First description of the ranging behaviour of Asian woollynecks *Ciconia episcopus* using GPS tracking in Cambodia

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មូលន័យសង្ខេប

យើងបង្ហាញការពិពណ៌នាលើកដំបូងអំពីអាកប្បកិរិយានៃការកំណត់តំបន់ក្រោយប្រលែងសត្វកុកពាក់អំបោះ *Ciconia episcopus* ចំនួនបួនក្បាលដែលបានប្រលែងក្នុងព្រៃរបោះជម្រុះស្លឹក នៅដែនជម្រកសត្វព្រៃសៀមប៉ាងនៃព្រះរាជាណាចក្រកម្ពុជានាឆ្នាំ២០១៩។ សត្វកុកពាក់អំបោះចំនួនបីក្បាលត្រូវបានជួយសង្គ្រោះពីការជួញដូរខុសច្បាប់ រីឯសត្វកុកមួយក្បាលទៀតត្រូវបានបង្កាត់ និងថែរទាំក្នុងទីបង្កាត់រយៈពេលប្រាំឆ្នាំមុននឹងធ្វើការប្រលែង។ សត្វកុកពាក់អំបោះទាំងបួនក្បាលត្រូវបានភ្ជាប់ជាមួយឧបករណ៍ GPS ដើម្បីអង្កេតពីអេកូឡូស៊ី និងទំនោរទីជម្រករបស់ពួកវាក្រោយធ្វើការប្រលែង។ យើងបានគណនាព្រំខណ្ឌតំបន់រស់នៅរបស់ឯកត្តៈនីមួយៗដោយប្រើវិធីសាស្ត្របីផ្សេងគ្នា (minimum convex polygon, kernel-density estimation, និង Brownian bridge) ហើយបានសិក្សាពីទំនាក់ទំនងរវាងឥរិយាបទដែលបានកត់ត្រា និងវត្តមាននៃអូរ វាលស្រែ និងថ្លុកទឹក។ ដោយរួមបញ្ចូលវិធីសាស្ត្រទាំងអស់ យើងបានរកឃើញតំបន់ប្រើប្រាស់ស្នូលដូចដែលបានកំណត់ដោយរបាយបម្រើបម្រាស់ (UD=50%) ដែលមានរបាយពី ២.៣ គម² ទៅ ៥០.៦ គម² ($\bar{x}$=15.66, SD=13.76) ចំណែកឯព្រំខណ្ឌតំបន់រស់នៅត្រូវបានកំណត់ដោយ UD=95% លាតសន្ធឹងពី ៨.២ គម² ទៅ ២៥៤.៥ គម²($\bar{x}$=89.22, SD=66.00)។ តំបន់រស់នៅមានទំនាក់ទំនងវិជ្ជមានជាមួយវត្តមានព្រៃឈើ ហើយមានទំនាក់ទំនងតិចតួចជាមួយវត្តមានវាលស្រែ និងថ្លុកទឹក។ ភាពរស់រានមានជីវិតរបស់សត្វកុកពាក់អំបោះពីរក្បាលអស់រយៈពេលបួនឆ្នាំ និងការបង្កាត់ពូជដោយជោគជ័យក្នុងព្រៃបង្ហាញពីការស្តារឡើងវិញនូវសត្វកុកពាក់អំបោះដែលបានរឹបអូសមកមានតម្លៃអភិរក្ស ហើយដែនជម្រកសត្វព្រៃសៀមប៉ាង និងតំបន់ការពារផ្សេងទៀតនៅព្រះរាជាណាចក្រកម្ពុជាជាកន្លែងសមស្របសម្រាប់នាំត្រឡប់មកវិញនូវប្រភេទសត្វកុកពាក់អំបោះ។

Abstract

We present the first description of the post-release ranging behaviour of four Asian woollyneck storks *Ciconia episcopus* released in 2019 in the deciduous dipterocarp forests of Siem Pang Wildlife Sanctuary, Cambodia. Three of the birds were rescued from illegal trade as chicks and the fourth was captive bred and rehabilitated in captivity for five years before release. The birds were fitted with GPS trackers to investigate the ecology and habitat preferences of the species after release. We calculated home ranges for each individual using three different methods (minimum convex polygon, kernel-density estimation & Brownian bridge) and studied correlations between recorded positions and the presence of streams, rice fields and waterholes. Combining all methods, we found core-use areas as defined by utilization distribu-

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tion (UD=50%) ranged from 2.3 to 50.6 km^2 ($\bar{x}$=15.66, SD=13.76), whereas home range as defined by UD=95% extended from 8.2 to 254.5 km^2 ($\bar{x}$=89.22, SD=66.00). There was a positive correlation with the presence of forest streams and a weaker correlation with the presence of rice fields and waterholes. Survival of two birds for four years and successful breeding in the wild demonstrates that rehabilitation of confiscated Asian woollynecks has conservation value and that Siem Pang Wildlife Sanctuary and equivalent protected areas in Cambodia are suitable reintroduction sites.

Keywords Asian woollyneck, Cambodia, *Ciconia episcopus*, home range, kernel density, woolly-necked stork.

Introduction

The Asian woolly-necked stork or Asian woollyneck *Ciconia episcopus* [Boddaert, 1783] (Fig. 1) occurs as *C. e. episcopus* in South and Southeast Asia and *C. e. neglecta* in Indonesia. Depending on the source, the species is usually split from its counterpart, the African woollyneck *C. microscelis*, based on geographical separation and remains one of the least studied waterbird species in the world (Sundar, 2020). Most studies concerning Asian woollyneck have been conducted in South Asia (India, Nepal & Bangladesh) (Sundar, 2006; Hasan & Ghimire, 2020; Roshnath & Greeshma, 2020; Ghimire *et al*., 2022), where the species inhabits a variety of habitats over a wide range, thrives in anthropogenic landscapes and the population is considered at least stable (Hasan & Ghimire, 2020; Roshnath & Greeshma, 2020; Win *et al*., 2020). As a consequence, the IUCN threat category for the species has recently been downgraded from Vulnerable to Near Threatened to reflect these findings (BirdLife International, 2023). However, in Southeast Asia, the population is thought to have undergone a considerable decline and the species' range is presumed to have contracted due to multiple factors including habitat loss, hunting and nest disturbance (IUCN, 2020). Contrary to what is observed in South Asia, it has also been proposed that habitat destruction and degradation, and conversion to agriculture has been the leading driver of the decline in Southeast Asia (IUCN, 2020). Habitat use and occupation of human modified landscapes has not yet been studied for populations in Southeast Asia and it is unclear what role they really play in the species ecology. The reality is that the species is poorly studied and as such, the lack of information on its behaviour, ecology and breeding success in Southeast Asia hinders its conservation and requires specific scientific and conservation attention (Ghimire *et al*., 2021a). It is also likely that the best conservation outcomes will be achieved by specifically addressing local particular threats.

At a national level in Cambodia, Asian woollyneck has been listed as Near Threatened (Goes, 2013). As elsewhere in Southeast Asia, conservationists lack reliable data to assess the population or range, as a census has yet to be undertaken. Occurrence data from the Global Biodiversity Information Facility (GBIF, 2023) suggests a decreasing population since 2017 (Fig. 2), but it is not possible to determine the Cambodian population trend from this data alone as it is biased by the number of observers or locations surveyed. In Siem Pang Wildlife Sanctuary (SPWS), the location of every sighting of the species has been recorded since November 2021. Histori-

Fig. 1 Asian woollyneck fitted with a GPS-GSM tracker on a nest in Siem Pang Wildlife Sanctuary, 2023.

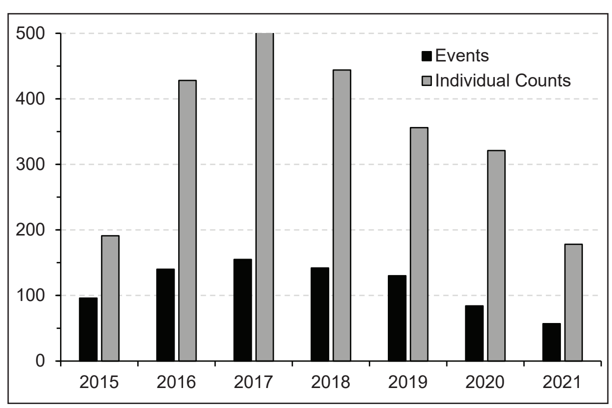

Fig. 2 Frequency of records in GBIF for Asian woollyneck in Cambodia, 2015–2021.

cally the species has been recorded breeding in Pong Kreel village (Eames, 2014) with one nest found along the O'Khampa river in 2021. Yet large numbers were recorded in the area in the past, with as many as 44 seen in a single flock over the sanctuary on 16 June 2010 (Eames, 2014) and a flock of 15 in July and 22 in October 2020. In 2022, 92 sightings were recorded, suggesting a total of 212 birds and a maximum of nine at the same time (Rising Phoenix, unpubl. data). Asian woollyneck has been identified as a species population in SPWS that could benefit from reinforcement from a captive source (Gray *et al*., 2019). Informed conservation of the species in SPWS requires at least a basic understanding of its ecology and habitat preferences and it is with this in mind that four Asian woollynecks were fitted with GSM-GPS trackers and released in SPWS in 2019. Habitats in SPWS were deemed suitable for the species given the numerous previous records and it was expected that the birds released would settle a short distance from the release site due to their captive origin. The aims of our study were to evaluate the survival of captive birds released in a new environment, to improve understanding of their ranging behaviour and habitat preferences and to compare soft-released and hard-released animals. Obvious limitations included a small sample and that birds of a captive origin may behave differently from wild birds. Initial planning included augmenting our sample size by annually releasing additional storks under the same conditions in subsequent years.

The concept of animal home ranges has experienced a new research boom in the last two decades, as demonstrated by a significant number of studies concerning the ranging behaviours of more and more species (Mertzanis *et al*., 2011; Silva-Opps & Opps, 2011; Ram *et al*., 2022). Home range was originally defined as the "area traversed by the individual in its normal activities of food gathering, mating and caring for young" (Burt, 1943). It has now given way to a more statistical approach, most commonly defined as "densities of use", that reflect estimates of the locations of an animal across a landscape (Powell, 2000; Laver & Kelly, 2008; Powell & Mitchell, 2012). The development of GPS technologies and their miniaturization have greatly improved our ability to track animal movements over large temporal and spatial scales (Bridge *et al*., 2011; Udyawer *et al*., 2018), allowing researchers to refine and improve knowledge of habitat species preferences. These have especially been an asset in the study of elusive or migratory species.

Several methods have been developed to calculate home range, although the two most common approaches are traditionally the minimum convex polygon and the kernel-density estimation (Worton, 1987; Laver & Kelly, 2008). Minimum convex polygon continues to be used for comparative purposes, although the technique has numerous biases (Börger *et al*., 2006; Nilsen *et al*., 2008). For example, minimum convex polygon may overestimate the actual home range by incorporating unused areas between peripheral locations or underestimate it if sampling duration is too short (Burgman & Fox, 2003; Getz *et al*., 2007). This is particularly a problem for migratory species or species that travel between feeding and nesting grounds and explains why kernel-density estimation is often preferred for estimating a species home range (Fieberg & Börger, 2012). However, the main issue with the kernel-density estimation model lies in the selection of a proper bandwidth and the assumption that locations are not correlated, which is not respected for data recorded from animals equipped with GPS devices (Nelson, 2011; Walter *et al*., 2011). The Brownian bridge movement model, an evolution of the fixed kernel-density estimation method, appears to solve the problem of autocorrelation as it also considers the time between successive locations in estimation of the utilization distribution (Horne *et al*., 2007) and is of particular interest for migratory species. However, for species that occupy a relatively small home range, area differences calculated by the different models are likely to be small (Fieberg & Börger, 2012).

In this study, we present the first description of post-release ranging behaviour of four Asian woollynecks in Cambodia using GPS tracking. In doing so, we provide results of home range calculations for this species using different methods to allow for greater comparison with other studies, as well as spatial correlation analysis between recorded positions and the presence of streams, rice fields and waterholes.

Methods

Study area

Siem Pang Wildlife Sanctuary is a 130,000 ha (1,300 km²) protected area in Stung Treng Province, Cambodia. It has been identified as a Key Biodiversity Area (Tordoff *et al*., 2012) and was designated as a wildlife sanctuary in 2016. The sanctuary is bordered to the north and west by the Xe Pian National Park (2,400 km²) in Laos and to the east by Virachey National Park (3,380 km²) in Cambodia. Habitats in SPWS include a mosaic of deciduous dipterocarp forest which account for 50% of the sanctuary and semi-evergreen forests which comprise 40%. The remaining area comprises degraded forests or grassland (8%) and riverine habitat (2%) (BirdLife International Cambodia Programme, 2012). The sanctuary's connectivity with neighbouring protected areas is a conservation asset, in allowing animals to move between the different geographies (Brennan *et al*., 2022).

Equipment and satellite tracking

Four Asian woollynecks (ACCB local ID numbers 0160009, 0160010, 0160012 and 0160015, hereafter WNS 09, WNS 10, WNS 12 and WNS 15, respectively) were released in October 2019 in SPWS following a protocol designed by the Angkor Centre for Conservation of Biodiversity (ACCB), a conservation centre of the Allwetterzoo Münster, Germany. All individuals were sourced from ACCB where they were either captive bred (WNS 12) or had been rescued from the illegal wildlife trade as chicks (WNS 09 & WNS 10) or a sub-adult (WNS 15) and rehabilitated between 2014 and 2015. Two of these were hard-released directly into the wild on 29 October, without previous acclimatization or supplementation (WNS 12 a female and WNS 10 a male) and two were soft-released (WNS 09 a male and WNS 15 a female). Hard release usually excludes any training, but in our protocol, we ensured that our hard-released birds were able to catch live prey and did not exhibit imprinted behaviour before release. Conversely, soft-release normally includes an acclimatization period, pre-release animal training and post-release food supplementation (Resende *et al*., 2021), whereas in our protocol, our soft-released birds were kept in an aviary in the sanctuary and fed with live prey for one month until their release on 6 November. Supplementary food was also offered for one week after release and then discontinued as the storks did not return to the aviary. Birds were sexed by DNA testing on feather samples collected at ACCB and analysed in Germany. Before their release, all four birds were fitted a solar-powered OrniTrack-25 GSM-GPS tracker (Ornitela, Vilnius, Lithuania) which was attached with a teflon ribbon. The total weight of the system was 33g, representing 1.65% of the body weight of each bird (2 kg), less than the 3% usually deemed acceptable for this kind of tracking (Murray & Fuller, 2000; Kenward, 2001; Barron *et al*., 2010). Following the same protocol, a fifth bird (a male Asian woollyneck, WNS 0160002) was hard-released on 4 December 2020. Rescued from the illegal wildlife trade, this bird arrived at ACCB in December 2009 and hence was at least 11 years old at the time of release. Release sites in the sanctuary were chosen in deciduous dipterocarp forest, not far from cultivated areas located on the edge of SPWS, as it was anticipated that the birds might favour a mix of both habitats.

We programmed our transmitters to record a GPS position every three to six hours depending on the battery load and to attempt to transmit data by GPS every three hours. Because of these restrictions, we did not extract a daily time-budget from our data and all datapoints were pooled in analysis, irrespective of their time of day (morning, afternoon or evening).

Home range calculations

Data were processed in R 4.2.2 (R Core Team, 2022) using the adehabitatHR package (Calenge, 2006) and ArcGIS Pro for graphical presentation. Prior to calculations, coordinates in our datasets were converted in R from WGS 1984 to UTM 48N. A total of 67,944 raw positions were recorded from four storks (WNS 09=27,729 logs, WNS 10=4,126 logs, WNS 12=7,605 logs, WNS 15=28,484 logs). These data were cleaned by removing logs that lacked latitude or longitude coordinates, were triangulated by less than three satellites, where recorded speed was higher than 90 km/h and logs with inconsistent figures for altitude (i.e., under -200m or over 1,000m). Data points obtained before release were also removed (before 29 October 2019 for WNS 12 and WNS 10 and before 6 November 2019 for WNS 09 and WNS 15), as well as outliers. The tracker of the fifth bird (WNS 0160002) released in December 2020 was not fully functional and recorded only 57 datapoints between 5 December 2020 and 26 January 2021 and was not included in the study. This stork was found dead of unknown causes in February 2021 at which point the tracker was recovered.

We calculated home range using three methods, the minimum convex polygon (MCP) method, the kernel-density estimation (KDE) method and the kernel-density Brownian bridge method (BBM). Home ranges were calculated for the dry season (November to April) and the wet season (May to October) using the three methods, as it was hypothesized that habitat use would differ seasonally, consistent with variation in habitat use observed for the species in India and Nepal (Kittur & Sundar, 2020; Roshnath & Greeshma, 2020; Tiwary, 2020). It should be noted that each method has its own biases, which is why they are often used in combination for comparative purposes. For instance, MCP often overestimates home ranges as it includes outermost locations and so includes areas that an animal never uses (edge effect). The KDE method is heavily influenced by the bandwidth parameter and is also subject to edge-effect, whereas BBM requires a high frequency of location data to accurately estimate home range and assumes that the movement of an animal follows a Brownian motion model, which may not always be accurate. These biases are usually balanced by confining the analysis to a smaller utilization distribution. In our study, core-use area was defined as the 50% isopleth area of the utilisation distribution and home range as the 95% isopleth area. Those thresholds are standard in ecological research and are commonly used to facilitate comparisons between studies and species as they balance precision and accuracy and may be of behavioural relevance in often corresponding to areas of highest use (Laver & Kelly, 2008; Silva-Opps & Opps, 2011; Abril-Colón *et al*., 2022; Lee *et al*., 2022).

In employing the KDE method, we set the smoothing parameter *h* to *href*. For BBM, we calculated the smoothing parameter *sig1* related to the speed of the animal using the function *liker* to estimate *sig1* using the maximum likelihood approach (Calenge, 2006; Horne *et al*., 2007). The *liker* function determines the most likely path an animal took between observed locations, which in turn helps estimates the better-suited smoothing parameter *sig1*. We then used a Mann-Whitney test to compare home ranges provided by the different methods and to compare these between seasons and sexes.

Spatial regression analysis

Spatial regression analysis was conducted in ArcGIS Pro v3.0.3 (Esri Inc., California, USA). A rectangular grid of 139,435 cells each measuring one hectare was created, covering all positions recorded of storks within and outside of SPWS. Shapefiles of known rivers, trapeangs (seasonal waterholes) and rice fields were obtained. These features were selected due to higher detection of storks around streams and trapeangs inside the sanctuary, and because of the hypothesized importance of rice fields, as demonstrated in South Asia (Kittur & Sundar, 2020; Ghimire *et al*., 2021b). Forest cover and land cover were not employed as variables, as deciduous dipterocarp forest is the dominant landscape in the area. The analysis was undertaken by fitting a Poisson model using the number of GPS logs in each cell as the dependent variable, and the presence of a stream, a waterhole, or a rice field as the explanatory variables. The same protocol was used to explore spatial correlation of 107 positions of stork sightings recorded by Rising Phoenix staff between November 2021 and July 2023.

Ethics

Every precaution was taken during the reseach to minimize stress and disturbance to the study birds. The weight of the transmitters and the fitting method were chosen in accordance with standard protocols and recommendations. Handling was minimal and undertaken by professionals. Release protocols were designed to maximize the chances of each individual returning successfully to the wild according to the IUCN/SSC (2013) and were approved by the Forestry Administration of the Cambodian Ministry of Agriculture, Forestry and Fisheries and the Cambodian Ministry of Environment.

Results

Following cleaning of datasets, a total of 65,468 data points remained inside the boundaries of 13.99–14.32°N and 106.12–106.42°E for analysis (WNS 09=26,527 logs over 1,364 days, WNS 10=3,963 logs over 196 days, WNS 12=7,243 logs over 463 days & WNS 15=25,454 logs over 1,364 days). The last recorded movement of WNS 10 occurred on 11 May 2020, 196 days after hard release, after which the bird was found dead and the tracker recovered on 2 June 2020. The last recorded position of WNS 12 occurred on 3 February 2021, 464 days after hard release (battery was 94% charged) and the last data transmission was on 13 February 2021, indicating a low battery. The latter tracker was not recovered and the fate of the stork is unknown. The trackers of WNS 09 and WNS 15 trackers remain active at the time of writing, over three years and nine months after their soft release.

We considered that the birds would be settled into their new habitats by the end of December 2019, more than a month after release. At that time (mean position from 25–31 December 2019), three of the birds had moved an average of two kilometres from their release site (WNS 09=1.4 km, WNS 10=2 km, WNS 12=2.6 km), whereas WNS 15 had flown 12 km to the west. At the start of September 2023, both of the remaining tracked birds had paired with wild individuals within the sanctuary, with two chicks successfully fledging from one of the two nests.

Home ranges

Combining all methods, core-use areas (defined as 50% of the utilization distribution) ranged from 2.3 to 50.6 km^2 ($\bar{x}$=15.66, SD= 13.76), whereas home ranges (defined as 95% of the utilization distribution) extended from 8.2 to 254.5 km^2 ($\bar{x}$=89.22, SD=66.00) (Table 1, Fig. 3).

WNS 10 and WNS 15 had the smallest and largest home ranges respectively, regardless of season (Fig. 4). Home ranges in the wet season (May to October) were not significantly smaller than the dry season (November to April) (Mann-Whitney test, p>0.05). Ranges calculated using MCP for 50%, 90% and 95% of the utilization distribution were always larger than those provided by KDE and BBM, although not significantly and the differences in ranges provided by KDE and BBM were not significant. Additionally, no significant differences in range size were found between soft and hard released birds or between males and females. These results should be

Table 1 Home range areas for different percentages of the utilization distribution for four study birds. N/A indicates failure to successfully compute a test.

Home Range (km²)	WNS 09 (Male, hard release)			WNS 10 (Male, soft release)			WNS 12 (Female, hard release)			WNS 15 (Female, soft release)		
	50%	90%	95%	50%	90%	95%	50%	90%	95%	50%	90%	95%
Minimum convex polygon												
Dry & wet season	11.0	57.5	88.2	9.0	20.5	24.3	50.6	102.7	111.0	31.7	199.1	248.5
Dry season	14.2	72.1	136.2	8.6	19.8	22.9	28.0	95.4	101.6	49.6	179.5	254.5
Wet season	8.7	27.0	50.5	3.1	8.0	8.2	36.7	55.5	61.2	14.4	101.5	162.4
Kernel-density estimation												
Dry & wet season	2.3	30.5	42.2	6.0	19.8	24.3	17.8	61.1	81.1	16.8	81.3	106.5
Dry season	11.4	57.1	82.3	5.7	19.5	23.8	15.6	58.9	76.7	23.2	100.3	133.8
Wet season	0.0	21.1	30.5	5.7	20.6	27.0	14.3	51.8	69.7	9.7	52.2	67.7
Brownian bridge movement												
Dry & wet season	8.4	52.4	78.7	3.7	18.1	23.9	9.5	52.2	72.2	21.1	109.6	169.2
Dry season	20.4	7.4	N/A	3.8	18.1	23.7	19.9	820.2	N/A	40.4	1753.7	N/A
Wet season	11.5	N/A	N/A	7.6	N/A	N/A	9.2	N/A	N/A	26.3	N/A	N/A

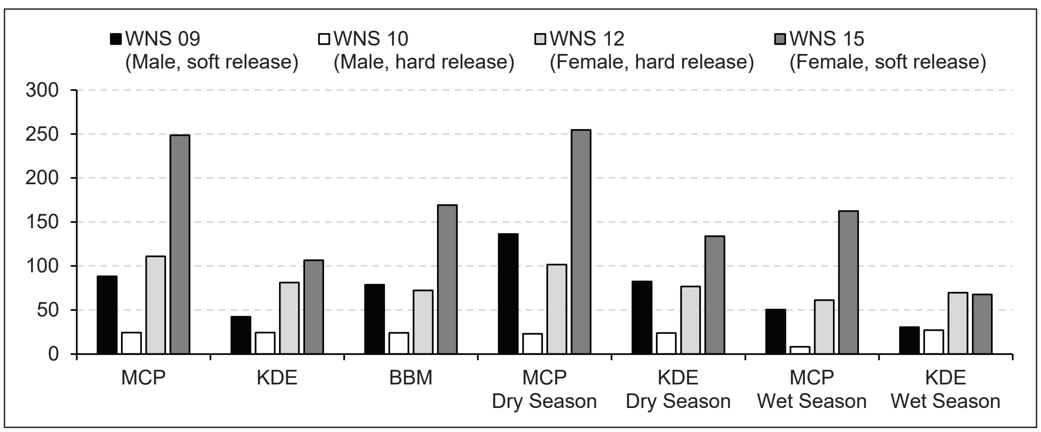

Fig. 3 Home ranges in km² (95% of utilization area) of study birds by season using different estimates.

regarded with caution however, considering our sample comprised only four individuals.

Spatial regression analysis

A generalized linear regression undertaken using the number of GPS logs in each cell as the dependent variable and the presence of a rice field, a waterhole or a river as explanatory variables returned respective log coefficients of 0.502, 0.808 and 1.079 (Table 2), all of which were statistically significant at $p<0.01$. These results indicate that all else being equal, we observed a positive correlation between the presence of storks and the three explanatory variables, with the presence of a river being the most strongly associated (Fig. 5). Moran's I index value was 0.5 and z-score was 265.4, indicating spatial auto-correlation of the data.

Performed on our set of 107 sightings, the same analysis returned log coefficients of 0.247 for rice fields, -11.342 for waterholes and 0.520 for streams (Table 3). As such, the occurrence of storks and presence of rice fields and streams was positively correlated, with no or very little correlation with the presence of waterholes (expo-

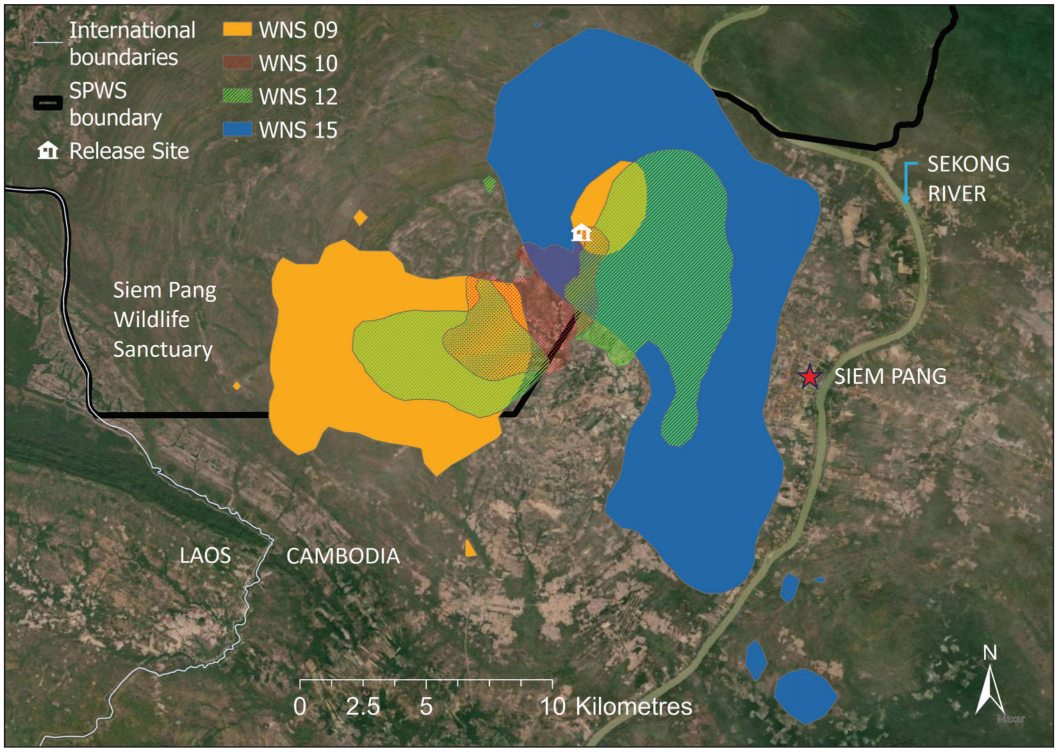

Fig. 4 Home ranges of four study birds based on 95% of utilization area and Brownian bridge method.

Table 2 Results of model of habitats in locations recorded for four study birds.

Variable	Coefficient	Standard Error	z	*p*
Intercept	-0.986	0.004	-218.024	<0.01
Rice fields	0.502	0.005	99.584	<0.01
Waterholes	0.808	0.045	17.574	<0.01
Streams	1.079	0.008	134.861	<0.01

Table 3 Results of model for habitats of Asian woollyneck sightings from November 2021 to July 2023.

Variable	Coefficient	Standard Error	z	*p*
Intercept	-7.040	0.095	-73.997	<0.01
Rice fields	0.247	0.156	1.581	0.114
Waterholes	-11.342	482.122	-0.024	0.981
Streams	0.520	0.240	2.167	0.030

nentiated coefficient of 0.000012). However, only the correlation with waterways was statistically significant at $p<0.05$. Further, the standard error for the presence of waterholes was very large, indicating that this estimate is very imprecise.

Discussion

We tracked four Asian woollynecks over a period of three and half years, from their release in October 2019 to July 2023. Based on the data collected, these individuals were sedentary and spent significant time in SPWS. One month after release, three of the four individuals had settled less than 3 km from the release site, which could reflect the captive habituation of the birds but also indicates the availability of suitable habitat for the species. The two storks that were soft released remain alive after 3.5 years with active trackers and bred in 2023. This proves that captive-reared woollynecks can survive to breed in the wild. Of the two storks that were hard released, one was found dead almost 200 days afterwards and contact with the transmitter of the other bird was lost after more than 15 months. It is difficult to draw significant conclusions as our sample is very small, but this suggests that soft release may be beneficial for the long-term survival of

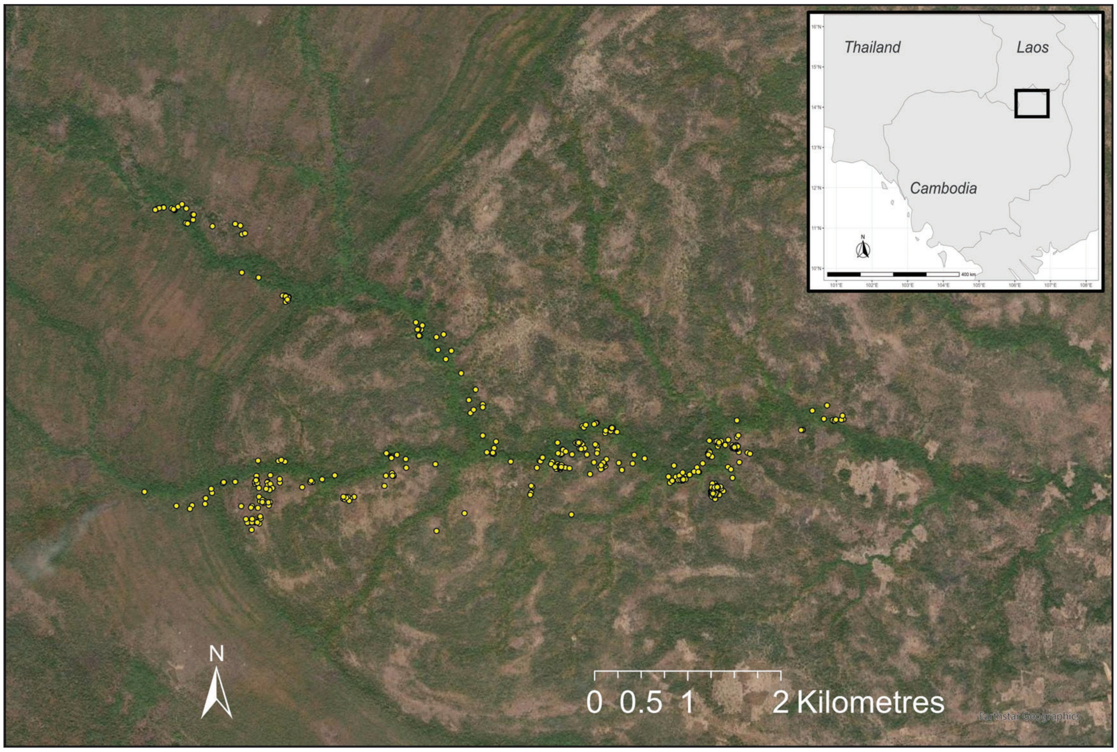

Fig. 5 Data points for WNS 09 in April 2020 (dry season), highlighting the occurence of the bird in the immediate vicinity of watercourses, which are dry at this time of year.

released birds. Our study also demonstrates that SPWS provides suitable habitat for rehabilitated and released Asian woollynecks, as we also documented breeding of released birds with wild partners. Release of additional individuals of this and other stork species should be considered to strengthen local populations.

To our knowledge, we provide the first estimate of the core-use and home range areas for Asian woollynecks. As our results are based on captive released birds, it would be interesting to compare our results with metrics obtained from wild birds. We found MCP 50% was 25.6 ± 19.6 km^2, MCP 90% was 95 ± 77.1 km^2, MCP 95% was 117.75 ± 94.4 km^2 and KDE 95% was 63.5 ± 37.1 km^2 (Table 2). Of the eight species in the *Ciconia* genus, white storks *C. ciconia* have been the most studied. Zurell *et al*. (2018) found the home range of the species was variable with an overall mean of 78.3 ± 219.9 km^2 for MCP 95%. No significant differences in home range were found between sexes, locations or years, whereas breeding status significantly reduced home ranges, consistent with findings for other bird species (Tanferna *et al*., 2013; Stenhouse & Moseby, 2023). Mean MCP 95% was 21.4 ± 29 km^2 for breeding individuals, compared to 205.8 ± 80.5 km^2 for non-breeding storks. This likely reflects pressure to gather food to feed young under time and movement constraints, whereas non-breeding birds are relieved from such constraints (Johst *et al*., 2001; Zurell *et al*., 2018). As the breeding status of our study birds was uncertain, we did not investigate home range in this context.

Xu *et al*. (2021) studied four juvenile Oriental white storks *C. boyciana* which were tagged in the nest in the wetlands of Xingkai Lake National Reserve in China and followed by telemetry in the wild before they migrated. They found that the core home range (50% MCP) of fledglings ranged from 0.08 to 6.15 km^2, whereas the 95% MCP ranged from 6.10 to 14.24 km^2. The birds were tracked for 31 to 44 days in summer and provided 3,253 locations in marsh meadow habitats. In studying the reintroduction of *C. boyciana* in Japan, Ezaki & Sagara (2014) calculated a home range (90% MCP) of less than 12.5 km^2 for seven breeding pairs, which was centred around the nest. This contrasts with Jiguet & Villarubias (2004) who found a mean core range of 538.5 ± 278.58 km^2 (core range defined as 75–95% of the utilization distribution, based on fixed kernel density estimation) for 12 black storks *C. nigra* of varying status (breeding, non-breeding, young and adults). They also noted that range sizes between breeding and non-breeding adults were similar.

Our results suggest that *C. episcopus* may occupy a smaller home range compared to *C. nigra* and *C. ciconia*, but a larger one compared to *C. boyciana*. Asian woollynecks occur in the tropics where food availability per unit of area may be greater than temperate latitudes where the other species occur. A smaller home range could be expected for this tropical species, but this was not the case compared to *C. boyciana*. This could be due to the small sample size of both studies, alongside other limitations inherent to these. For instance, Jiguet & Villarubias (2004) studied free-living black storks, whereas Xu *et al*. (2021) studied fledglings of oriental white storks in the first days of flight and our study concerns captive-released adult birds. This is a major caveat which may bias our understanding of ranging behaviour. Indeed, birds released from captivity often tend to range around release sites (Wilson *et al*., 1992; Van Heezik *et al*., 2009), although this is not always observed and may be species dependent and influenced by variables such as the presence and density of conspecifics around the release site (Lockwood *et al*., 2005). It should also be noted that species have differing breeding habits that may influence their home range. For example, *C. ciconia* breeds in colonies and may have to share resources with other breeding pairs, increasing its foraging area. *Ciconia nigra* and *C. episcopus* are solitary breeders but do not depend on the same habitats as *C. nigra* uses temperate forests, which could also account for the higher home range. Consequently, it must be kept in mind that our results should be regarded as preliminary and that studies of entirely wild birds will be required to determine if these behave in similar ways. Furthermore, studies of wild birds are needed to understand the impact of captive released birds on wild populations and if such these releases could lead to populations with restricted or biased behaviours as a result of the released birds having been in captivity for a long period of time.

We found a positive correlation between the occurrence of storks and from the least to the strongest association, rice paddies, waterholes and streams. The correlation with streams seems obvious when visually displayed on a satellite basemap (e.g., Fig. 5). The positive Moran's index value of 0.5 indicates a moderate to strong spatial autocorrelation in the data, which is easily explained by autocorrelation of recorded GPS logs. This is unavoidable and warrants caution in interpreting the results of spatial regression. When comparing these results with analysis of visual sightings of storks in and around SPWS, we found the same positive association with streams and rice fields and no correlation with trapeangs. However, our sample only comprised 107 locations which is a relatively small data set. Both datasets indicate that the presence of waterways is the most useful indicator for the occurrence of Asian woollynecks and this should be considered in planning for future releases.

It is hard to draw definitive conclusions in relation to our release protocol or the sex of the birds due to our small sample size and a larger sample will be needed to improve understanding of how these factors may influence ranging behaviour. We hypothesized that the home range of the storks would vary seasonally in relation to food availability, water levels in waterholes or streams and/or breeding status. However, no significant differences were found, which is not consistent with observations in South Asia (Kittur & Sundar, 2020). Likewise, the home range of some of our birds overlapped at times during the first study year but it is unknown whether the birds actually interacted or not.

White storks frequently use artificial nests or artificial structures when nesting (Vaitkuvienė & Dagys, 2015; Bialas *et al*., 2020) and habitat quality and food availability are regarded as deciding factors for breeding success and positive population trends (Nowakowski, 2003). Numerous studies have shown *Ciconia* species (or at least *C. ciconia*, *C. boyciana* and *C. episcopus*) favour nesting close to human settlements and crops and are positively associated with traditional agriculture but negatively associated with pesticide use (Ezaki & Sagara, 2014; Kittur & Sundar, 2021; Xu *et al*., 2021). Our study suggests that Asian woollynecks in Cambodia may have habits similar to the species in Nepal, Myanmar and India where positive associations with agricultural landscapes have been reported (Sundar, 2006; Win *et al*., 2020; Ghimire *et al*., 2021b).

In Japan, friendly farming methods play an important role in conserving reintroduced oriental white storks by preserving biological diversity and sufficient prey to support their feeding in paddy fields (Naito *et al*., 2014). These approaches could provide a solution for Asian woollyneck conservation in Cambodia. Wildlife-friendly agricultural practices that do not use pesticides are already in use in Siem Pang District as a result of the IBIS Rice scheme (Rising Phoenix, unpubl. data). Further development of farming methods to reduce or eliminate pesticide use could also be encouraged for conserve other waterbird species in Cambodia.

Reliable and increasingly smaller GPS trackers can provide very precise and frequent data on bird movements, allowing for better understanding of habitat preferences and ranging behaviour. Our successful use of data loggers on Asian woollynecks in SPWS demonstrates that the sanctuary provides suitable habitats, with sufficient foraging opportunities for the birds to settle at short distances from release sites and occupy a mean home range of <65 km^2 (KDE 95%). No significant differences were found home ranges between seasons or sex and the influence of breeding status could not be assessed. Further studies with a large sample size are needed to facilitate more robust estimates of the home range and habitat preferences of Asian woollynecks in Cambodia.

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