Using motus automated telemetry to quantify habitat use and movement in a Far Eastern Curlew within the Hunter Estuary, NSW, Australia

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We report a case study which illustrates how motus automated telemetry can reveal biologically interesting and management-relevant regional patterns of movement and habitat use of threatened shorebird species. The study reports the behaviour of a first-year Far Eastern Curlew *Numenius madagascariensis* equipped with a motus automated telemetry tag over a one-month period within the Hunter Estuary on the east coast of Australia. The bird showed a seasonal change in habitat use, which may be indicative of young birds using less frequented and potentially less favourable foraging grounds. The study contributes knowledge necessary for protecting the nonbreeding habitat of IUCN red-listed migratory shorebirds in Australia, thereby supporting evidence-based estuary-level land management.

INTRODUCTION

The last decade has seen phenomenal progress in mapping the interhemispheric flight paths of long-distance migratory shorebirds, driven by significant expansion of global satellite coverage and miniaturisation of satellite tracking technology (Chan *et al*. 2019; Gould *et al*. 2024). This global research effort has revealed awe-inspiring levels of spatial detail about the bi-annual, long-distance journeys of a range of shorebird species and has played a key role in mobilising political attention to the dramatic population declines of this taxonomic group, as well as in motivating international cooperation to discover and address the causes of decline at the flyway level (East Asian-Australasian Flyway Partnership 2024; Rogers *et al*. 2023).

About 2 million individuals from 37 species use the East Asian-Australasian Flyway (EAAF) to make bi-annual flights between their northern hemisphere breeding grounds in the Arctic tundra and their nonbreeding grounds in Australia's rich landscape of coastal estuaries (Department of Climate Change, Energy, the Environment and Water 2023). Arriving late September and departing the following April, Australia's migratory shorebird community spends more than half of its annual cycle in nonbreeding habitat, more than in staging and breeding areas combined. There is an increasing awareness that lack of knowledge about the ecology and behaviour of sexually mature birds in their nonbreeding habitat, and sexually immature birds that remain in Australia year-round, is hampering effective land management decisions at the intra-estuary level, as well as conservation strategies and priorities by government agencies (BirdLife Australia 2020).

Motus is the largest global automated telemetry network, centrally managed by Birds Canada (https://motus.org). Motus operates via fixed antenna stations which listen continuously for the signals of small, lightweight VHF nanotags (Taylor *et al*. 2017; Griffin *et al*. 2018). Each nanotag emits an individually identifiable digital pulse. Detection patterns across a local array, as individuals disappear from one station's antenna(s) and re-appear on another station's antenna(s), identify where the individuals are day and night, 7 days/week. Signal strength variability yields additional behavioural information (e.g., feeding versus roosting). Motus technology has the major advantage of providing an affordable means of tracking technically unlimited numbers of individuals simultaneously on a local to global scale, providing adequate sample sizes to begin studying, for example, relationships between individual health profiles and variation in movement patterns. A further advantage is that tags can be as small as 0.13 g. This technological advancement makes it possible to track a range of low body weight shorebirds that cannot be tracked currently with other systems. The global motus network now spans 34 countries across five continents, with >2000 stations and 402 tagged species (https://motus.org/about/, last accessed 3 December 2024). This significant growth since its inception in 2012 is testament to the power of this technology and the confidence that it will remain a technology of choice, complemented by other more expensive tracking methods where appropriate.

The Hunter Estuary, which includes the Ramsar-listed Hunter Wetlands National Park contains internationally significant shorebird habitat (Roderick & Stuart 2016; BirdLife Australia 2020; Stuart & Lindsey 2021). The Hunter has a long history of heavy industry and is the largest coal exporting port in the southern hemisphere. Of Australia's 37 migratory shorebird species, more than half are declining, and the Hunter has been noted as one of the areas with sharper declines (Clemens *et al*. 2016). The reasons why some estuaries are losing shorebirds faster than others remains a matter of speculation. Given that many migratory shorebirds are known to show strong levels of site fidelity, returning year after year to the same estuary (Buchanan *et al*. 2012; Coleman & Milton 2012; Little *et al*. 2023; Ross *et al*. 2023; Sandercock & Gratto-Trevor 2023), one possible explanation is that environmental factors local to the area and detrimental to shorebird health (e.g., contamination of the food chain) may increase mortality during northbound migratory journeys, meaning that site-loyal birds fail to return the following year.

The Hunter Estuary has a rich history of community-led surveys conducted by a regional birding club, the Hunter Bird Observers Club (Stuart & Lindsey 2021). Monthly whole-estuary surveys have been conducted for over 20 years and the significant declines they have revealed have provided the impetus for complementary monitoring methods to fill the knowledge gaps that high-tide, diurnal counts cannot address, including where the birds forage and roost across the tidal and circadian cycles (BirdLife Australia 2020). The Hunter Estuary currently hosts a network of eight motus automated telemetry stations, complemented by another three in the nearby Port Stephens Estuary. The array is being used to obtain key movement and habitat use information within and between estuaries, covering a range of migratory and resident shorebird species and recording continuously every day. This is a case study on a young female Far Eastern Curlew *Numenius madagascariensis* equipped with a motus automated telemetry tag over a one-month period within the Hunter Estuary.

METHODS

Location

The Hunter Estuary is located at the mouth of the Hunter River, approximately 150 km north of Sydney in New South Wales, Australia (**Figure 1**). The motus array in the Hunter Estuary has expanded gradually since 2020. At the time of the present study the estuary hosted four stations, each consisting of a 6.5 m steel mast with an antenna attached to the top (**Figure 2**). Each station is equipped with a SensorGnome radio receiver, which processes and registers the antenna detections along with date and time.

Three of the stations are equipped with an omnidirectional antenna approximately 9 m above the ground, yielding temporally high-resolution presence/absence data, while one is equipped with a 6-element directional Yagi antenna approximately 6.5 m above the ground to detect fly-bys across the estuary. Omnidirectional antenna sites were strategically placed near recently restored and intensively managed intertidal habitat, where usage by shorebirds at low tide and during the night was unknown. The directional antenna is positioned to detect movements along the north-south axis between the tidal mudflat in Fullerton Cove and the well-known high-tide roost at Stockton Sandspit. With tags set to emit a pulse every ~10-15 s, the motus stations provide temporally high-resolution detections, which can be mapped easily to the tidal and daylight cycles.

Subject

A young Far Eastern Curlew was caught during nocturnal shorebird mist netting activities at Stockton Sandspit (-32.883566, 151.790257), on 18 March 2023. The bird was fitted with a metal band on the left leg and colour flags engraved with 'AAE' on the right leg, with orange over green on the tibia. The bird was also fitted with a 2.7 g motus nanotag transmitter, glued to a small spot of trimmed feathers between the scapulae. Once in place, the tag was covered by feathers, except for the thin 9-cm long antenna that extended along the back. The bird was sexed, weighed, measured (length of wing, bill, tail), and was aged as a first-year bird based on plumage before being released unharmed.

The tagged bird was then detected whenever it was near one of the four automated telemetry stations. Data was downloaded from each of the stations for analysis. Detections ceased either when the tag fell off, or the bird did not return to the proximity of any station (which of these happened for this bird is not known). Tidal data were sourced from the Bureau of Meteorology. Spline interpolation was used to produce a continuous tidal curve and examine shorebird movements in relation to changes in water level.

Figure 1. The Hunter Estuary showing the initial catch site, Stockton Sandspit (green circle), the location of four motus automated telemetry stations (blue/white circles), and the Fullerton Cove mudflat. Blue circles are stations where the Far Eastern Curlew with flag 'AAE' was detected, and white circles are stations where it was not detected. The different shape at Fullerton Entrance represents the directional orientation of the 6-element Yagi antenna and illustrates how it detects birds flying between the mudflat and the high tide roost. N.B., the shape is not indicative of the detection range of the antenna (see text for more details). Note: Milhams Pond is located on Ash Island.

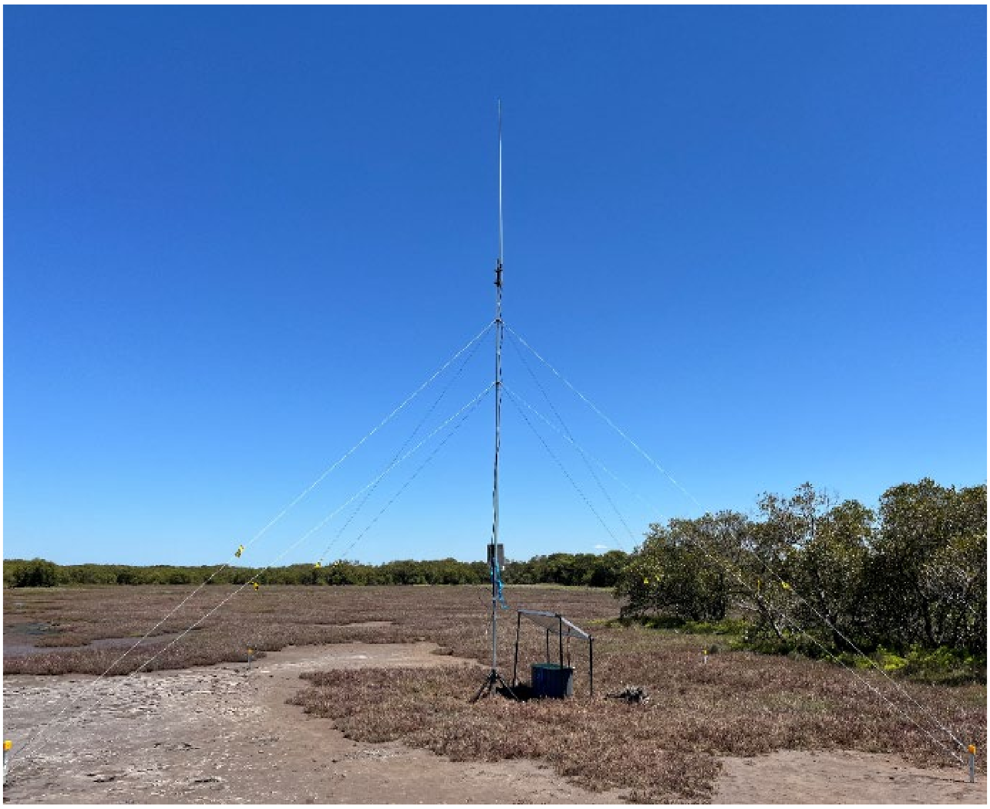

Figure 2. A typical Motus automated telemetry station with an omnidirectional antenna.

Motus automated telemetry

The features of motus are explained in detail elsewhere (Griffin *et al*. 2018). Briefly, nanotag transmitters emit a coded digital pulse that is specific to each tag, allowing for individual identification. The pulse interval is set by the user and can range from about 2 pulses/min to about 10 pulses/min. The pulse interval influences battery life and should be used strategically. In the present study, the curlew was equipped with a transmitter that pulsed every few seconds in order to ensure that rapid fly-bys past the directional antenna at Fullerton Entrance were not missed. As the battery life for this size nanotag is far longer than the expected glue attachment time, battery life was not a consideration. Knowing the pulse interval allows the researcher to calculate the total detection time for each motus station by multiplying the number of detections by the time interval between pulses. Detection range of a given station depends upon multiple antenna- (type, height), bird (height above ground), tag (size, residual battery life) and environmental (vegetation) factors, making it difficult to estimate. The estimated detection range of the stations used here can be found by visiting motus.org (https://motus.org/data/receiversMap) and selecting the option "show estimated antenna ranges". As a bird moves around its environment (e.g., searching for food), turning towards and away from the antenna, the signal reaching the antenna varies in strength. For this reason, periods of high variability in signal strength can be indicative of periods of activity, while periods of low variability can be indicative of periods of resting (Griffin *et al*. 2018).

RESULTS

The curlew was detected by the telemetry array on a total of 29 days, with the first detection on 25 March 2023 (7 days after transmitter attachment), and the last detection on 23 April 2023. **Figure 3** depicts the repeated pattern of tag detections across two telemetry stations, namely Milhams Pond and Fullerton Entrance (note: Fullerton Entrance refers to the telemetry station, and Fullerton Cove to the mudflat). The pattern reveals that the curlew visited Milhams Pond daily during late March, with regular fly-bys detected on the Fullerton Entrance station when leaving Milhams Pond. Mid-April, this pattern of repeated visitation to Milhams Pond ceased after a last visit to Milhams Pond on 16 April 2023 and from there onwards only fly-bys on the Fullerton Entrance station were detected. The curlew spent continuous bouts of up to 17 h at Milhams Pond, but only very brief duration bouts (maximum 7 min) at Fullerton Entrance, indicative of flying past the antenna (**Figure 4**).

Examining the detections patterns in more detail and superimposing tidal and circadian cycles revealed that the bird spent the low tides of late March at Milhams Pond and remained there for high tides during the daytime where the tidal amplitude was relatively low (**Figure 5**). An analysis of signal variance suggests that, during these periods of low high-tide amplitude, the curlew was either inactive

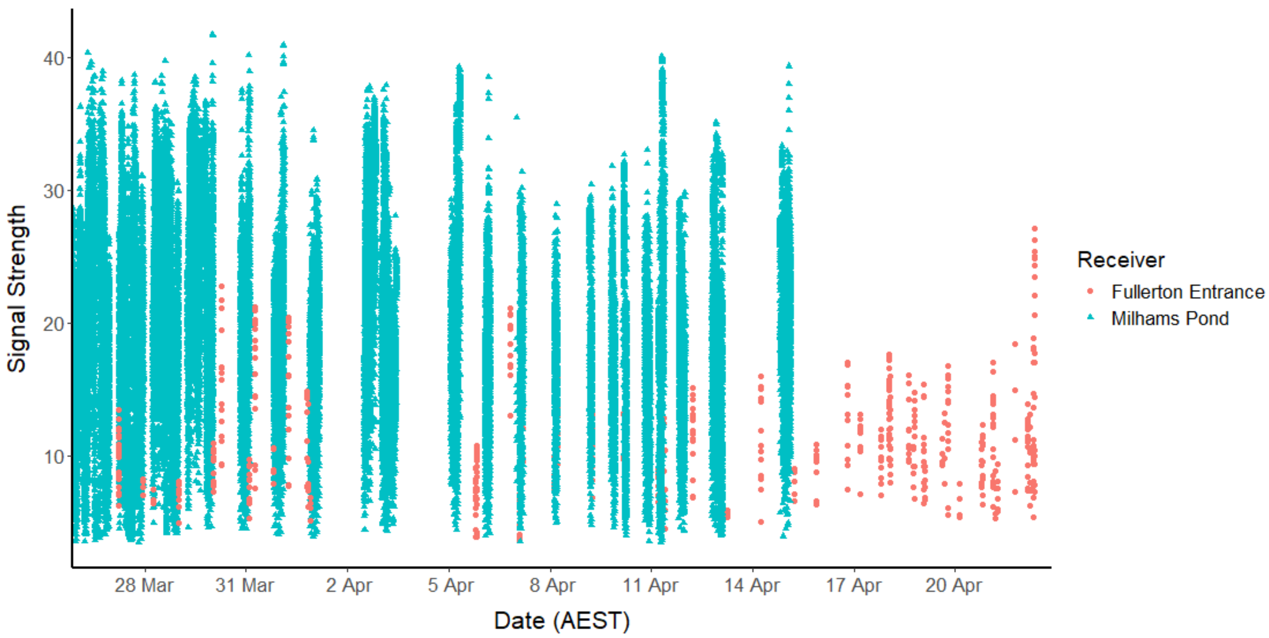

Figure 3. All detections of the tagged Far Eastern Curlew individual, from first (25 March 2023) to last (23 April 2023) detection. Dates on the horizontal axis correspond to the start of the day (i.e. 12 am).

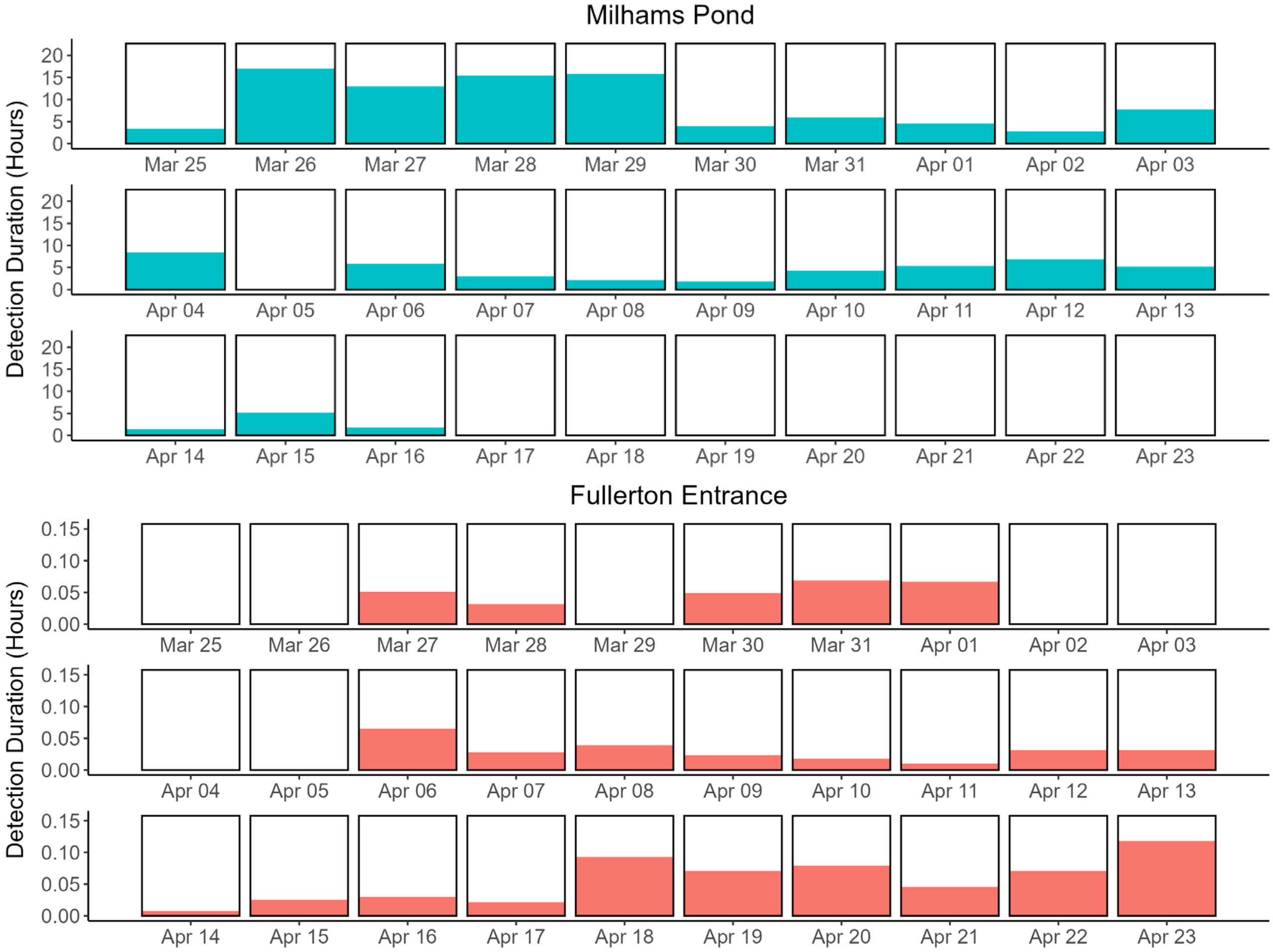

Figure 4. The amount of time each day (in hours) that the tagged curlew was detected at Milhams Pond (top panel) and Fullerton Entrance (bottom panel). Note the different scales on the y-axis across the two panels to improve readability.

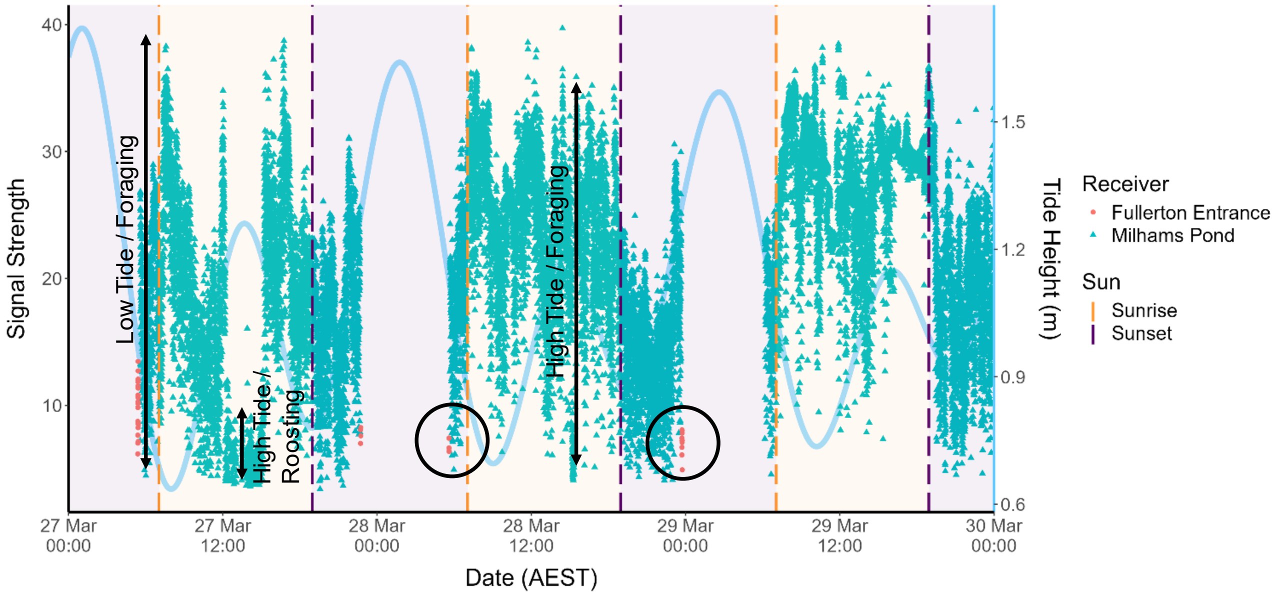

Figure 5. Detections of the curlew for 27-29 March 2023 on two stations within the Hunter Estuary (see **Figure 1**). The undulating blue line indicates the changing tide within the estuary (using Stockton Sandspit as the reference location). The shaded orange and purple backgrounds correspond to daytime and night-time respectively, with dotted vertical lines indicating dawn (orange) and dusk (dark purple), respectively. Vertical arrows show how variation in signal strength is indicative to behaviour (see text for more details). The black circles show examples of a fly-by as referred to in the text.

(low signal strength variation indicative of likely roosting; e.g. 27 March 2023) or was active (high signal strength variation indicative of likely foraging; e.g. 28 March 2023) (**Figure 5**). Arrival and departure at Milhams Pond were flanked by fly-by detections on the Fullerton Entrance antenna. This pattern of detections reveals for the first time that Far Eastern Curlew use Milhams Pond during both the day and the night to feed, that remaining there at high tide is associated with low high-tide amplitudes, and leaving is associated with high high-tide amplitudes. None of these facts were previously known from whole-estuary, high-tide, diurnal population counts.

On 13 April 2023, the bird began missing the low tide foraging period at Milhams Pond despite flying by the Fullerton Entrance station (**Figure 6**), pre-empting full cessation of visits to Milhams Pond on 16 April 2023 (**Figure 7**). During the final period of detections from 17 - 23 April 2023, the curlew repeatedly flew past the Fullerton Entrance antenna on the dropping and rising tide until it was last detected at 7.23 am on 23 April 2023. The most likely interpretation of these fly-by detections on the changing tide is that the curlew was moving between foraging at the large natural mudflat in Fullerton Cove to the north at low tide, and resting within the higher elevation area at Stockton Sandspit to the south, which is well known to be the most important high-tide roost in the Hunter Estuary (Spencer 2010; Stuart & Lindsey 2021).

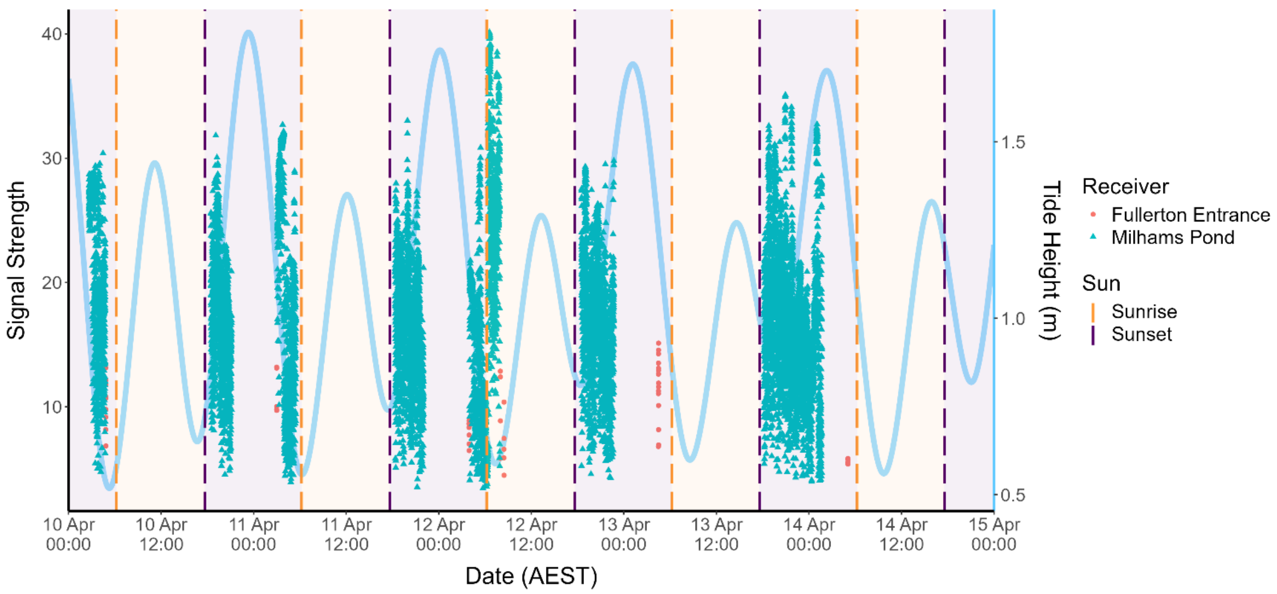

Figure 6. Detections of the Far Eastern Curlew "AAE" for 10-14 April 2023. See **Figure 5** for additional details.

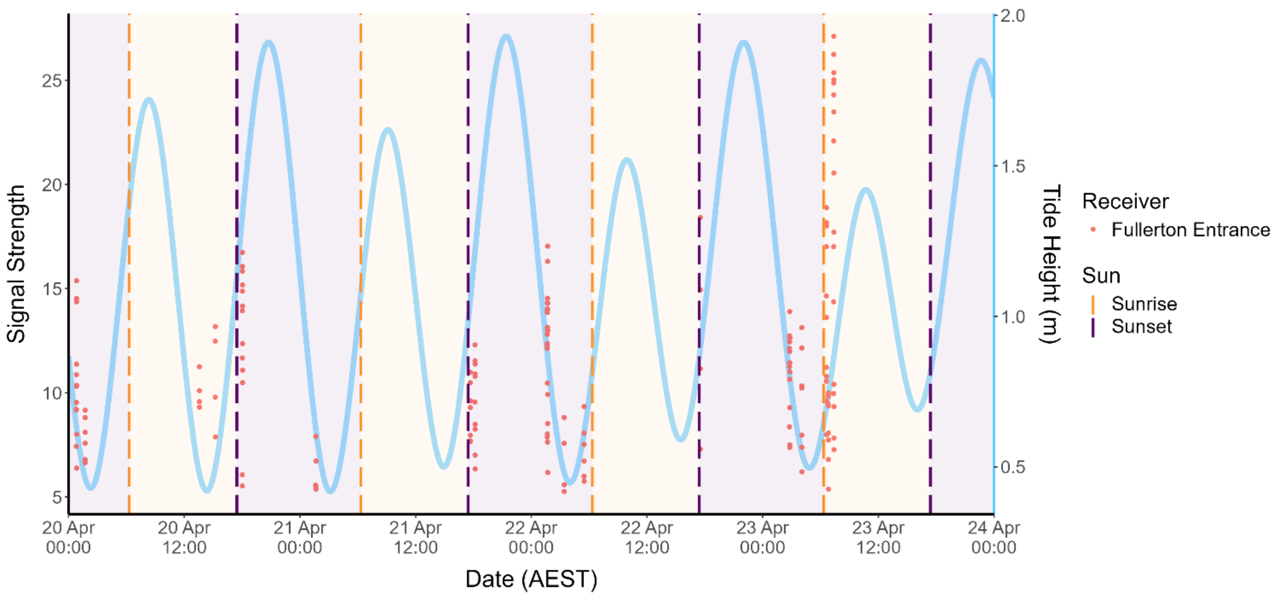

Figure 7. Detections of the Far Eastern Curlew "AAE" for 20-23 April 2023. Pulses of detection on the directional antenna of the Fullerton Entrance station are indicative of fly-bys (see text for details).

There have been several sightings of the banded individual in the Hunter Estuary (see **Table 1**), including one during the motus detection period on which the transmitter antenna was visible on the bird, and several since radio detections ceased on 23 April 2023, on which the transmitter antenna was no longer visible. The first re-sighting after radio detections ceased occurred at the Stockton Sandspit high-tide roost on 29 August 2023**.** The timing of these bird and transmitter sightings confirm first, that the transmitter was detected reliably when it was attached to the bird, and second, that by 29 August 2023, the absence of radio detections was attributable to transmitter loss and not battery failure. It remains unknown whether the absence of detections between 24 April and 29 August 2023 was due to transmitter detachment on 23 April 2023 or due to the bird briefly leaving the estuary (with its transmitter attached).

Table 1. Sightings of Far Eastern Curlew 'AAE' within the Hunter Estuary.

Date	Time	Location	Coordinates	Observer
30 Mar 2023[1]	13:26	Stockton Sandspit	-32.883566, 151.790257	T. Elks
29 Aug 2023	16:00	Stockton Sandspit	-32.883566, 151.790257	G. Little and D. Garnett
22 Oct 2023	12:07	Stockton Sandspit	-32.883566, 151.790257	G. Little and J. Little
04 Nov 2023	16:00-17:00	Stockton Sandspit	-32.883566, 151.790257	G. Little and J. Little
11 Nov 2023	morning	Stockton Sandspit	-32.883566, 151.790257	T. Clarke
22 Nov 2023		Stockton Sandspit	-32.883566, 151.790257	G. Little and J. Little
23 Dec 2023	7:45 – 9:15	Stockton Sandspit	-32.883566, 151.790257	G. Little and L. Williams
02 Jan 2024	12:17	Stockton Sandspit	-32.883566, 151.790257	T. Elks
9 March 2024	8:27	Phoenix Flats	-32.845843 151.714384	A. Stuart, R. Zimmerman, J. Garnham

[1]Transmitter was present

DISCUSSION

The pattern of detections on a fixed array of motus stations across the Hunter Estuary revealed that a first-year Far Eastern Curlew shifted from foraging in an area of intertidal habitat interior to Ash Island to foraging in the tidal mudflat in Fullerton Cove around the time when curlews leave the Hunter Estuary to begin their migratory northbound journey (in April). The habitat shift occurred approximately a week prior to the bird's last detection which would have coincided either with the tag falling off, or the bird leaving the estuary.

Milhams Pond is an area of intertidal habitat on Ash Island with a history of shorebird habitat management. Tide water enters the Milhams Pond system along creek lines flanked by mangroves that link the area to the south arm of the Hunter River. To address an increasing encroachment of mangroves into existing saltmarsh in the early 2000s associated with increasing tidal influence (Herbert 2007), the area was cleared of mangroves in 2009 and Mangrove Propagule Exclusion Devices placed along creek lines where tidal waters enter (Clarke 2009). The area now undergoes annual manual mangrove seedling removal (Clarke 2009; 2010; 2011). There is currently an area of mud below the saltmarsh where tidal inundation is more frequent. Ongoing low-tide surveys at Milhams Pond indicate that the mud is typically used by a small number of Far Eastern Curlew (typically < 10) to forage, in contrast to the large numbers of curlew (typically up to 85) regularly found foraging in Fullerton Cove (Williams *et al.*, in preparation). Sediment penetrability is a reliable predictor of foraging substrate selection in Far Eastern Curlew and biomass intake rate increases as substrate resistance decreases (Congdon & Catterall 1994; Finn *et al.* 2007). The restored mud flat at Milhams Pond is not only a much smaller area, its top layer of soft mud is also replaced at around a depth of 15 cm with a very compact clay layer, which is much harder to penetrate than the large expanse of very soft, >1 m deep mud in Fullerton Cove (ASG pers. obs.). While in need of further research, this substrate difference may contribute to explaining why Milhams Pond is used less than Fullerton Cove (Williams *et al.*, in preparation), while also suggesting that some individuals, like the tagged bird studied here, forage in less optimal habitat. The exact date on which Far Eastern Curlew leave the Hunter Estuary is not known but typically occurs around early to mid-April. This implies that the curlew's shift to the more commonly used natural mudflat at the end of April may have occurred around or after the time when most curlew were leaving the estuary.

While past work has recorded low instances of intraspecific aggression in this species, the usage of potentially sub-optimal foraging substrate, and a shift to a potentially more optimal foraging substrate around the time when population density would have been decreasing raises the question of whether more subtle social interactions may be influencing access to feeding sites by some individuals (Finn 2010). The individual studied here was a young bird, which may explain why it foraged away from the larger group. Our study calls for more work to compare foraging habitat quality across mudflats with different tidal dynamics and their usage by individuals of different sex and age classes to assist evidence-based land management decisions and shorebird conservation, particularly to prepare for sea level rise.

This case study illustrates how effectively a strategically-designed array of automated telemetry stations, combining omni and directional antennas, can quantify habitat use by shorebirds at a regional level. Automated telemetry yields high temporal resolution, low spatial resolution presence/absence information continuously every day. While the system differs from Global Positioning Satellite technologies that calculate flight paths with varying degrees of accuracy, we argue that conservation of shorebird habitat at the regional level does not typically depend upon detailed path information. Knowing which areas are used, by which species, how often, and for what, is adequate to ensure that critical low-tide feeding, and nocturnal roosting grounds are identified and that investment in protection is guided by relative usage. In the present study, the transmitter yielded 29 days of information. Lotek nanotags set to pulse every few seconds, like the one used here, have battery durations of many months. Hence, that the bird was not tracked for longer was no doubt a result of our attachment method (glue versus harness) and not a limitation of the technology. Careful consideration should be given to attachment methods to make sure the benefit to cost ratio is maximised. In our case, we sought to minimise animal welfare impact while still obtaining enough information to unveil light- and tide-dependent patterns of habitat use. Shorebirds are known to use foraging and roosting grounds repeatedly so shorter periods of tracking can be sufficient to yield the necessary information. Not only did motus yield new knowledge of habitat use, it was also a technically highly reliable system. While the bird was only tracked within the confines of the estuary, the system functioned with high reliability and yielded data every day. While spatial coverage of our motus array is limited, this is not a limitation of the technology per se, but rather of how we are currently using it. Not only can stations be added or moved around to increase coverage, the collaborative nature of motus automated telemetry means the more researchers using it, the greater the economy of scale (Griffin *et al.* 2018). Lastly, the comparatively low-cost of motus automated telemetry make this technology well suited to addressing questions related to individual variation like those raised by the present study, and it is, in fact, currently the only technology that can be used on very small shorebirds.

CONCLUSION

Using motus automated telemetry, this study was able to demonstrate for the first time in this region of Australia repeated foraging in an area of restored intertidal mudflat located on the interior of an island, and also a shift to a potentially higher quality large soft-sediment mudflat open to more tidal influence from the ocean. These patterns call for more research to identify the ecological and social drivers of foraging habitat selection by shorebirds.

PERMITS AND FUNDING

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AUTHOR CONTRIBUTIONS

ASG, CG, LAW and MT contributed to deploying the motus stations and assembling detection data. ASG, CG, LAW and MT wrote the manuscript. CG conducted the analysis of motus detections with the guidance of ASG. All authors contributed to the inception of the project and the significant catching effort required to attach tags to shorebirds.

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