

Darwin Harbour, Northern Territory

We defined the Darwin Harbour study region as the area between Charles Point and East Point and classified all coastal and intertidal habitat within those bounds (Figure 10). The total area of soft substrate in the Darwin Harbour study area was 50.3 km^2, hard substrate was only 4.8 km^2, while mangroves made up 196 km2, saltmarsh made up 11.3 km^2 and the artificial East Arm Wharf ponds made up 0.5 km^2 (Figure 11).

Exposure of intertidal soft substrate was linear between grid codes 1 to 5, representing almost 90% of the soft substrate exposure. Between gridcodes 5 to 9 the relationship plateaus. The average predicted tide height across the study years was 4.23 m. The intertidal mudflats between the mangrove edge and the low tide mark becomes exposed on tides less than approximately 3 m. The saltpans and saltmarsh habitat in Darwin Harbour becomes inundated at approximately 7.5 m, which is classified as grid code 9.

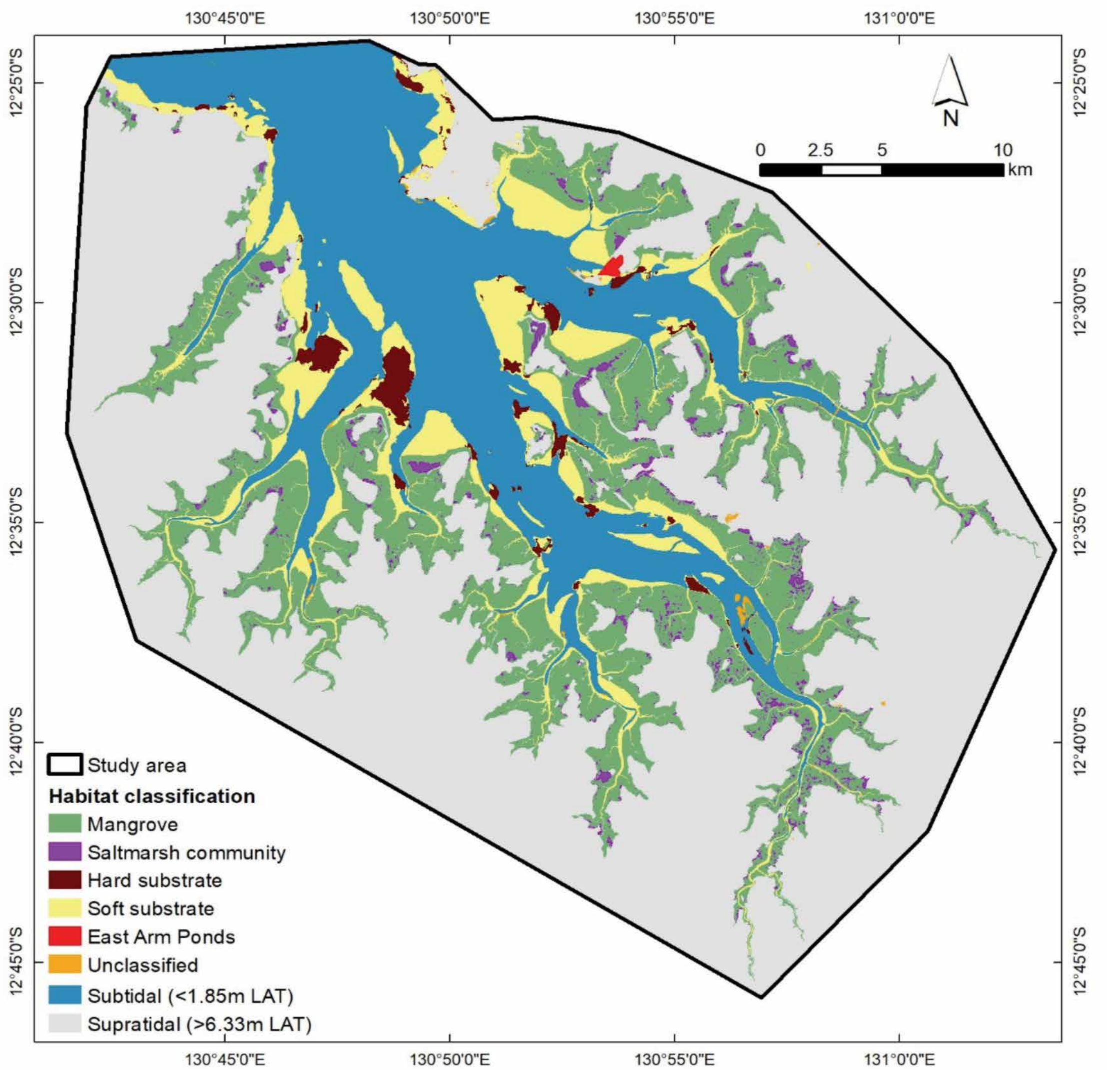

Figure 10. *Map of study site in Darwin Harbour, Northern Territory, showing the habitat classifications.*

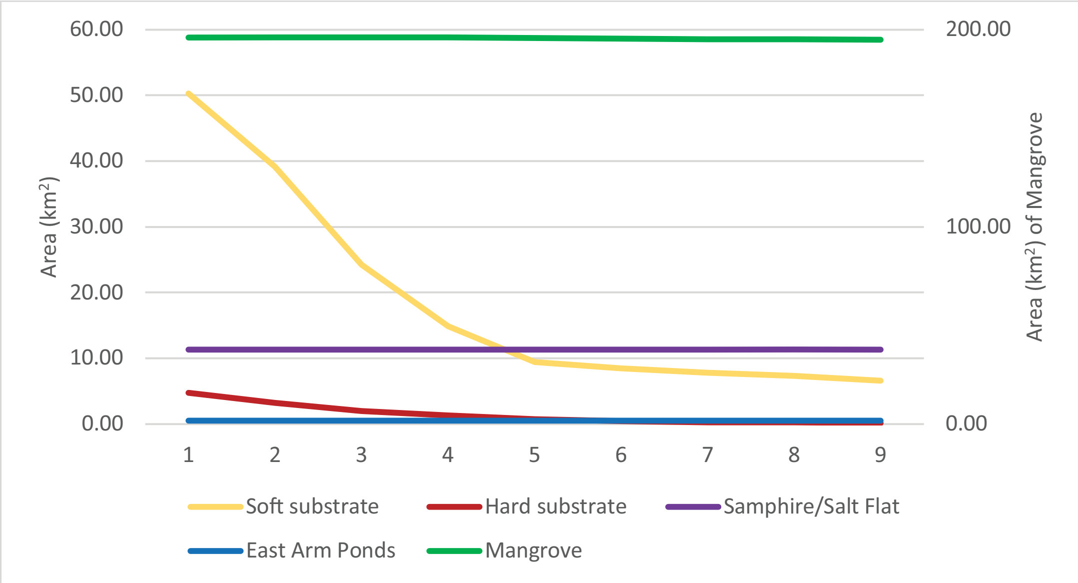

Figure 11. Cumulative habitat availability from low tide (left) to high tide (right) in Darwin Harbour, Northern Territory.

There is extensive intertidal mudflat throughout the entire coastal area of Darwin Harbour; but the largest intertidal areas occur adjacent to the mangroves of Charles Darwin National Park, next to East Arm Wharf and Bleesers Creek, and along the Middle Arm peninsula (Figure 12). For the month of March when Curlews would be fattening up before migration, the average time of exposure of gridcodes 1 to 4 was between 50 and 241 hours, compared to gridcodes 5 to 9, when the average time of exposure was between 300 and 640 hours (Table 6).

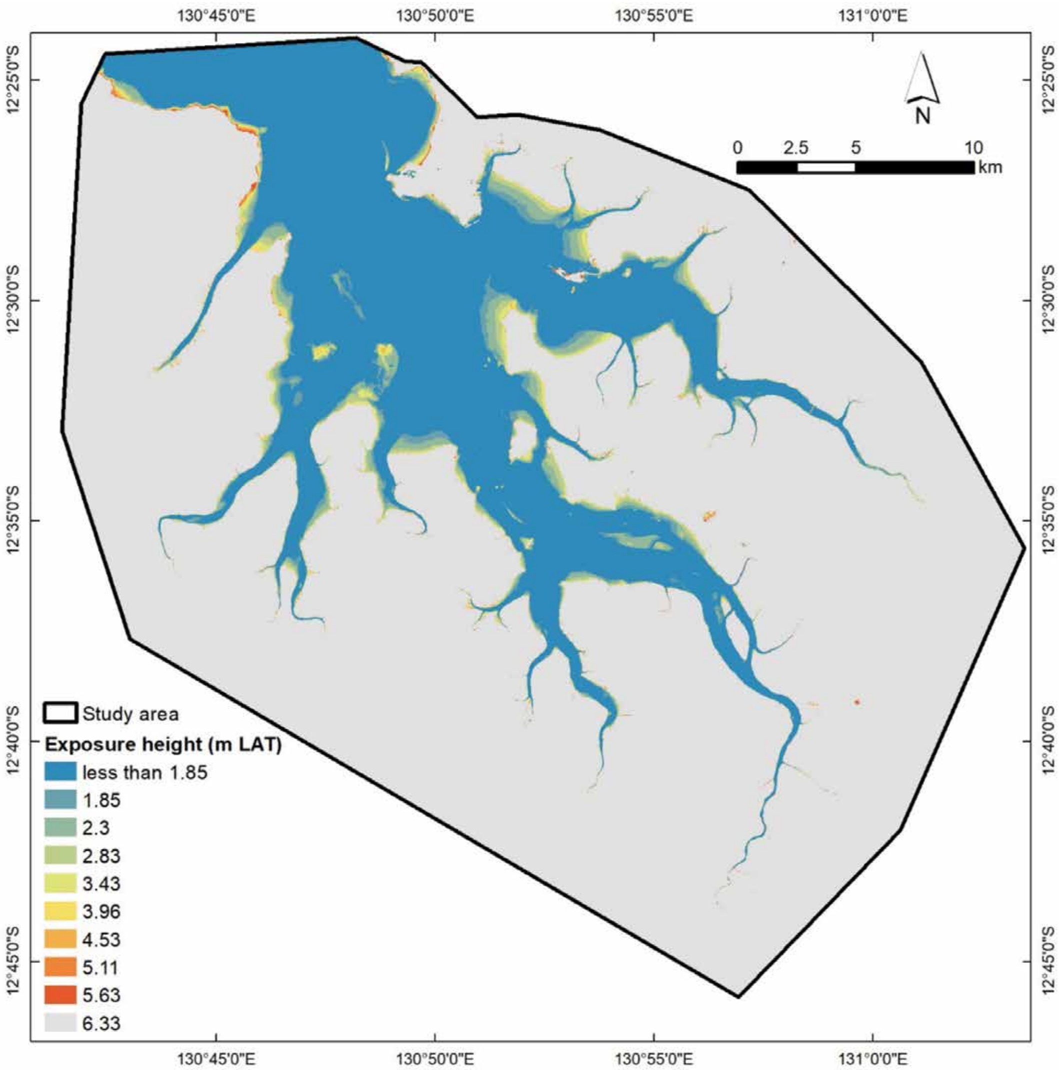

Figure 12. Map of intertidal exposure for the Darwin Harbour study area in the Northern Territory.

Table 6. *Table of average hours each tidal band (ITEM = intertidal extent model gridcodes) was exposed for the years 2017 – 2020 in Darwin Harbour, Northern Territory.*

	ITEM gridcode									
Month	1	2	3	4	5	6	7	8	9	10
January	47.8	78.8	149.2	238.8	317.7	402.8	486.6	571.6	660.3	744
February	38.4	79.5	145.3	219.8	283.8	364.0	447.0	518.3	590.1	678
March	50.5	96.5	159.6	242.0	313.1	402.4	491.1	563.4	640.5	744
April	48.1	91.0	151.6	234.1	310.3	397.2	480.5	549.8	624.7	720
May	49.8	84.0	152.0	252.1	338.4	419.1	505.1	580.7	666.1	744
June	51.2	82.6	153.3	261.9	340.3	413.4	494.7	577.2	664.2	720
July	53.3	97.3	179.2	274.7	356.2	432.0	518.5	604.7	689.9	744
August	59.3	112.8	190.9	272.6	350.4	434.0	523.8	597.6	674.8	744
September	64.4	112.4	180.0	259.5	331.2	419.2	499.7	566.1	637.6	720
October	59.5	106.4	170.7	256.2	337.3	427.2	507.2	576.7	652.8	744
November	52.9	82.2	143.4	234.2	322.4	405.3	486.1	554.9	637.5	720
December	53.7	80.6	131.1	234.9	327.9	409.3	494.8	572.6	668.1	744

Most (41%) of the GPS tracking points of Far Eastern Curlews in Darwin Harbour were from the saltmarsh/saltpan habitat and then the soft substrate (Table 7). While the saltmarsh/saltpan habitat is infrequently inundated, it provided attractive habitat to curlews for both roosting and feeding through both neap and spring tide cycles. The dredge ponds at East Arm Wharf provided important habitat for the curlews and tagged birds were recorded at these ponds at almost the same percentage as the intertidal soft substrate.

Table 7. *Percent of Far Eastern Curlew GPS tracking points within each habitat class in Darwin Harbour, Northern Territory.*

Habitat classification	Count	Percent
Unclassified	93	2%
Soft substrate	952	23%
Hard substrate	0	0%
Mangrove	603	15%
Saltmarsh community	1656	41%
East Arm Ponds	774	19%
Total	4078	100%

The position of where tagged birds occurred and the predicted tide height for the time of the record matched up nicely with the intertidal gridcode availability, showing that birds predominantly followed the tide (Figure 13).

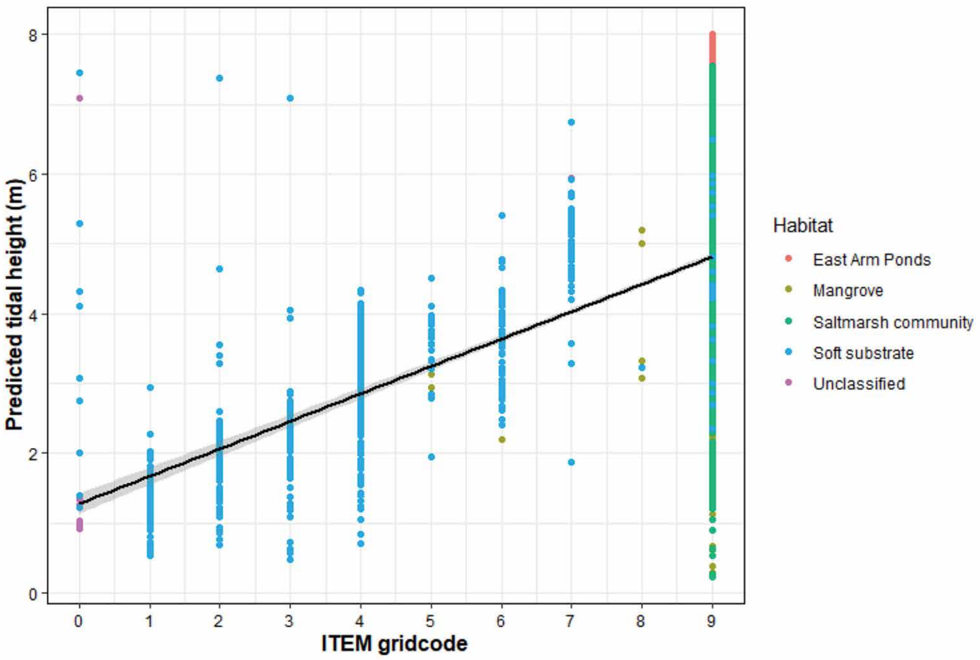

Figure 13. *Predicted tidal height based on the time recorded on the GPS tag against the ITEM gridcode (intertidal band) where tagged Far Eastern Curlew were recorded based on habitat classification in Darwin Harbour, Northern Territory.*

Roebuck Bay, Western Australia

We defined the Roebuck Bay study region as the area south of the town of Broome to Bush Point and classified all coastal and intertidal habitat within those bounds (Figure 14). The total area of soft substrate in the Roebuck Bay study area was 156 km^2, hard substrate was only 1 km^2, while mangroves made up 27.43 km^2, saline wetlands (made up of saltmarsh habitat and swamp grasslands) made up 227.9 km^2 (Figure 15).

Exposure of intertidal soft substrate was linear between grid codes 1 to 8. The average predicted tide height across the study years was 5.47 m.

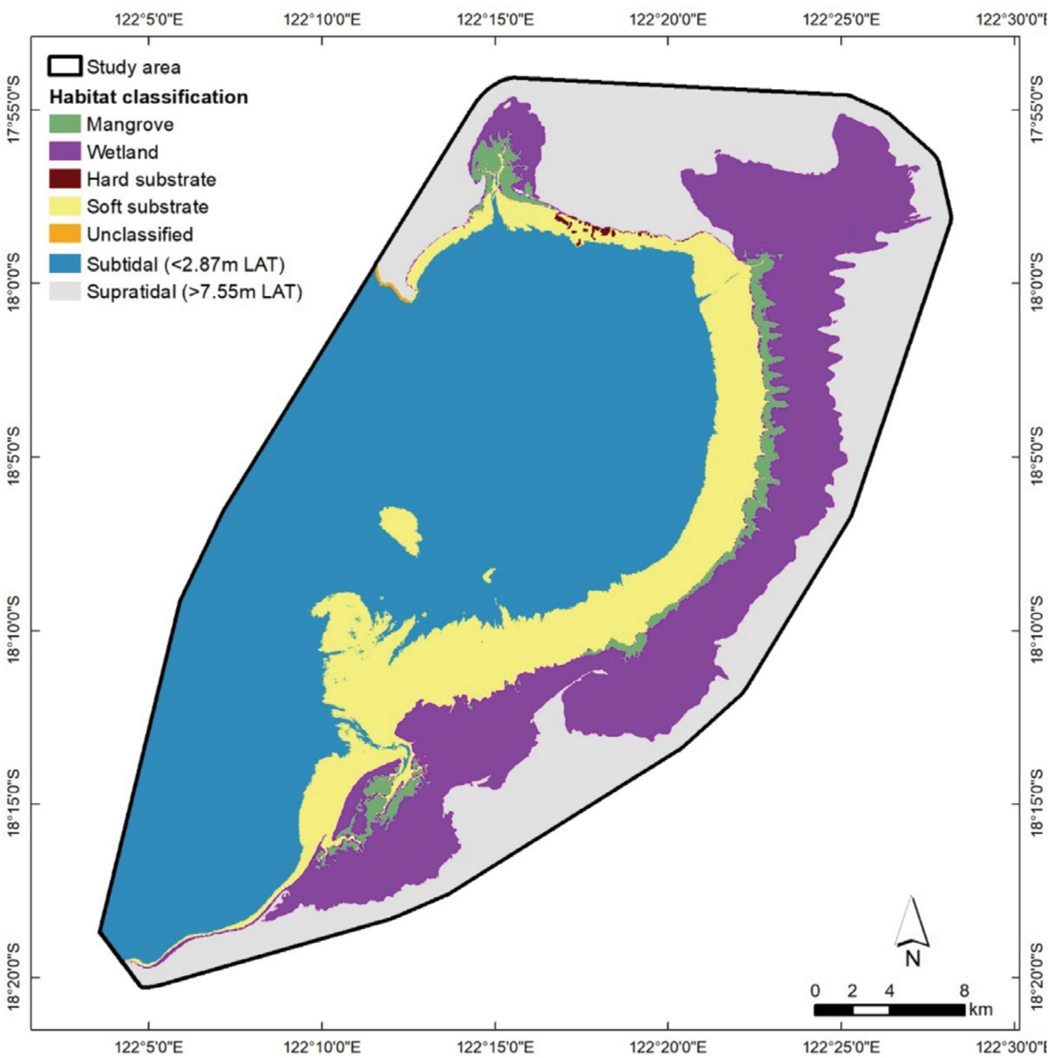

Figure 14. *Map of study site in Roebuck Bay, Western Australia showing the habitat classifications.*

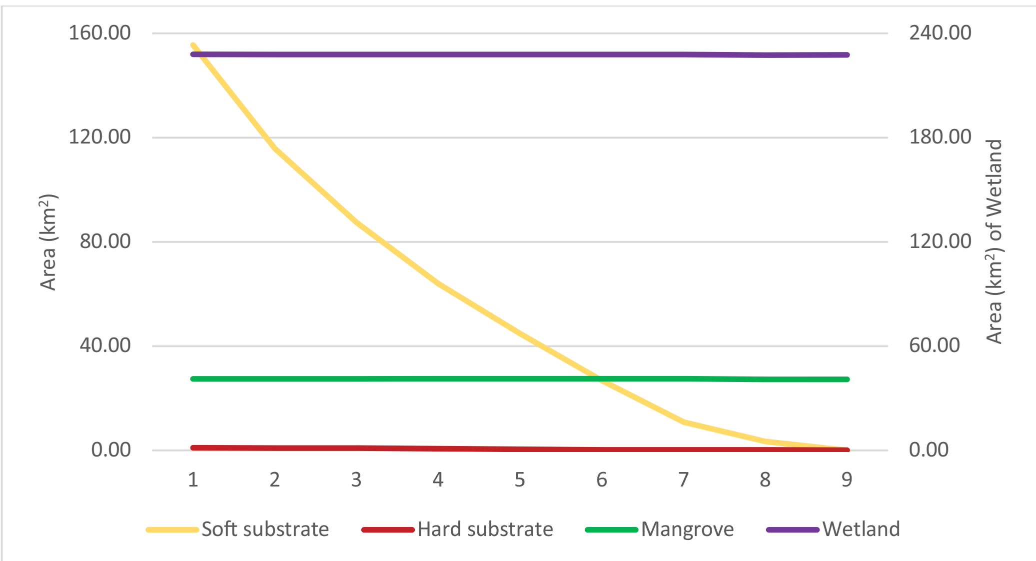

Figure 15. *Cumulative habitat availability from low tide (left) to high tide (right) in Roebuck Bay, Western Australia.*

There is extensive intertidal mudflat throughout the entire coastal area of Roebuck Bay; with the most extensive intertidal area in the southern part of Roebuck Bay at Bush Point (Figure 16). For the month of March when Curlews would be fattening up before migration, the average time of exposure of gridcodes 1 to 8 was between 99 and 597 hours (Table 8).

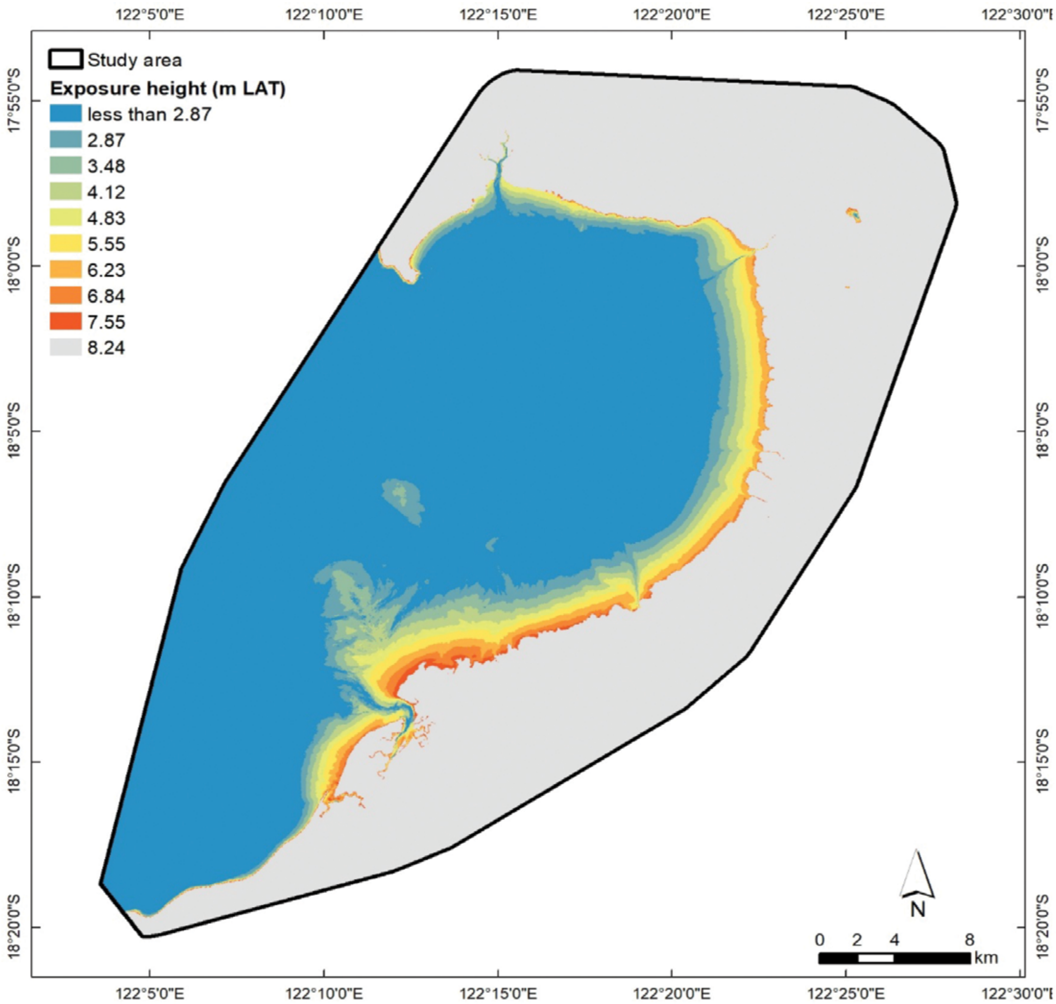

Figure 16. Map of intertidal exposure for the Roebuck Bay study area in the Western Australia.

Table 8. Table of average hours each tidal band (ITEM = intertidal extent model gridcodes) was exposed for the years 2017 – 2020 in Roebuck Bay, Western Australia.

	ITEM gridcode									
Month	1	2	3	4	5	6	7	8	9	10
January	81.4	130.5	196.8	289.9	374.2	454.5	532.3	611.2	669.5	744
February	84.1	125.6	178.1	258.1	340.4	418.4	487.3	550.4	599.0	678
March	99.0	142.7	195.2	272.5	370.5	464.7	535.8	597.2	647.5	744
April	91.9	132.6	186.4	264.0	357.0	445.9	519.5	581.4	630.3	720
May	85.4	130.4	192.6	283.5	373.4	456.8	539.5	612.6	666.5	744
June	76.4	127.6	200.5	290.9	369.6	444.7	524.0	605.3	663.0	720
July	85.7	140.4	218.3	310.1	390.7	470.1	551.5	631.3	689.7	744
August	101.6	150.7	215.3	307.6	395.4	483.4	557.6	624.3	675.1	744
September	105.4	149.9	204.0	285.9	380.1	470.2	534.5	591.9	638.4	720
October	104.6	148.2	201.9	285.0	382.8	478.1	547.8	607.8	655.1	744
November	86.4	130.3	186.4	273.3	363.4	448.5	525.5	591.4	642.1	720
December	75.2	125.1	193.4	288.3	373.5	453.6	534.5	617.4	676.2	744

Most (81%) of the GPS tracking points of Far Eastern Curlews in Roebuck bay were from soft substrate, while the remaining records were from the saline wetland habitat (Table 9).

Table 9. Percent of Far Eastern Curlew GPS tracking points within each habitat class in Roebuck Bay, Western Australia.

Habitat classification	Count	Percent
Unclassified	6	0%
Soft substrate	3359	81%
Hard substrate	2	0%
Mangrove	3	0%
Wetland	786	19%
Total	4156	100%

The position of where tagged birds occurred and the predicted tide height for the time of the record matched up nicely with the intertidal gridcode availability, showing that birds predominantly followed the tide (Figure 17).

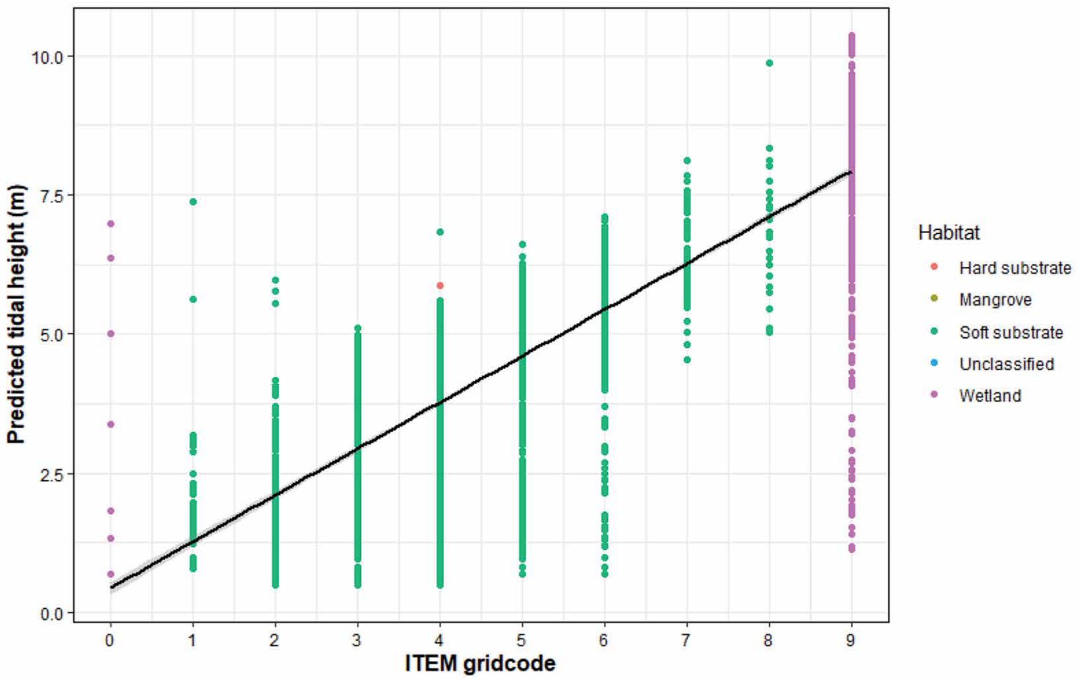

Figure 17. *Predicted tidal height based on the time recorded on the GPS tag against the ITEM gridcode (intertidal band) where tagged Far Eastern Curlew were recorded based on habitat classification in Roebuck Bay, Western Australia.*

Moreton Bay, Queensland

We defined the Moreton Bay study region as the area from the northern point of Pumicestone Passage near Caloundra to the southern extent of South Stradbroke Island, inclusive of North Stradbroke Island and Moreton Island. We classified all coastal and intertidal habitat within those bounds (Figure 18). The total area of soft substrate in the Moreton Bay study area was 246.5 km^2, hard substrate was only 0.2 km^2, while mangroves made up 151.9 km^2, and saltmarsh made up 31.6 km^2 (Figure 19).

Exposure of intertidal soft substrate was linear between grid codes 1 to 5. Between gridcodes 5 to 9 the relationship plateaus. The average predicted tide height across the study years was 1.32 m.

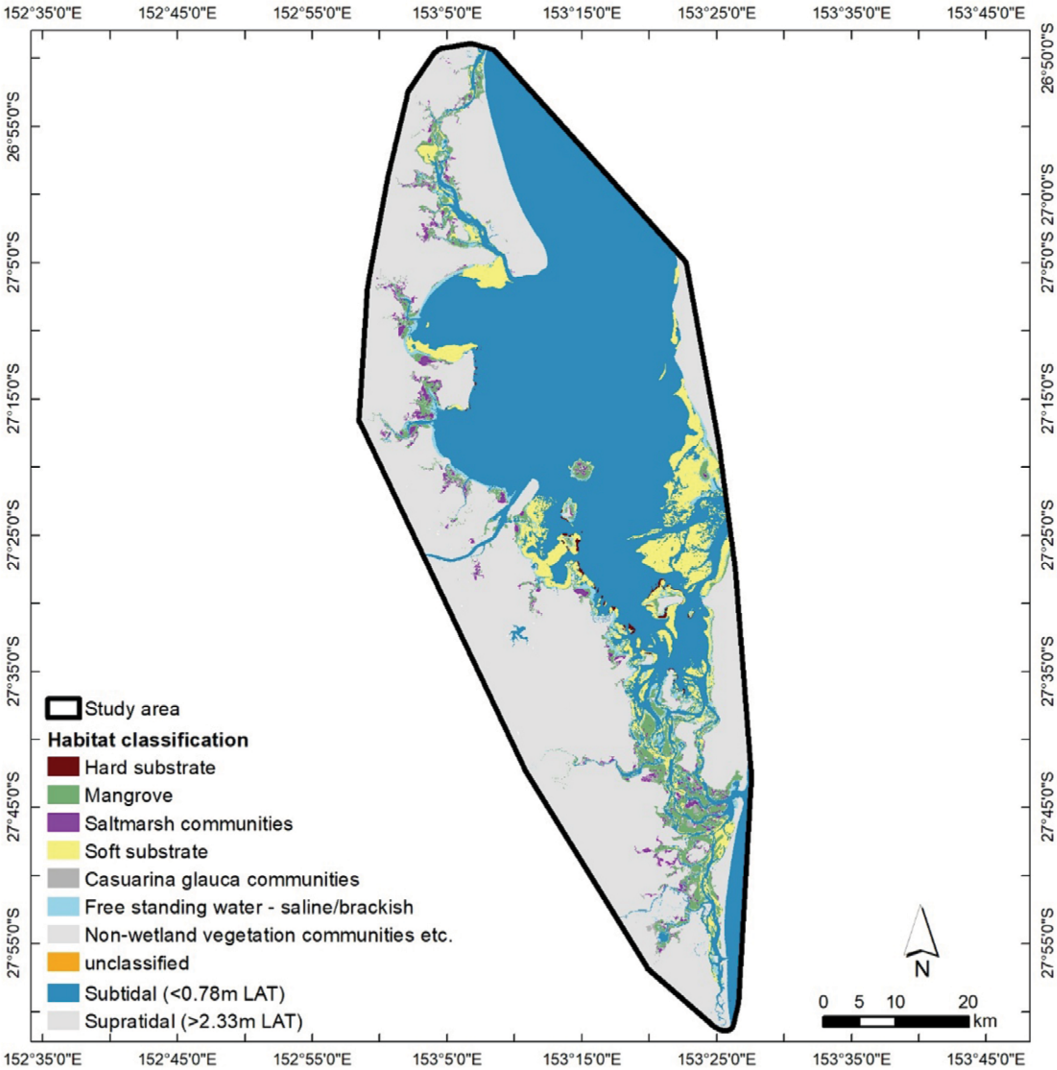

Figure 18. *Map of study site in Moreton Bay, Queensland, showing the habitat classifications.*

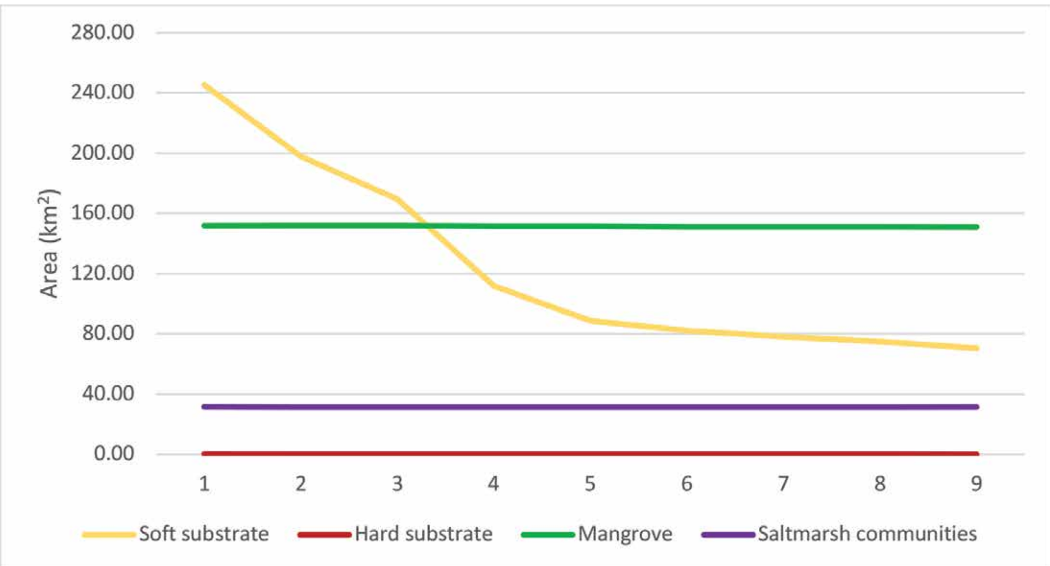

Figure 19. *Cumulative habitat availability from low tide (left) to high tide (right) in Moreton Bay, Queensland.*

The largest soft substrate intertidal areas occur at the southern tip of Bribie Island and in Deception Bay, between the Port of Brisbane and Wellington Point (Waterloo Bay), between the south-western tip of Moreton Island, around Peel Island, and to a lesser extent along the north-western side of South Stradbroke Island (Figure 20). For the month of February when Curlews would be fattening up before migration, the average time of exposure of gridcodes 1 to 4 was between 130 and 335 hours, compared to gridcodes 5 to 9, when the average time of exposure was between 399 and 652 hours (Table 10).

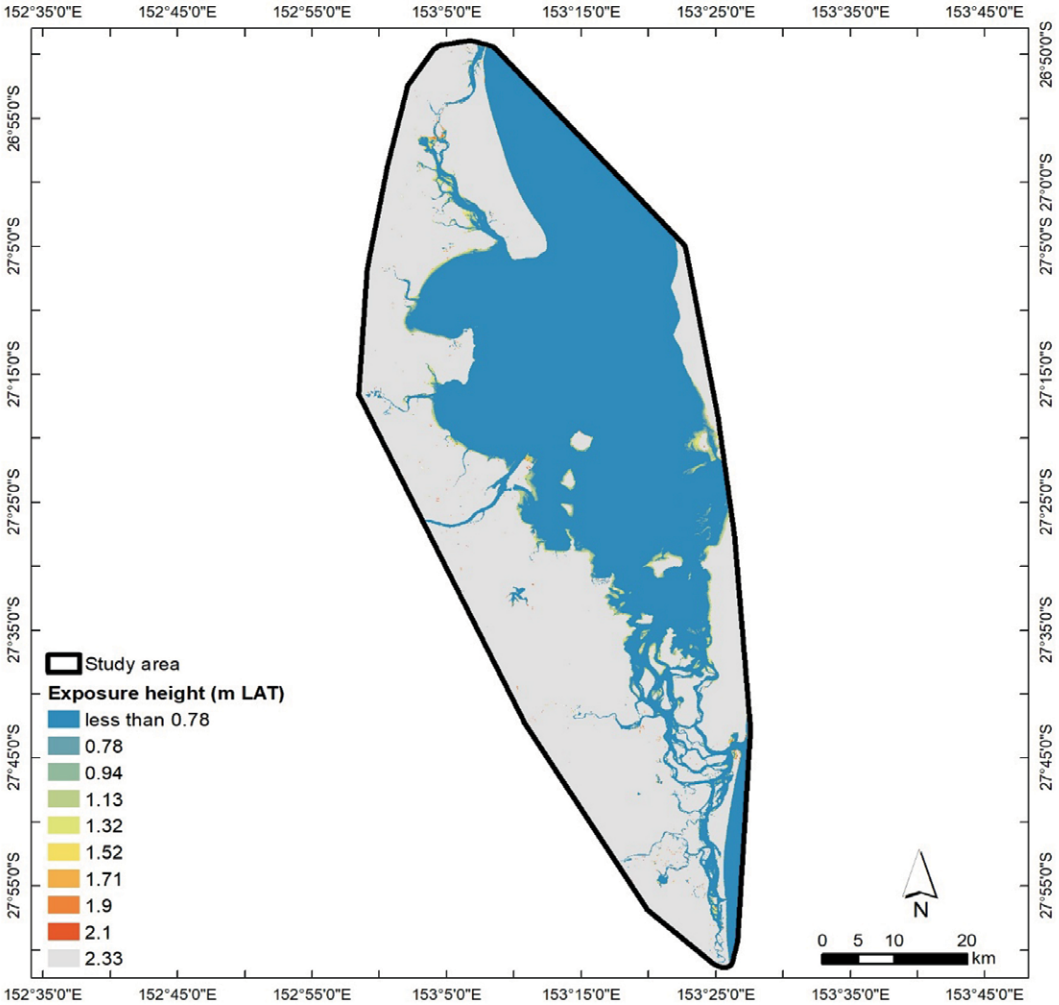

Figure 20. *Map of intertidal exposure for the Moreton Bay study area in Queensland.*

Table 10. *Table of average hours each tidal band was exposed for the years 2017 – 2020 in Moreton Bay, Queensland.*

	ITEM gridcode									
Month	1	2	3	4	5	6	7	8	9	10
January	158.5	231.8	305.1	374.3	443.6	518.5	613.1	672.5	710.8	744
February	134.9	201.1	271.0	335.6	399.7	470.5	544.7	614.3	652.2	678
March	135.4	214.1	292.5	365.1	437.4	515.2	585.7	659.6	722.3	744
April	127.2	206.1	281.8	351.6	422.0	496.5	562.1	632.8	700.2	720
May	138.1	218.7	293.9	365.0	435.3	513.2	585.0	657.2	714.5	744
June	147.4	221.0	291.5	358.5	425.2	499.3	581.1	644.3	688.2	720
July	166.6	239.0	311.2	380.2	449.1	525.8	619.1	673.6	713.0	744
August	177.9	248.9	321.4	391.5	464.4	545.1	623.7	684.7	719.7	744
September	173.7	246.6	317.2	386.4	461.9	531.0	597.9	665.0	706.9	720
October	177.6	255.9	327.5	399.4	477.5	546.7	609.9	683.1	734.7	744
November	166.5	242.2	311.3	380.1	453.8	525.9	588.8	654.9	704.2	720
December	166.4	241.1	313.4	383.1	455.0	533.7	612.5	672.3	715.9	744

Most (64%) of the GPS tracking points of Far Eastern Curlews in Moreton Bay were from the soft substrate habitat and then non-wetland vegetation communities and mangroves (Table 11). to a lesser extent, Curlews were recorded in saltmarsh habitat just 9% of the time.

Table 11. *Percent of Far Eastern Curlew GPS tracking points within each habitat class in Moreton Bay, Queensland.*

Habitat classification	Count	Percent
Unclassified	4	0%
Soft substrate	4014	64%
Hard substrate	67	1%
Mangrove	603	10%
Saltmarsh communities	593	9%
Casuarina glauca communities	13	0%
Non-wetland vegetation communities etc.	960	15%
Free standing water - saline/brackish	0	0%
Total	6254	100%

The position of where tagged birds occurred and the predicted tide height for the time of the record showed that birds were mostly recorded in the lower gridcodes of 1 to 4 (Figure 21).

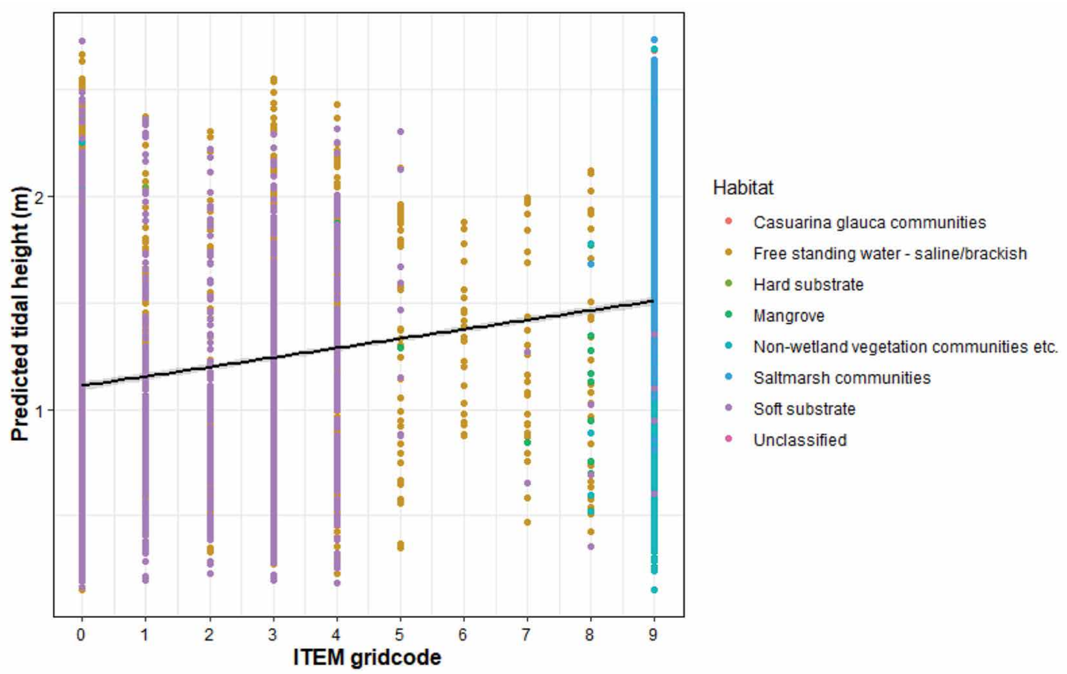

Figure 21. *Predicted tidal height based on the time recorded on the GPS tag against the ITEM gridcode (intertidal band) where tagged Far Eastern Curlew were recorded based on habitat classification in Moreton Bay, Queensland.*

Western Port, Victoria

We defined the Western Port study region as the entire coastal area between the suburb of Flinders and the western end of Phillip Island (the Nobbies). We classified all coastal and intertidal habitat within those bounds (Figure 22). The total area of soft substrate in the Western Port study area was 161.6 km^2, hard substrate was only 2.9 km^2, while mangroves made up 17.6 km^2, and saltmarsh and saline reedbeds made up 26.5 km^2 (Figure 23).

Exposure of intertidal soft substrate was linear between grid codes 1 to 7. Between gridcodes 7 to 9 the relationship plateaus. The average predicted tide height across the study years was 1.75 m.

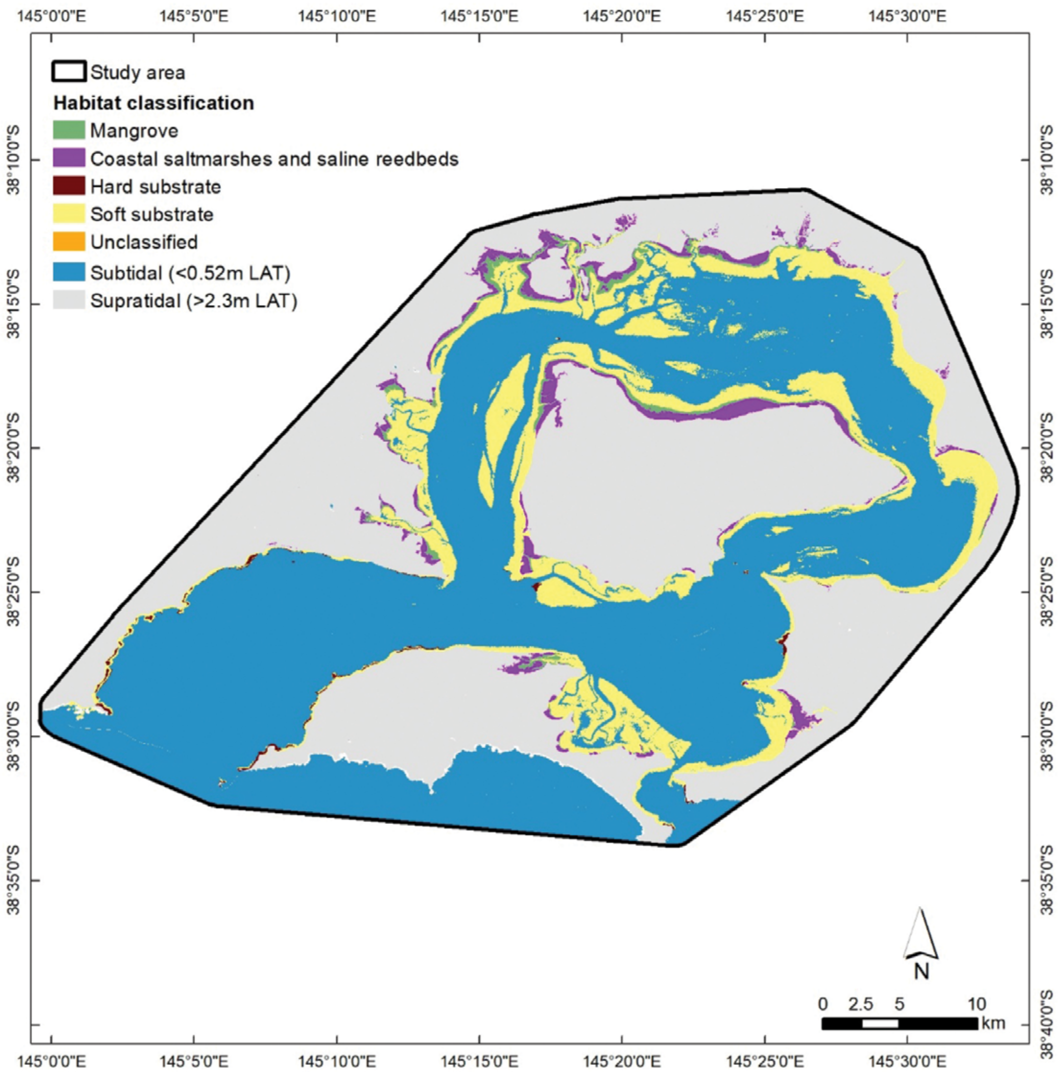

Figure 22. *Map of study site in Western Port, Victoria, showing the habitat classifications.*

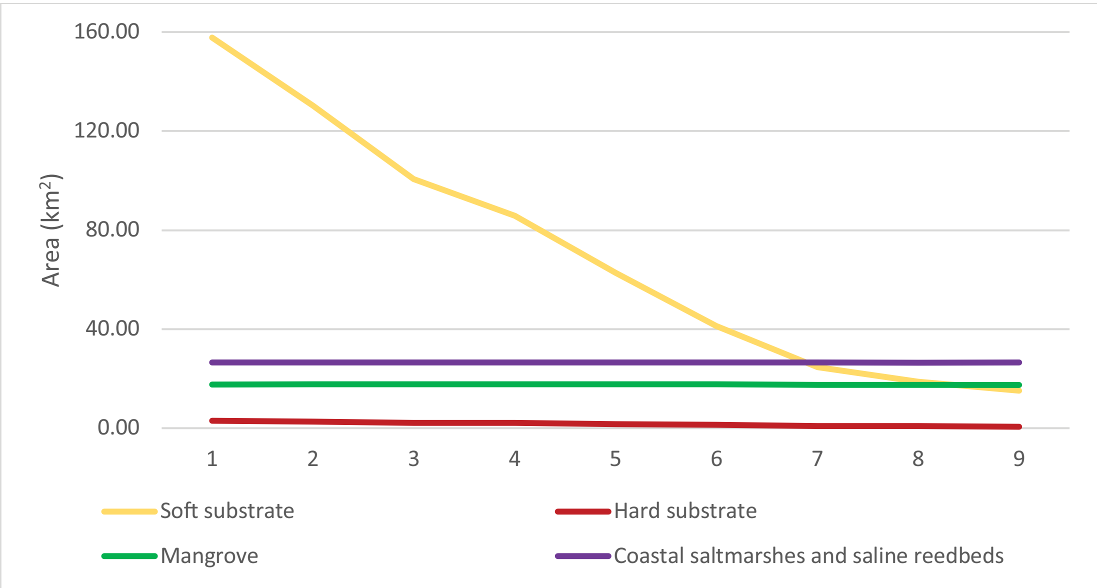

Figure 23. *Cumulative habitat availability from low tide (left) to high tide (right) in Western Port, Victoria.*

There is extensive intertidal mudflat throughout the entire coastal area of Western Port between Rhyll and Hmas Cerberus. The largest intertidal areas occur around French Island, but the intertidal areas most often exposed are found along the coast of Tooradin, Yallock Creek, around to Jam Jerrup and The Gurdies (Figure 24). For the month of February when Curlews would be fattening up before migration, the average time of exposure of gridcodes 1 to 6 was between 19 and 303 hours, compared to gridcodes 7 to 9, when the average time of exposure was between 360 and 489 hours (Table 12).

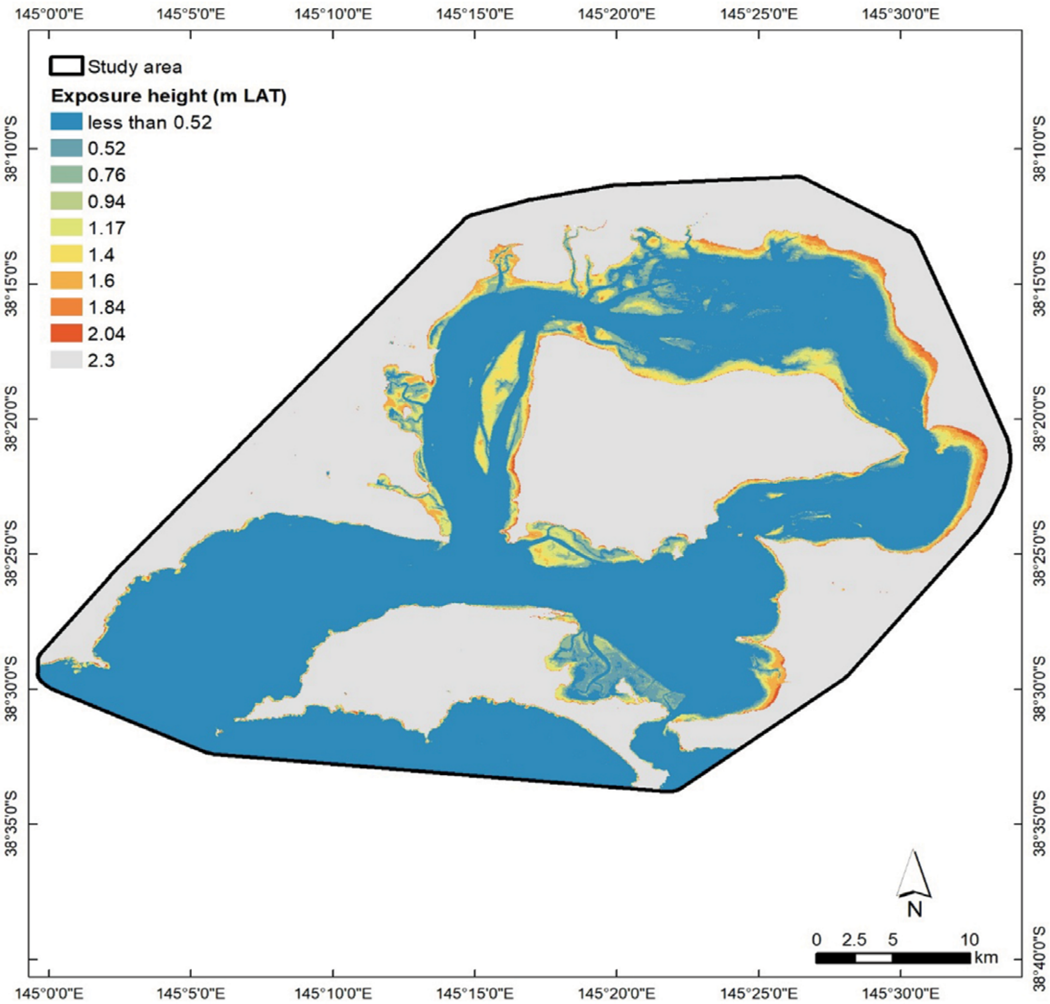

Figure 24. Map of intertidal exposure for the Western Port study area in Victoria.

Table 12. Table of average hours each tidal band was exposed for the years 2017 – 2020 in Western Port, Victoria.

	ITEM gridcode									
Month	1	2	3	4	5	6	7	8	9	10
January	20.5	79.6	130.3	195.7	271.2	330.4	396.3	450.7	532.4	744
February	19.4	72.3	120.3	181.0	249.8	303.0	363.2	413.3	489.7	678
March	17.6	64.7	117.7	194.5	271.8	329.9	395.5	451.1	534.4	744
April	17.4	47.7	88.8	171.6	251.6	308.7	373.6	427.9	508.0	720
May	13.8	44.3	76.6	155.7	242.0	304.8	373.4	429.3	509.9	744
June	8.9	39.0	77.0	145.5	222.9	286.3	353.4	407.6	482.9	720
July	7.0	47.0	94.7	158.3	231.5	297.6	366.6	422.4	499.7	744
August	7.3	55.4	107.8	172.2	245.4	309.1	376.7	432.1	511.2	744
September	12.2	55.5	108.0	176.3	252.1	310.5	374.7	428.5	507.7	720
October	21.2	54.3	103.5	188.2	268.1	326.4	392.9	448.6	532.3	744
November	23.0	53.3	97.2	184.9	260.1	316.1	380.5	434.6	516.2	720
December	21.5	66.2	116.3	189.5	266.8	327.0	393.6	449.2	531.9	744

Most (88%) of the GPS tracking points of Far Eastern Curlews in Western Port were from the soft substrate (Table 13). The remaining 12% of records were from saltmarsh and saline reedbeds and mangroves.

Table 13. *Percent of Far Eastern Curlew GPS tracking points within each habitat class in Western Port, Victoria.*

Habitat classification	Count	Percent
Unclassified	0	0%
Soft substrate	2246	88%
Hard substrate	0	0%
Mangrove	18	1%
Coastal saltmarshes and saline reedbeds	293	11%
Total	2557	100%

The position of where tagged birds occurred and the predicted tide height for the time of the record showed that birds were mostly recorded in the gridcodes 5 to 9, showing a linear pattern of records across these intertidal bands that were more frequently exposed (Figure 25).

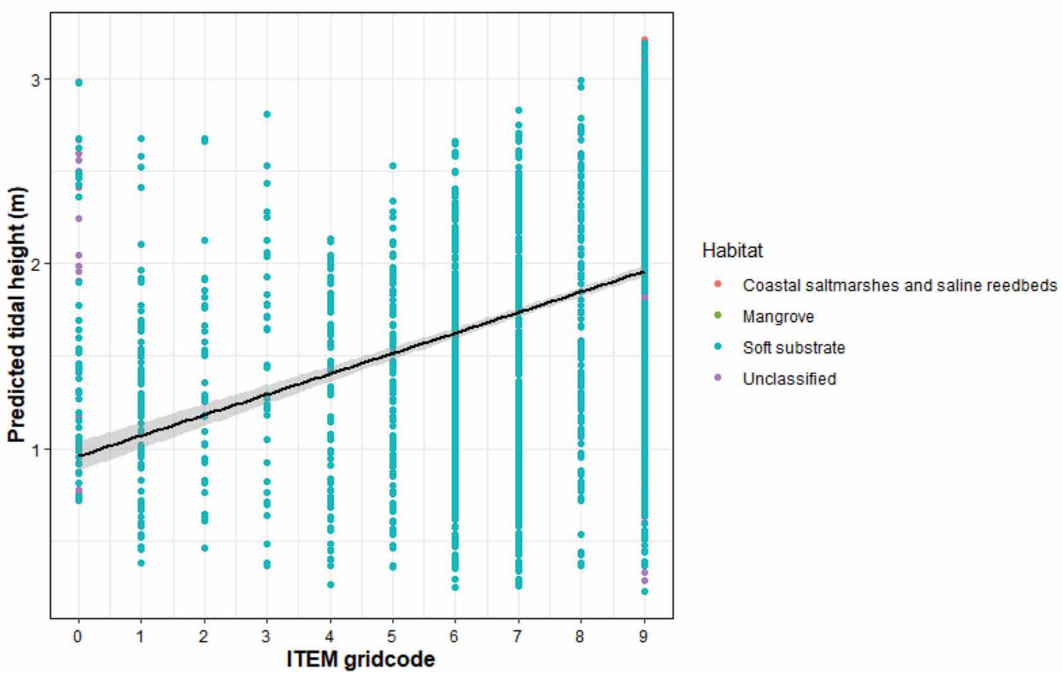

Figure 25. *Predicted tidal height based on the time recorded on the GPS tag against the ITEM gridcode (intertidal band) where tagged Far Eastern Curlew were recorded based on habitat classification in Western Port, Victoria.*

Commonalities of habitat use across the non-breeding grounds

From our GPS tracking study of Far Eastern Curlew across four study regions on the non-breeding grounds, we have shown that while there is a great deal of overlap in home ranges of individuals within study regions, there is also substantial variation between regions. There are many factors that might be driving the regional variation, including the overall size and general geographical layout of the different study regions, number of individuals in the population, suitable high-quality roosting and feeding habitat, presence or absence of disturbances at sites, and ratio of female to male individuals in the population. We found that the average core area used at both feeding and roosting sites was relatively small in NT curlews but larger in all other regions and both feeding and roosting habitats were used repeatedly by each individual over multiple seasons (average KUD 50%: NT = 2 km^2; WA = 22.3 km^2; QLD = 39.6 km^2; VIC = 32.4 km^2). We compared home range estimates between regions and seasons using nonparametric Kruskal-Wallis tests in R v 4.1.0 (R Core Team 2020). We found a significant difference between home range size (KUD 50%) between the states ($\chi 2$ = 11.7, p-value = .008), and between individuals ($\chi 2$ = 28.4, p-value = .040), but no significant difference between seasons ($\chi 2$ = 3.9, p-value = 0.14).

That there was no difference in home range size between seasons suggests that birds are repeating their behaviours each year and moving between reliable roosting and feeding sites. This is expected of migratory shorebirds that are known to show fidelity to a site. Many species of bird display strong site fidelity to areas throughout their life cycle (Newton 2008). Site fidelity is beneficial to individuals as it can improve survival indirectly through knowledge habitat resources (Newton 2008). Having strong site fidelity can however negatively affect shorebirds in coastal areas where there are competing interests such as coastal development (Rehfisch et al. 2003). The removal of a site can impact an individual's fitness through poor body condition and reduced survival (Burton et al. 2006). Where shorebird site fidelity is high, there is the potential that habitat loss could be detrimental to the species' population (Rehfisch et al. 2003). This places importance on a network of sites being available to shorebirds so that if an important site is lost through development or recreational purposes (disturbance), then birds can take refuge elsewhere. Given the relatively small sample size of tagged Far Eastern Curlew in our study, we cannot be certain that our home range estimates can be generalised for the species across the entire distribution of the non-breeding grounds. We suggest that proponents take caution when estimating possible home range size for species, unless there is tracking data available for that region, or leg-flag information with adequate mark-recapture analyses to support any estimates.

In areas where the coastline was less developed, birds were predominantly recorded in natural ecological systems (such as curlews in Roebuck Bay and Western Port). In Darwin and Moreton Bay, some curlews spent time in modified environments or directly adjacent to industrialised areas. There were similarities in the environmental structure in Roebuck Bay, Moreton Bay and Western Port, where 20-30% of the study area was mapped as soft substrate, whereas in Darwin Harbour, only 6.5% of the study region was mapped as soft substrate. Moreton Bay and Darwin Harbour had similar coverage of mangrove habitat in the study regions, 19 and 23.7%, respectively; whereas Roebuck Bay and Western Port had between 2-4% of their study regions mapped as mangrove. Further similarities across all study regions was the low coverage of hard substrate, this habitat type was mapped as covering 0.02-0.1% of the four study regions.

We recommend that proponents and developers consider the entire life stages of Far Eastern Curlew, examine all suitable habitat for the species within at least a 30 km radius of any potential coastal development site, as our study shows that some individuals can make wide-ranging movements within a non-breeding season. Other considerations include, but are not limited, to examining intertidal benthic food availability for Far Eastern Curlew, determine number of roost sites within a site network, examine number of and source of disturbances to birds within the site network, understand population trends, and where local population trends are declining, attempt to mitigate threats and potential causes for local declines.

Collaborating with Indigenous Rangers in Darwin Harbour

AIM 4 Engage with and train local Indigenous rangers to monitor migratory shorebirds in an industrial harbour.

The goals of engaging Indigenous rangers in Darwin Harbour on Larrakia country are to collaborate with Traditional Owners of the land and sea that Far Eastern Curlew use and to ensure that monitoring of threatened migratory shorebirds succeeds beyond the length of this hub project. This aspect of the project is focused on developing suitable methods using a two-way science framework to obtain robust scientific data while ensuring that rangers are mentored and trained and given a voice in managing threatened species alongside a developing harbour.

Background

The Larrakia Land and Sea Rangers from Larrakia Nation Aboriginal Corporation are an urban-based Aboriginal ranger group in the Northern Territory of Australia. They work across Larrakia land and sea country, which comprises the greater Darwin region west across the Cox Peninsula and east to the Adelaide River (Figure 26). The Larrakia People are saltwater people and have a strong cultural connection to the coastal environment. The Larrakia Rangers work with commercial businesses, universities and research organisations using a fee-for-service model. The Larrakia do not own any land under the western system so they work in partnership with landholders to care for Larrakia country. The Larrakia Land Sea Ranger unit is relatively young (approximately 10 years) compared to other long-running ranger programs across Australia.

Figure 26. Map of Larrakia country in the Northern Territory. Image credit: Larrakia Nation Aboriginal Corporation.

Development of fieldwork program

During the beginning of this project we trialled field methods to establish common goals in the collaboration before deciding on final methods and areas to focus. We started working on shell middens in this project once we discovered from GPS tracking of the Far Eastern Curlew that it was using coastal saltpans where shell middens exist. We realised that the bird overlapped in geographical space with important cultural sites and decided that we would incorporate patrols of saltpans into our fieldwork program. One outcome of this has been the documentation of these important sites and we have stated this in a recent report to government. It has been beneficial to learn more about shell middens and to know that we can pass this kind of information and connection on to our future generations.

In addition to spending time in mangroves and saltpans, we have spent considerable time on the boat in the harbour examining the distribution and abundance of Far Eastern Curlew and other shorebirds and waterbirds using a survey method following transect lines in Middle Arm and East Arm. We have completed this survey monthly for two years. At the same time, we have completed monthly surveys of Gunn Point beach in Shoal Bay.

During the monthly surveys in Darwin Harbour and Shoal Bay, we followed transect lines and marked waypoints for individual birds along the waypoints and within sections of the transects (Figure 27 and Figure 28). In Darwin Harbour we followed a transect line during a falling tide and counted all birds within sight, with most of the focus on the intertidal zone where birds were feeding.

In Shoal Bay we followed one transect line either on foot or on the Kubota all-terrain vehicle, employing the same method as in Darwin Harbour. At both these sites we recorded the start and end time of the surveys, the temperature, tidal conditions, marine activity, pollution and compliance of harbour users, and any other marina fauna present.

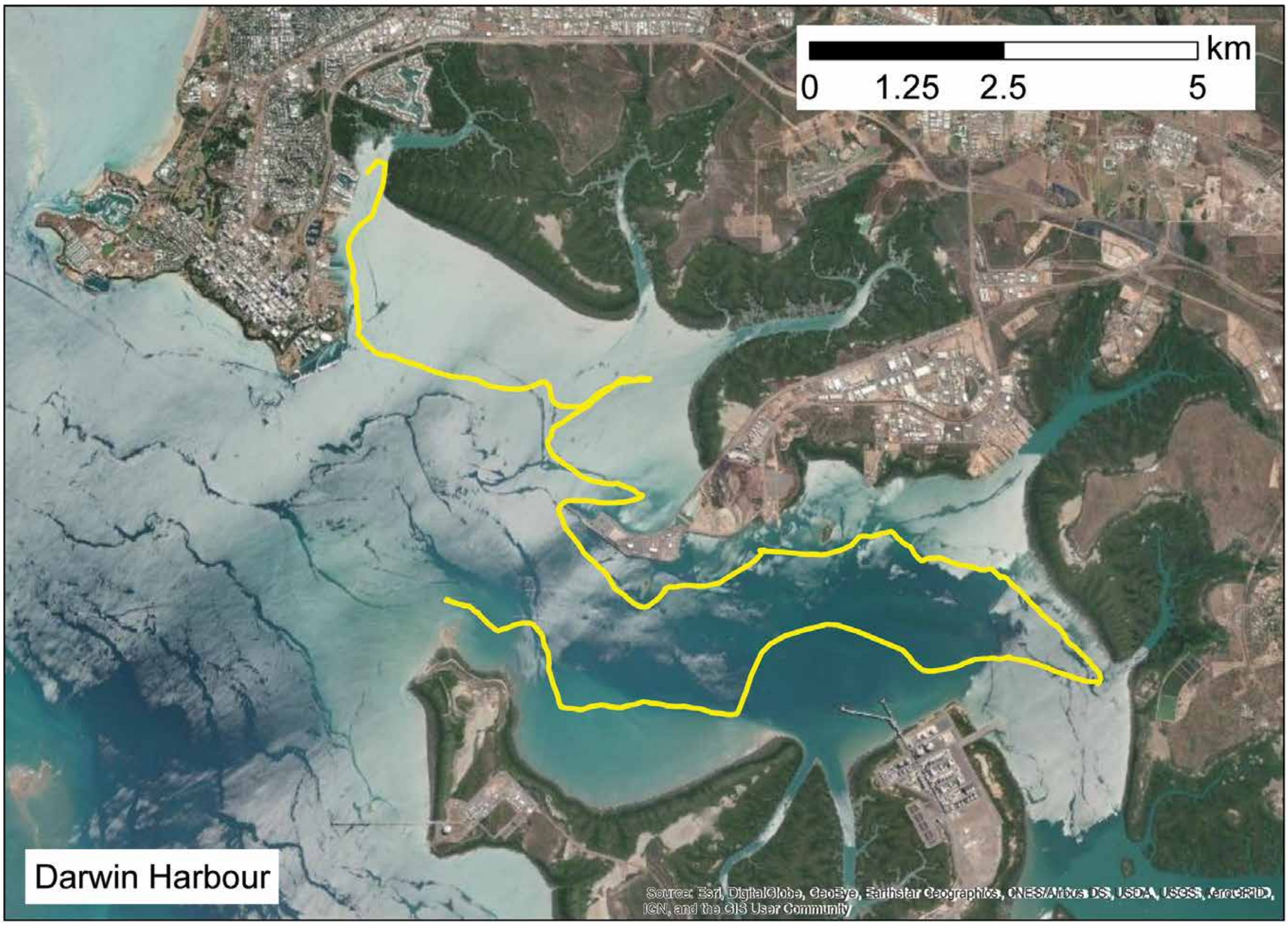

Figure 27. Boat survey transect for shorebirds in Darwin Harbour, Northern Territory.

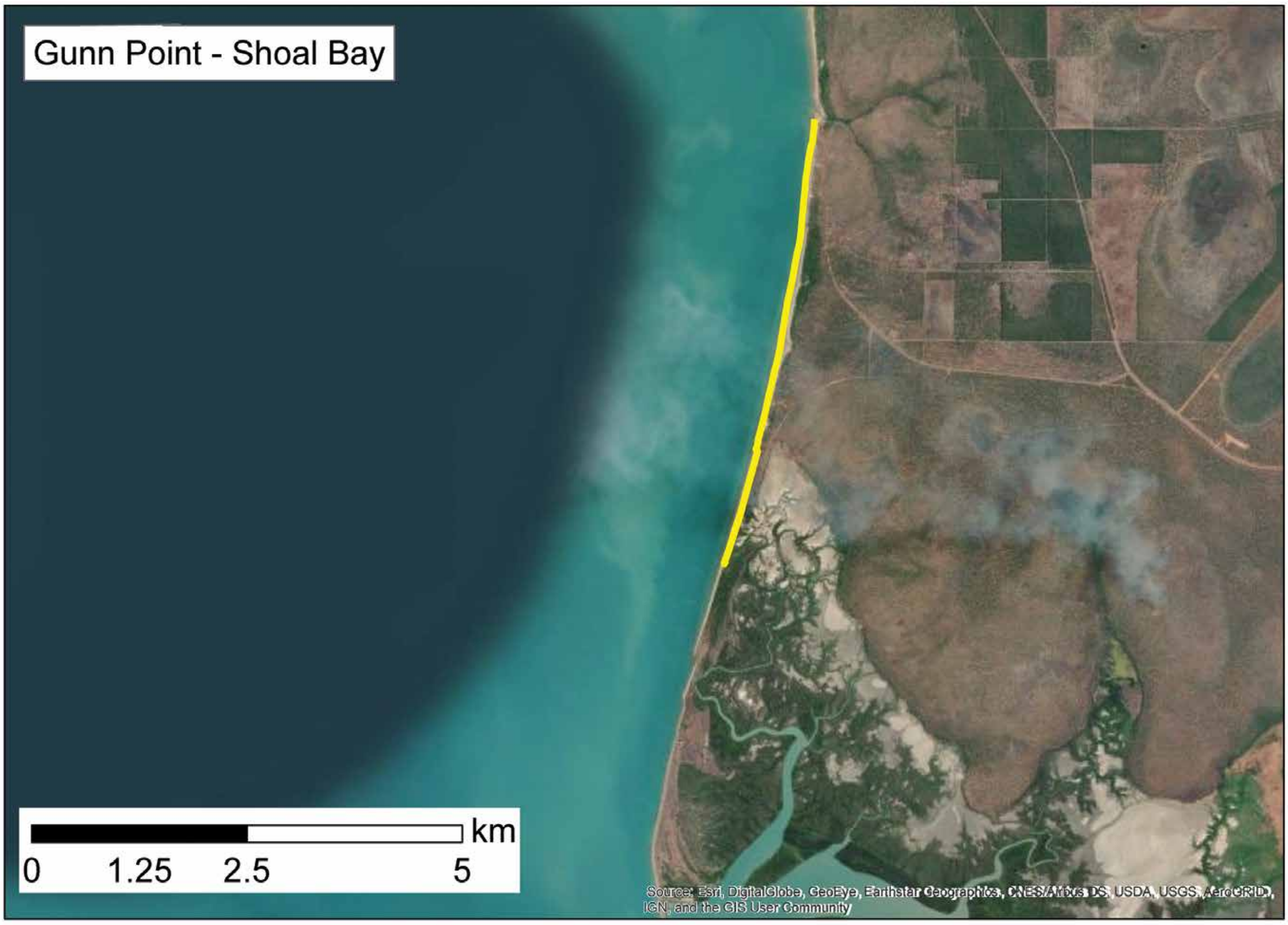

Figure 28. Transect along Gunn Point beach, Shoal Bay, Northern Territory.

Survey results

We conducted boat surveys from March through to December 2019 and then all months of the year in 2020. We spent a total of 41.3 hours surveying Darwin Harbour in 2019, and 81.9 hours in 2020. In Shoal Bay, we spent a total of 5.1 hours in 2019 and 11.4 hours in 2020. We recorded 64 species in Darwin Harbour and Shoal Bay over the two years of surveys (Table 14). In Darwin Harbour, the areas with the most birds recorded were the intertidal mudflats adjacent to Charles Darwin National Park and next to East Arm Wharf (northern side), the mudflats between the north-western tip of Middle Arm and the Inpex work site, the mudflat between Hudson Creek and Mitchell Creek (Figure 29). The Shoal Bay site showed varying numbers of birds along the length of the transect (Figure 30).

Table 14. *List of all bird species recorded during surveys in Darwin Harbour and Shoal Bay during boat and ground-based surveys over the years 2019-2020.*

Migratory Shorebird	Bar-tailed Godwit Black-tailed Godwit Common Greenshank Common Sandpiper Curlew Sandpiper Far Eastern Curlew Great Knot Greater Sand Plover Grey Plover Grey-tailed Tattler	Lesser Sand Plover Pacific Golden Plover Red-necked Stint Ruddy Turnstone Sharp-tailed Sandpiper Shorebird Medium Shorebird Small Terek Sandpiper Whimbrel
Resident Shorebird	Australian Pied Oystercatcher Beach Stone-curlew Black-winged Stilt	Bush Stone-curlew Masked Lapwing Red-capped Plover
Water Bird	Australasian Darter Australian Pelican Australian Pied Oystercatcher Australian White Ibis Black-necked Stork Eastern Reef Egret (Grey) Eastern Reef Egret (White) Egret Glossy Ibis Great Egret	Intermediate Egret Little Black Cormorant Little Egret Little Pied Cormorant Pied Heron Radjah Shelduck Royal Spoonbill Striated Heron White-faced Heron
Seabird	Australian Gull-billed Tern Caspian Tern Common Gull-billed Tern Common Tern Crested Tern Large Tern	Lesser Crested Tern Silver Gull Small Tern Tern Whiskered Tern White-winged Black Tern
Bush/Mangrove bird	Collared Kingfisher Orange-footed Scrubfowl Rainbow Bee-eater	Sacred Kingfisher Torresian Crow White-breasted Woodswallow
Raptor	Black Kite Brahminy Kite Osprey	Whistling Kite White-Bellied Sea-Eagle

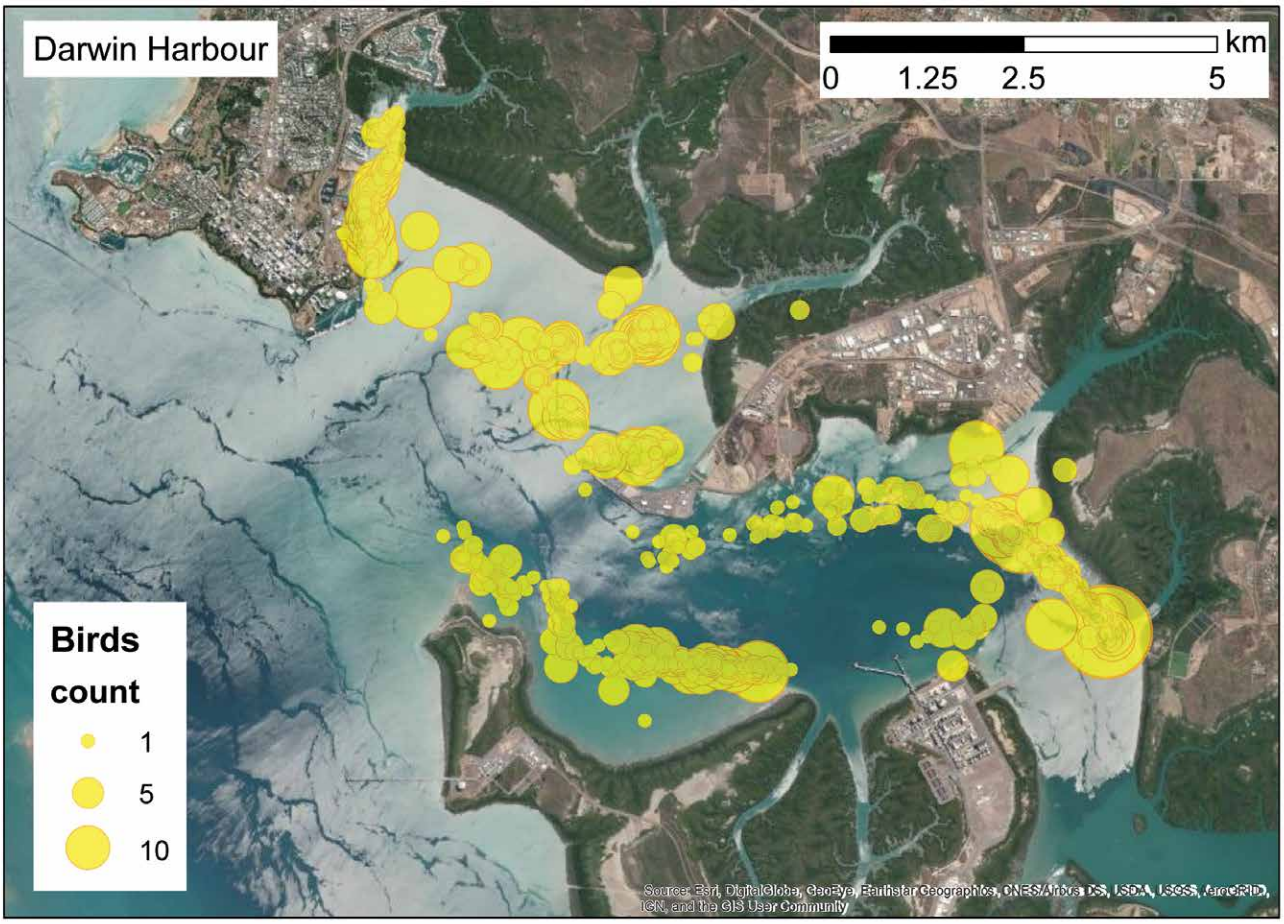

Figure 29. *Map of bird count data (as graduated symbols) from Darwin Harbour boat surveys with the Larrakia Land and Sea Rangers, from 2019 – 2020. Note that GPS waypoints were taken on the boat and thus follow the path of the boat but provide a general indication of where birds were recorded.*

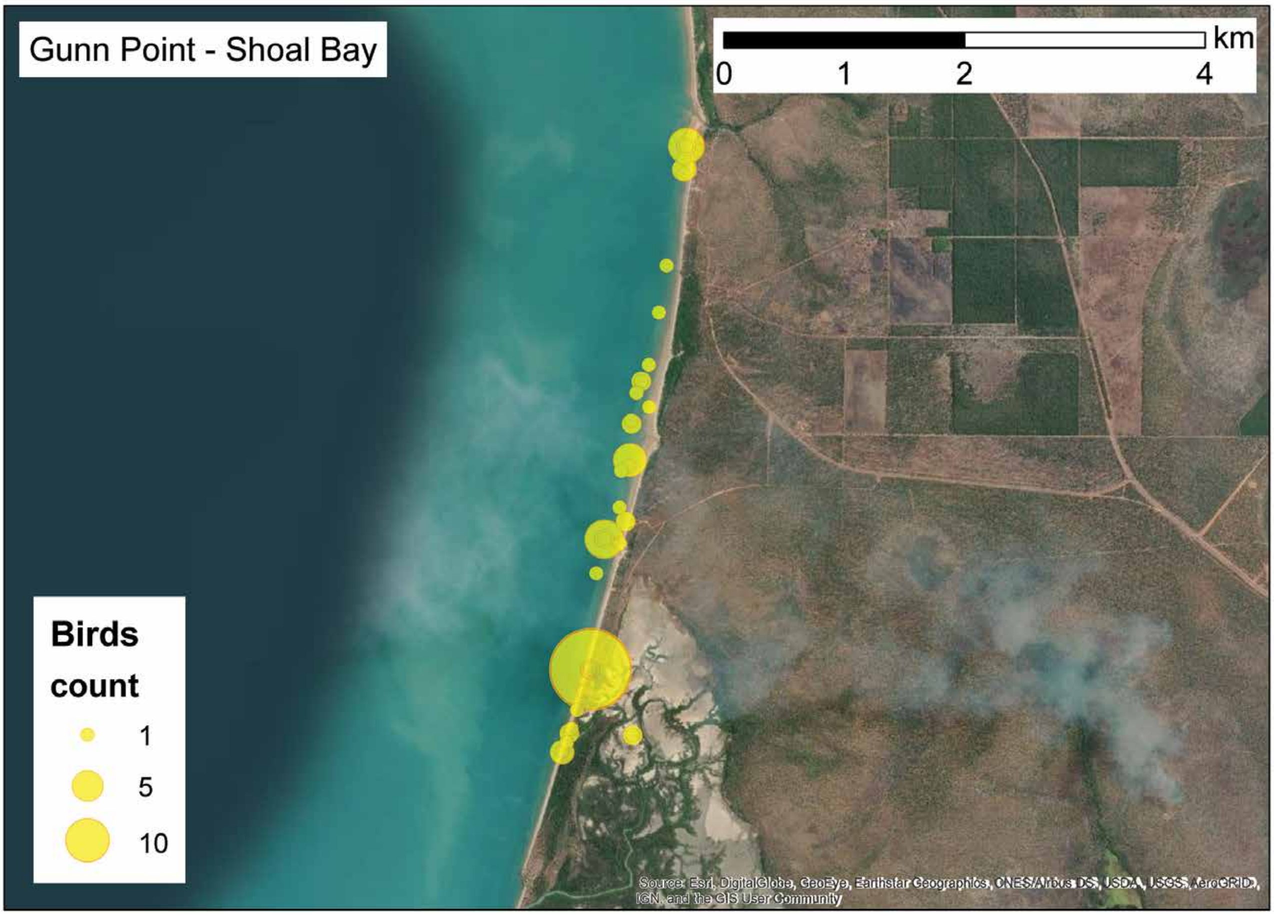

Figure 30. *Map of bird count data (as graduated symbols) from Shoal Bay ground-based surveys with the Larrakia Land and Sea Rangers, from 2019 – 2020.*

Cultural significance of the area

Contributions from Larrakia Land and Sea Rangers, Larrakia Nation Aboriginal Corporation

The Larrakia Land and Sea Rangers have concerns regarding the protection of culturally important shell middens within saltpan areas of Darwin Harbour. There is evidence of some shell middens being washed away by natural weather events, and there is potential for sea-level rise to further affect the structure of these middens. Elsewhere in the Darwin region some shell middens are fenced off with metal bollards, but these have been destroyed and cars have driven over the shell middens causing irreversible damage to the culturally sacred site. If there is future development in Darwin Harbour, Larrakia People want anyone visiting or working on the land to show respect and acknowledge that the workplace is located on Larrakia Country.

Recommendations:

- Fence off the shell middens with sturdy material that cannot be destroyed or vandalised.
- Erect educational signs to inform people about the local cultural importance of the area and about the shell middens.
- Set up annual monitoring of shell middens by Larrakia Land and Sea Rangers.
- Design a poster about shell middens and the cultural importance to Larakia People to send to all stakeholders involved in any future development or use of the coastal area.
- Consider including information on the cultural importance of Darwin Harbour during site inductions on current and any future developments.

Future opportunities with the Larrakia Land and Sea Rangers

There is an opportunity to continue working with the Larrakia Land and Sea Rangers and supporting them in their ongoing coastal patrols of the Darwin Harbour region and by providing ongoing training and support to their surveys of coastal birds. This collaboration has been highly successful and was recently recognised at the Territory Natural Resource Management Awards ceremony, with the project on 'Coastal Birds of Larrakia Country' (Figure 31) by the Larrakia Land and Sea Rangers and Amanda Lilleyman awarded the Indigenous Natural Resource Management award.

Figure 31. *Front cover of Coastal Birds of Larrakia Country booklet.*

Discussion

Home range size and habitat use

Our study addresses for the first time the movement patterns of the globally endangered Far Eastern Curlew on the non-breeding grounds of Australia. In this study, curlews used the study regions intensively and individuals repeatedly used familiar roosting and feeding sites. Understanding the movements and home range sizes of individuals across the non-breeding grounds will help planners and managers to mitigate any potential effects from coastal development on the Far Eastern Curlew.

Based on the KUD estimator, we found that home range size of Far Eastern Curlew varied between the four regions across the non-breeding grounds. Home range variation was greatest between individuals in QLD and then WA, VIC and smallest in NT. This high variation between individuals was largely due to birds acting as outliers; for the most part, home range size was similar within regions, but a minority of individuals used a greater area within the study region. Our study has shown there is considerable overlap between home ranges of curlews within each region. Overlap between home ranges might suggest that there is enough food resources and roosting space available to support those birds. Core home range size also varied between seasons for each individual, but this seasonal variation might be influenced by the tag performance, for instance if tags had reduced battery power due to feathers covering the tag.

The mean maximum daily displacement distance travelled was greatest in the VIC curlews 8.4 km (range 0 – 74.4 km) and was shortest in NT curlews 2.8 km (range 0.01 – 6.9 km). The curlews showed a strong preference for intertidal habitats with a soft substrate. It was surprising that the NT birds spent most of their time in saltmarsh habitat surrounded by mangroves. The average core area used at both feeding and roosting sites was relatively small in NT curlews but larger in all other regions and both feeding and roosting were used repeatedly by each individual over multiple seasons (average KUD 50%: NT = 2 km^2; WA = 22.3 km^2; QLD = 39.6 km^2; VIC = 32.4 km^2). Simply put, all the resources a curlew needs are found within smaller areas for NT birds, compared to the VIC birds. We acknowledge that these differences are also dependent on where birds were tagged during the study, and the geographical layout of the study regions.

This study has increased our understanding of the ecological requirements and habitat use of the Far Eastern Curlew across four regions in Australia where birds roost and feed based on tidal cycles. The home range estimates we present here should be used to inform areas to conserve for the ongoing protection of the species. Developers and planners should consider both 50% and 95% KUD home range sizes when proposing any coastal development and should work to mitigate the potential impact to the species and the intertidal habitat that it uses.

Developers and planners should consider the availability and extent of suitable habitat (soft substrate, saltpans and saltmarsh habitat, and coastal wetlands) and the home range estimates reported here in assessing impacts of development on the species.

KEY FINDING: soft substrate is critical to the survival of the species.

Planning guidelines

The regularity of habitat used by individuals benefits planning because the areas occupied by curlews when roosting and feeding in one survey are likely to be those required by the species at all times. Both habitat types need protection, but the species does not require areas outside these two used areas.

Roost sites, particularly those used during spring tides when habitat availability is likely to be most constrained, can be important to curlew using habitat within a 30 km radius and may be particularly valuable in places like Western Port given the long commuting distance of multiple individuals. Given the proven propensity of curlews to use artificial roost sites, any development of roost sites needs to be offset by creation of alternative roost sites that can be used at all tides and, if possible, are at least as close to feeding areas as existing roost sites and have similar properties in terms of protection from disturbance and in allowing curlews the visibility they need to detect potential predators. Offsetting by protection of potential sites not currently used by curlew close to feeding areas is not recommended unless the reasons they are not used are determined and mitigated and there is demonstrable evidence that the curlews then find such sites suitable. Criteria to determine suitable offsetting sites should be based on number of birds using the region, and the area of suitable habitat for roosting and feeding to support the current population. All survey work to detect roost sites and populations of Far Eastern Curlew and other migratory shorebirds should follow guidelines set out in Commonwealth of Australia (2015). This study does not have implications on the estimates of the population size for the species.

Characteristics of suitable roost sites for Far Eastern Curlew:

- Protection from predators (such as feral cats, foxes, wild dogs)
- Protection from human disturbance stimuli (people, people and dogs, boats, jet skis etc)
- Proximity to feeding grounds (roost site should be close to where birds forage)
- Shallow water for birds to stand in to help cool down (thermoregulation)
- Open and clear areas free of surrounding tall vegetation

Feeding areas are less readily offset. Potentially soft sediments currently unused because of excessive disturbance could be protected from that disturbance, allowing their use. Given the strong philopatry of curlew to existing feeding areas, the efficacy of augmented protection of sites that are currently unused could only be determined over multiple seasons to provide curlew time to find and use such areas. At this stage, while it is known that curlew eat crustaceans and other relatively large invertebrates living within soft sediments, the minimum density of such prey required is not known so establishing new feeding habitat to replace any rendered unsuitable by development would require additional research. Based on an 800 g Far Eastern Curlew, the daily basal metabolic rate (BMR) would be 371 kJ^{-day}, that is, the minimum energy cost for the bird to stay alive. All activities (feeding, roosting, flying, walking) have energy costs that will be in addition to this BMR (Piersma et al. 2003). The required daily consumption of dry mass food (g; V_d = *Daily Energy Expenditure (DEE)*/0.8/23) for the hypothetical 800 g Far Eastern Curlew is 50.5 g of dry meat (Piersma et al. 1995, Piersma et al. 2003). These calculations are estimates only derived from laboratory estimates on a Calidris species of shorebird, so care should be taken when interpreting these estimates.

Ideally any areas used regularly by feeding curlew should be avoided in development. Surveys of habitat to detect the presence of feeding curlew should be undertaken at least three times over the non-breeding period of September to March to assess the numbers and limits to the home ranges of any curlews using a site. Surveys also need to determine the location of likely roost sites that also need protection, potentially by assessing direction of travel (in the absence of tagging and tracking) of any curlew departing feeding areas as the tide rises. There is still work to be done to investigate prey preferences and densities across the non-breeding range.

In Darwin Harbour, the tagged curlews are protected within the bounds of the Charles Darwin National Park, but they are not afforded protection across the intertidal zone and in this study, we recorded multiple disturbances to the birds from an airboat operating across the unprotected and unregulated intertidal zone. In Roebuck Bay, Moreton Bay and Western Port, most of the GPS locations of tagged curlews were from within the RAMSAR site and thus the birds and their habitat are protected. This does not mean that there are no threats to curlews and other shorebirds in these study areas; birds are still faced with disturbances and ongoing development and encroaching anthropogenic pressures.

Human population is highest in the Moreton Bay study region, and then the Western Port study region, followed by Darwin and Broome. All study regions face a growing human population and demands for more development and economic growth. The region in Broome is least affected by anthropogenic activities due mostly to the area’s remoteness and reduced accessibility.

This study has not dealt with potential differing threats from different development types and understanding how curlews might be affected by different developmental threats is an area that will require further work.

Future work and recommendations

Currently, it is not known how shorebirds will be affected by climate change on the non-breeding grounds where birds face threats such as coastal development. There is an opportunity to examine how Far Eastern Curlew might adapt to climate change scenarios. In addition, there is much to be discovered about the body condition of birds that spend most of the non-breeding season in Australia. Other knowledge gaps include how light and noise affect Far Eastern Curlew and other shorebirds, particularly where populations exist alongside development. Overall, if we want to improve the chances of birds migrating successfully, then we must protect suitable and high-quality habitat for the population of shorebirds that visit Australia.

The single most important management action to conserve migratory shorebirds on the non-breeding grounds is to conserve key habitat. This will involve working with governments and site managers at all levels, from local councils and governments through to state and territory and federal.

Shorebirds

There is an urgent need to conserve coastal habitat to manage migratory shorebird populations throughout the East Asian-Australasian Flyway. Darwin Harbour and much of northern Australia has the potential to provide a stronghold for many migratory shorebird species from the East Asian-Australasian Flyway. Migratory shorebirds continue to face threats from habitat loss throughout the flyway and there is increasing pressure from coastal development and human disturbances along the coastline of Australia.

Appropriate management of migratory shorebirds on the non-breeding grounds will involve:

- Identifying key areas used by birds during all stages of the austral summer period.
- Identifying the connectivity of habitat used by shorebird species.
- Minimisation of threats through holistic development planning to reduce impact on shorebirds.
- Minimisation of disturbance vectors (boats and airboats) from important shorebird habitat.
- Constraints on dredging activities so important intertidal foraging areas are not disturbed.
- Limits on construction of any development to a time when the impact on shorebirds will be minimal.

Protection of coastal habitat for shorebirds will involve:

- Whole-of-harbour assessment and guidelines made for the protection of shorebirds.
- Regulation of threats by appropriate regulatory bodies.
- Protection of all coastal areas (including saltpans and saline wetlands) from development so that these areas remain available for shorebirds. This is particularly important for neap tide periods when birds cannot feed on intertidal mudflat.
- Ongoing monitoring of shorebirds to ensure no reduction of populations as a result of local activities.

Habitat protection in Darwin Harbour

While most of the Darwin Harbour coastline is in good condition (Munksgaard et al. 2018), there is a need to consider the management of shorebirds in an holistic whole-of-harbour approach to ensure that the cumulative impacts of individual developments do not result in the reduction of the current population of shorebirds.

Development is not the only threat to shorebirds on the non-breeding grounds. Disturbance to shorebirds is a key threat in Australia and there is evidence of this happening in Darwin Harbour and surrounds (Lilleyman et al. 2016a). In Darwin Harbour, we recorded motorbike or quadbike tracks in saltpan areas, and this poses a threat to the saltmarsh vegetation and also has the potential to disturb shorebirds that use this habitat for roosting or feeding. In addition to this, we recorded disturbances by a commercial airboat to migratory shorebirds using the intertidal mudflat of Charles Darwin National Park and in Reichardt Creek during boat surveys.

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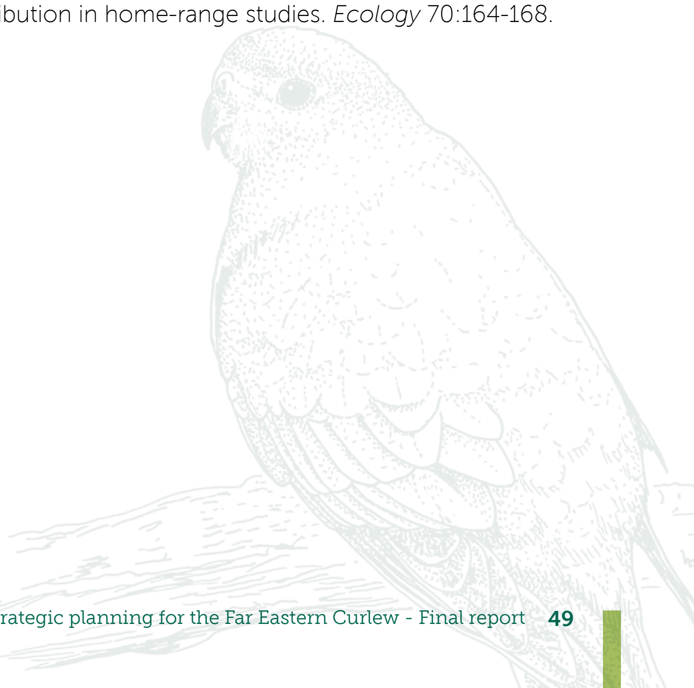

Amanda Lilleyman holding a tagged Far Eastern Curlew in Darwin. Image: Gavin O'Brien

Further information:

http://www.nespthreatenedspecies.edu.au

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