Journal of Environmental Management 373 (2025) 123508

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Will red-crowned cranes avoid coastal wind farms? A research based on satellite tracking in Yancheng coastal wetland

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ARTICLE INFO

Keywords:
Grus japonensis
Wind farms
Coastal wetland
Satellite tracking
Kernel density analysis

ABSTRACT

The number of wind farms operating along coastal wetland in East China has rapidly increased in recent years, and it may have an adverse effect on various large wading birds including red-crowned crane (*Grus japonensis*), such as collision mortality, flight changes, and habitat loss. The Yancheng coastal wetland, a Ramsar site, serves as a critical habitat for the vulnerable red-crowned cranes and is densely populated with wind turbines. Risks associated with wind-energy infrastructure are not well understood for red-crowned cranes. More than 20 captive-bred cranes were released into the Yancheng coastal wetland to augment wild crane population, and 6 of them were tagged by GPS for tracking their movement. We used 36,609 GPS locations to analyze their spatial response to coastal wind farms. Results revealed that the cranes concentrate their activities (89.64% of the 36,609 GPS locations) within the Yancheng National Nature Reserve for Rare Birds where there are no turbines. While there is some overlap between wind farms and red-crowned cranes, these cranes tend to avoid wind farms—the average distance from cranes to the nearest wind turbine was 6.97 km. This indicates that the collision risk between red-crowned cranes and wind turbines in the coastal wetlands of Yancheng is relatively low. However, this also means that the construction of wind farm has led to a reduction of suitable habitats for cranes.

1. Introduction

Wind energy is important in reducing carbon emissions and mitigating global climate change (Barthelmie and Pryor, 2014). However, numerous studies have shown that the construction of wind energy facilities can negatively impact birds (Drewitt and Langston, 2016; Wang et al., 2015; Laranjeiro et al., 2018). Collisions between birds and wind turbines and their associated facilities can result in direct mortality of the birds (Schuster et al., 2015; Loss et al., 2013; Grodsky et al., 2013; Aschwanden et al., 2018), besides the construction of these facilities can directly lead to fragmentation and functional loss of existing habitats (Pedrana et al., 2023; Marques et al., 2020). Observations from existing wind farms reveal that the construction activities often involve the removal of vegetation in the area. This loss of vegetation decreases the availability of habitat for birds, negatively impacting their nesting and foraging behaviors (Zhao et al., 2020). Additionally, the visual barriers, electromagnetic radiation, noise, and vibration associated with wind farms can indirectly affect bird distribution and habitat use (Pruett et al., 2009). Birds may avoid foraging, nesting, and roosting near the wind farm, and in some cases, even cease using relatively suitable habitats within the wind farm area altogether (Fox et al., 2006; Stenhouse et al., 2020). Consequently, both the number and diversity of bird species are significantly lower in areas with wind farms compared to regions without them (Cai et al., 2021).

With the rapid growth of the clean energy sector in China, the total installed capacity on the mainland has reached 474,600,000 kW, including 436,900,000 kW from onshore wind power and 37,700,000 kW from offshore wind power (Chinese Wind Energy Association, 2024). Yancheng, located along the Yellow Sea coast, is abundant in wind resources, with exploitable wind potential of 1,000,000 kW on its coastal beaches, establishing it as a national green energy hub (Tian et al., 2013). Yancheng Coastal Wetland is also a critical wetland ecosystem along the eastern coast of China, featuring the largest and most continuous area of muddy intertidal wetlands on the Pacific West Coast

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https://doi.org/10.1016/j.jenvman.2024.123508
Received 22 September 2024; Received in revised form 5 November 2024; Accepted 27 November 2024
Available online 4 December 2024
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and the Asian continental edge (Chinese Wind Energy Association, 2024; Hua et al., 2015). This makes it an essential habitat and migratory stopover for waterfowl, particularly large crane species (Chinese Wind Energy Association, 2024; Hua et al., 2015). However, the expansion of wind farms has raised concerns about risks for bird collisions in coastal wetland.

The red-crowned crane *Grus japonensis*, one of the 15 existing crane species in the world, is a flagship species for wetland conservation (Xu et al., 2020). It is primarily distributed in East Asia and is classified as a national first-class protected animal in China. In 2023, the red-crowned crane was assessed as a vulnerable species by the IUCN (IUCN, 2023). Recent unpublished reports from partners compiled via the International Crane Foundation suggest that the total global population may be closer to 4150 (Wu et al., 2024). In recent decades, due to habitat loss and degradation, human interference, climate change and other reasons, the distribution range of the western migratory population has gradually shifted towards the Yancheng National Nature Reserve for Rare Birds (YNNR) in winter, and the population size has shown a downward trend (Lin, 2021). Although no collisions with wind turbines have yet been reported for red-crowned cranes, this region also hosts 60% of the wind power industry in Yancheng coastal wetland (Gu et al., 2023)(Fig. S1). It is critical to assess the potential risks of wind farms on the survival of red-crowned cranes in this region.

In recent years, more than 20 captive-bred cranes have been released into YNNR to augment wild crane population, which can survive and even breed in the wild, and their offspring may also migrate with the wild population (Xu et al., 2020; Wu et al., 2024; Zhao et al., 2023). In this study, 6 of them were tagged by GPS for tracking their movement. We analyzed 36,609 GPS locations of these 6 individuals collected between November 2022 and November 2023. Our goal is to understand the relationship between the spatial movement of these cranes and the location of wind farms, and to explore their response to the presence of wind farms.

2. Methods

2.1. Study area

The study area is in the Yancheng National Nature Reserve for Rare Birds (YNNR) in Jiangsu Province and includes surrounding coastal wetlands (such as Dafeng David's Deer National Nature Reserve, Tiaozini Wetlands, and Chongmingdongtan National Nature Reserve), which extend from Xiangshui in the north to Chongming Dongtan in the south (31°26′4.7466"~34°29′51.3198"N, 119°42′0.8994"~121°59′10.0998"E) (Fig. 1). The YNNR follow the function zoning method of nature reserves in China, adopting in mode of "core zone-buffer zone -experimental zone" suggested by Man and Biosphere Reserve. Within core zone, no human activity is permitted. Within buffer zone, only a limited (but not clearly defined) amount of human activity is allowed. Within experimental zone, human development is allowed (including collaborative activities among researchers, managers, and local inhabitants) (Li et al., 1999). The study area is in the central part of the East Asian-Australasian Flyway (EAAF), one of the nine major migratory flyways in the world; this region provides important breeding, stopover, and wintering sites for millions of migratory waterbirds (Chinese Wind Energy Association, 2024; Hua et al., 2015). The YNNR in Jiangsu Province is in the transitional zone from the northern subtropics to the southern warm temperate climate of East Asia. It has a distinct monsoon climate with abundant sunlight and rainfall. The annual average temperature is 13.7–14.6 °C, and the annual average precipitation is 980~1050 mm (Xie et al., 2018). It is the largest wetland nature reserve in China with the primary purpose of protecting coastal wetland ecosystems, and it is an important habitat for many rare species, including red-crowned cranes (Xu et al., 2018). The Yancheng coastal wetland, where the reserve is located, is rich in flora and fauna, with 14 species of nationally protected wild animals at level I and 76 species at level II (Chen et al., 2023).

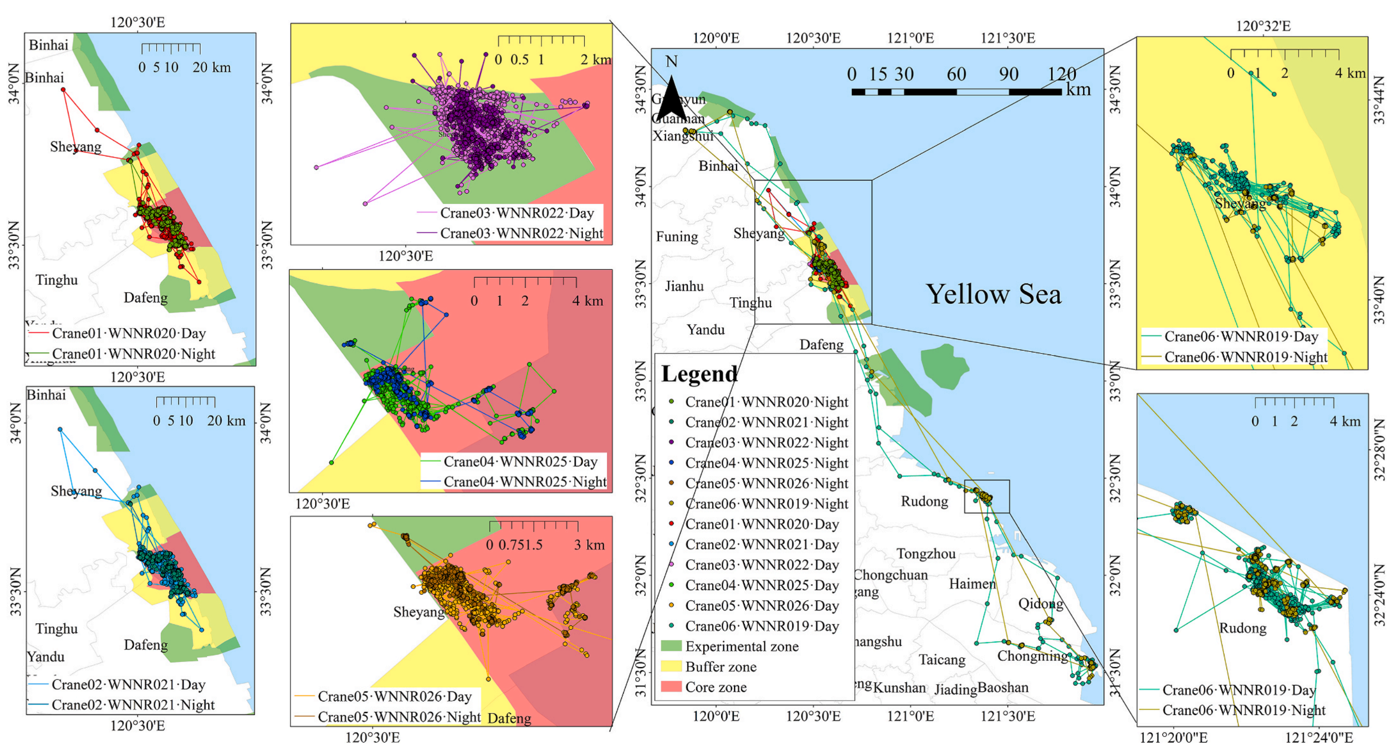

Fig. 1. The activity trajectories (day and night) of the GPS-tagged red-crowned cranes and the functional division of Yancheng National Nature Reserve.

2.2. Tagging and tracking cranes with GPS-GSM transmitters

For this study, we conducted field observations twice a week and collated GPS data from 6 red-crowned cranes (Table 1) tagged in 2022 and 2023. Among them, cranes 1, 2, and 3 were related to one another, with individual 3 being the offspring of cranes 1 and 2. Cranes 4 and 5 are in a spousal relationship. All the released cranes were bred in captivity within the YNNR and equipped with solar powered GPS-GSM transmitters. Release and GPS tracking have been approved by the local government and reviewed by the Experimental Animal Welfare and Ethics Committee of Nanjing Forestry University before being carried out in accordance with the law. Performed morphological measurements and gender identification before equipping the logger. The GPS-GSM leg-loop logger used were HQLG4037S, weighing less than 3% of the body weight of the red-crowned cranes. Positioning data were transmitted by GSM. Loggers were programmed to transmit timestamp, position, and height with a frequency of 1 h. The accuracy of locations was between 5 m and 2000 m. The GPS location data of three individuals were available for more than 300 days, two for more than 200 days, and one for more than 100 days. By utilizing the Global Messenger Tracking Data Service Platform, real-time monitoring of individuals was conducted (HQXS, 2019). The data, including the latitude and longitude, altitude (m), motion trajectory, instantaneous speed (km/h), temperature (°C), activity level, and positioning accuracy (m), were collected for the cranes. Only data with a positioning error of <10 m were retained.

A total of 36,609 GPS data were used in this study, obtained as early as November 3, 2022 and as late as November 15, covering all four seasons.

2.3. Wind turbine data collection

Based on the preliminary exploration of the flight trajectory and activity range of red-crowned cranes, cranes had not flown over the sea, so this study only selected onshore wind turbines to study the relationship between cranes and wind turbines. Using Overpassturbo (https://overpass-turbo.eu/), the onshore wind turbine sites along the coast of Yancheng were obtained. The accuracy of the sites was subsequently verified through visual interpretation, and any missing sites were included. According to the histogram of the remote sensing image, wind turbines exhibited significant differences in terms of reflectance compared to the agricultural background. Therefore, visual interpretation can be performed based on the obtained high-resolution imagery. Sentinel-2 MSI Level-1C remote sensing images for February 2023 with less than 10% cloud cover were obtained from the Copernicus Data Center of the European Space Agency (https://browser.dataspace.copernicus.eu/). The images were preprocessed using ENVI 5.3, including radiometric correction, atmospheric correction, image registration, and image cropping. Interpreted the landscape type map using a combination of supervised and unsupervised classification methods, and correct and reclassify the results based on field investigations to obtain the land cover map of the area where the wind turbine is located.

2.4. Data analysis

2.4.1. Activity tracks of the red-crowned crane

ArcGIS 10.8 was used to plot the activity tracks of the red-crowned cranes, and the displacement–time curve method was used to construct activity curves for the different individuals. The displacement–time curve method is based on the coordinates of a moving object at a certain time, with the coordinates at the reference point serving as the baseline, and the distances between the coordinates at different times and the reference point are plotted as a curve (Li and Guo, 2023). In this study, the coordinates of each individual red-crowned crane at 00:00 on May 13th were taken as the reference point, and the distances between the coordinates at 00:00 each day since the deployment of the tracking device and the reference point were calculated using the coordinate distance algorithm. Based on that, the displacement–time curve was plotted.

S = 6,371,004*ACOS(1-(POWER((SIN((90-B2)*PI()/180)*COS(A2*PI()/180)-SIN((90-D2)*PI()/180)*COS(C2*PI()/180)),2) + POWER((SIN((90-B2)*PI()/180)*SIN(A2*PI()/180)-SIN((90-D2)*PI()/180)*SIN(C2*PI()/180)),2) + POWER((COS((90-B2)*PI()/180)-COS((90-D2)*PI()/180)),2))/2)

S is the distance between the reference point and any point, *A2* is the longitudinal coordinate of any point, *B2* is the latitudinal coordinate of any point, *C2* is the longitudinal coordinate of the reference point, and *D2* is the latitudinal coordinate of the reference point.

2.4.2. Kernel density analysis of red-crowned cranes

Kernel density analysis is a spatial analysis method based on kernel density estimation (KDE), which can reflect the spatial clustering and dispersion characteristics of red-crown cranes in YNNR and its surrounding areas. A higher function value indicates greater crane clustering, and this value decreases as the distance from the center increases (Cai et al., 2012). We define the area with high function value (value = 1336.22) as the high-density distribution area. We used the ArcGIS 10.8 kernel density analysis tool to implement this analysis.

$$f(x)=\frac{1}{nh}\times\sum_{i=1}^{n}k\left(\frac{d(x-x_i)}{h}\right)$$

$f(x)$ is the kernel density estimation value at location x_i, x_i represents the coordinate position of point i, n represents the number of coordinate points, h represents the bandwidth of the kernel density function, k is the scale of the kernel density method, and $d(x-x_i)$ represents the Euclidean distance between two points.

2.4.3. Distance from red-crowned cranes habitat to the nearest wind turbine

Using the T-DBSCAN clustering algorithm in the Global Messenger Tracking Data Service Platform. T-DBSCAN is a modified density-based clustering algorithm that can identify bird habitats and resting places through the time-sequential characteristics of the GPS points along a trajectory (Chen et al., 2014). Import the obtained habitat into ArcGIS and calculate the distance from each crane's habitat to the nearest wind turbine.

2.4.4. Habitat selection for red-crowned cranes

Wild red-crowned cranes migrate to Yancheng for wintering at the end of October each year, and their wintering period is from November to March. Therefore, we selected three cranes (Crane1, 3, 4) with non-overlapping trajectories and complete wintering cycles from November to March, and used 95% of KDE as their winter home range. According to field investigations, the land cover types in the red-crowned crane home range are divided into 6 categories related to the use of red-crowned crane habitats: mudflat, farmland, smooth cordgrass, reed, seepweed, water. Based on the characteristics of habitat utilization and availability, the habitat selection rate of red-crowned cranes is calculated at the individual level and at the home range scale (Manly et al., 2002) in terms of land cover type. The formula for calculating the habitat selection preference index is as follows.

$$\widehat{W}_i=O_i/\widehat{\pi}_i$$

Table 1
Tracking information for red-crowned cranes.

No.	GPS-GSM Transmitters No.	Sex	Age(Years)	Release date
1	WNNR020	Unknown	0.5	2022/11/03
2	WNNR021	Unknown	0.5	2022/11/03
3	WNNR022	Female	8	2022/11/03
4	WNNR025	Female	10	2023/02/16
5	WNNR026	Male	10	2023/02/16
6	WNNR019	Male	3	2023/05/05

$\widehat{W}_i$ is the selection preference index for type i habitat; O_i is the proportion of GPS locations in type i habitat to the total number of GPS locations within the home range; $\widehat{\pi}_i$ is the ratio of the area of type i habitat within the home range to the area of the home range.

Use the " $\widehat{W}_i$" function in the R package "adehabitatHS" (Calenge, 2020) to calculate the result. If the 95% CI of the $\widehat{W}_i$ is greater than 1.0, it indicates positive selection or preference selection, a value less than 1.0 indicates negative selection or avoidance, and equal to 0 indicates no utilization. When the selection ratio and confidence interval results are different, the main reference is the confidence interval (Manly et al., 2002).

3. Results

3.1. The activity of red-crowned cranes

From November 3, 2022, to November 5, 2023, 89.64% of the 36,609 GPS locations received were located within the YNNR, 43.22% were in the core zone, 0.02% were in the buffer zone, and 46.39% were in the experimental zone. Cranes 1 and 2 had overlapping trajectories, flying to the Sheyang Wind Farm and returning to the YNNR. Subsequently, they primarily lived within the core area of the reserve. Before a new breeding season, they engaged in joint activities in the experimental area with their parent (crane 3). Crane 3 mostly stayed in the experimental areas, while cranes 4 and 5 mainly stayed in the core area without engaging in long-distance flights. Crane 6 had the widest range of activity, ranging from Yancheng in the north to Shanghai Chongming Dongtan in the south. After a brief stop in Rudong County, crane 6 returned to Yancheng on October 3, and was active within the YNNR (Fig. 1).

From the curve changes in Fig. 2, it could be observed that crane 6 had a much greater displacement distance than the other individuals. The curves of individuals 1 and 2 almost completely overlapped, indicating that the two cranes moved and roosted together. The curve of Crane 3 was relatively flat from March to May 2023, indicating that it entered the breeding period. On March 26, 2023, incubation behavior was observed in the wild, and on April 22, 2023, photos of the offspring were taken, indicating successful breeding. Individuals 4 and 5 were mates, and beginning in March 2023, their curves overlapped and became flat. On May 13, 2023, both individuals were observed in the wild taking care of their offspring.

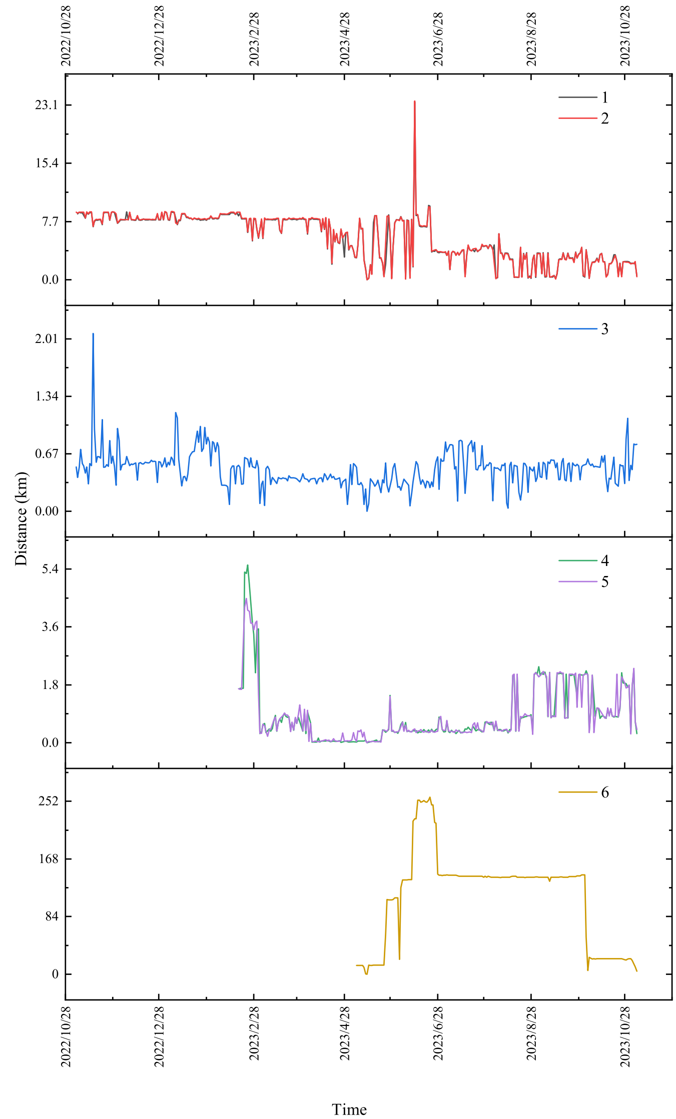

Fig. 2. Position control curve of red-crowned cranes.

3.2. Spatial distribution of red-crowned cranes and wind turbines

There were a total of 2592 onshore wind turbines in the study area. Due to the consistency of trajectories crane 1 and crane 2, crane 4 and crane 5, we only selected crane 1, crane 3, crane 4 and crane 6 for calculation. From November 2022 to November 2023, the average distance from four red-crowned cranes to the nearest wind turbine was 6.56 km, with the shortest distance being 1.06 km. And the average distance from crane habitat to the nearest wind turbine was 6.15 km. The small difference between the two average distances indicates that the result is reasonable. As shown in Fig. 3, the wind turbines in the study area were extending north-south along the coastline in a strip-like manner. The GPS locations of red-crowned cranes exhibited a highly concentrated trend in the core zone and buffer zone, indicating that the activity areas of the cranes were predominantly concentrated within these areas, which is consistent with the habitat of cranes obtained by the T-DBSCAN clustering algorithm. There is no overlap between high-density distribution area and wind turbines within the YNNR. In addition, the GPS locations in Rudong also showed a highly concentrated trend. By comparing the activity trajectory of the red crowned cranes, it can be seen that this high-density distribution area comes from the GPS location of Crane 6, the only crane with a long-distance displacement. This high-density distribution area indicated that it was once active in Rudong. In addition, the number of wind turbines in the high-density distribution area of Crane 6 accounts for 3.93% (19/483) of all wind turbines in Rudong, and the number of wind turbines in the overall distribution area of Crane 6 accounts for 46.17% (223/483) of all wind turbines in Rudong, which indicated that the distribution area of Crane 6 overlapped with the distribution of wind turbines to a certain extent.

3.3. Habitat selection of red-crowned cranes and land cover types of wind turbines

The winter home range and habitat types of cranes—crane 1, crane 3, and crane 4 are shown in Fig. 4. In the habitat selection of three individuals, the chi square test results ($x^2 = 137.33$, $df = 2$, $p < 0.001$) showed statistical significance, and the estimated selection ratio ($\widehat{W}_i$) and 95% CI can be used as references. These three individuals chose reeds and water, rejecting farmland, and did not use the smooth cordgrass, seepweed, and mudflat at all (Table 2).

41.32% (1071/2592) of wind turbines were built on farmland, 39.35% (1020/2592) are built near water (rivers, ponds, lakes, oceans, ditches and flooded salt plains), and 15.86% (411/2592) are built in built area. The remaining land use types were all below 3% (Fig. 4).

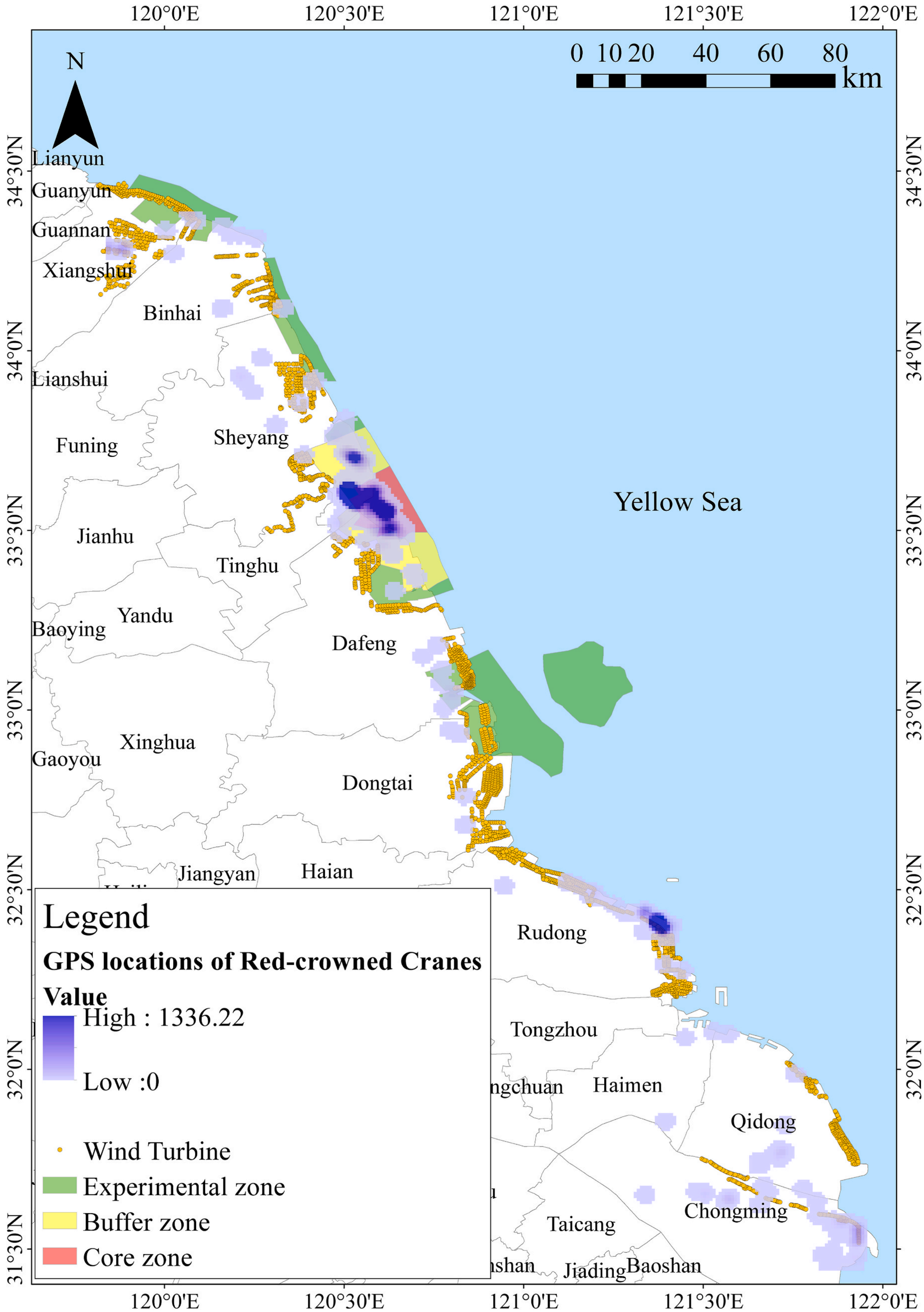

Fig. 3. Wind turbines sites and heat map of GPS locations from red-crowned cranes during 2022–2023 (Value means GPS locations per square kilometer).

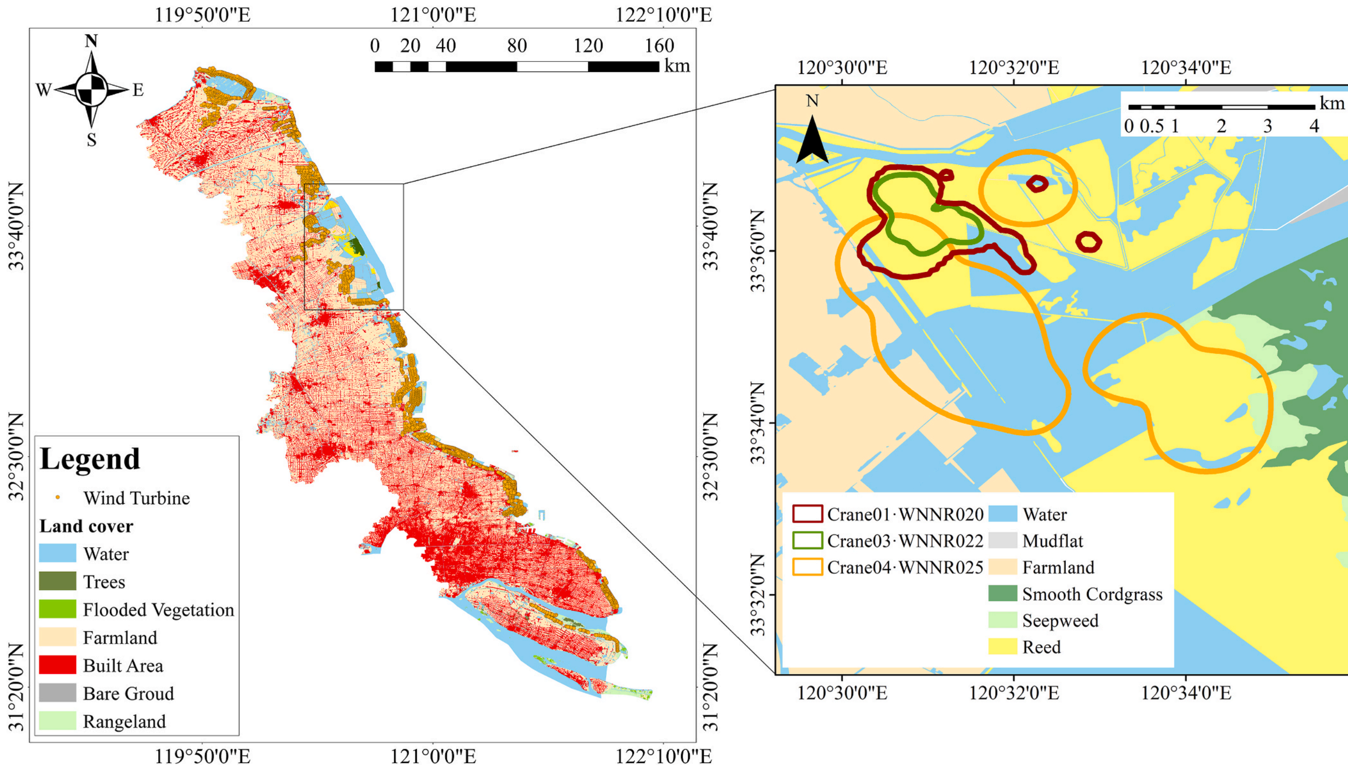

Fig. 4. Land cover map of wind turbine areas along the East China coast and home range distributions and habitat types of the three tracked cranes with a complete annual cycle.

4. Discussion

Birds respond to wind farms differently based on their ecological group (Zhao et al., 2024; Thaxter et al., 2017) and that species with good flexibility (small body weight and large wing area) were more likely to occur in wind farm areas (Herrera-Alsina et al., 2013), whereas sensitive or displaced populations tended to abandon areas close to wind farms or with high wind turbine densities (Kelsey et al., 2018; Dohm et al., 2019) and select harsher habitats with more competition or fewer resources (Meattey et al., 2019). Some studies have shown that wind turbines can interfere with waterbirds at distances up to 800 m (Larsen and Madsen, 2000; Leddy et al., 1999; Pearce-Higgins et al., 2009). Based on kernel density analysis, our results revealed that there is less overlap between the distributions of cranes and wind turbines. Red-crowned cranes are mainly active within the YNNR and tend to avoid wind farms, which is consistent with previous studies on ducks, egrets, and other crane species (Pearse et al., 2016; Zhao et al., 2022; Xu et al., 2021). This may be due to factors such as the presence of the wind turbines themselves, noise and vibration interference, human activities around the wind turbines, and habitat loss around the wind turbines (Zhao et al., 2022; Zhang et al., 2022; Cook et al., 2018; Watson et al., 2018).

In the Yancheng Nature Reserve's coastal wetlands, the flat terrain, proximity to the sea, and location within an economically developing area result in a high density of wind turbines. The extensive land use by wind turbines and related infrastructure, combined with the construction of wind turbine towers and roads, exacerbates habitat fragmentation (Dhar et al., 2020). Habitat fragmentation has led red-crowned cranes to adopt ecological adaptation strategies of reducing wintering and nesting habitat area (Li and Li, 2011; Wang et al., 2002). In Yancheng, red-crowned cranes show a dynamic trend of gathering towards the core zone and buffer zone. The spatial distribution has also evolved from a homogeneous continuous distribution to a fragmented discontinuous distribution, with decreased activity range and reduced habitat connectivity, ultimately leading to a decline in habitat quality (Li and Li, 2011). Wind turbines are primarily located in intertidal zones, farmlands, and fishpond habitats (Zhang et al., 2022), which is similar to our research. Our research, along with previous studies, have indicated that water (intertidal zones and fishponds) are suitable habitats for red-crowned cranes (Li and Fu, 2021). During field investigations in YNNR, we also discovered wild red crowned cranes in surrounding farmland. The disturbance of the Yancheng wind farm to red-crowned cranes has already affected their habitats (Wang et al., 2020). Based on that and our own research, it can be indicating the main negative impact of wind farm on red-crowned cranes is habitat loss. Pearse's research also confirms that the development of wind energy infrastructure results in habitat loss for cranes and causes them to avoid areas around wind farms (Pearse et al., 2021). Clearly, our study needs to further evaluate the impact of wind farm construction on the habitat selection of red-crowned cranes.

Compared to wild populations, the reintroduced red-crowned crane population has its unique ecological habits, especially in the coastal wetlands of Yancheng. Reintroduced red-crowned cranes are non-migratory populations with a smaller home range (Chen et al., 2024). Therefore, the risk of collision between the reintroduced red-crowned

Table 2
Habitat selection ratio of red-crowned cranes.

Habitat type	Selection ratio ($\widehat{W}_i$)	Standard error (SE)	95% Confidence interval (95%CI)
Mudflat	0	–	–
Smooth Cordgrass	0	–	–
Seepweed	0	–	–
Farmland	0.0047	0.0394	[0.0000, 0.1789]
Reed	1.1833	0.1746	[0.9648, 1.3359]
Water	0.8908	0.1823	[0.1064, 1.6752]

The selection ratio cannot be negative, so the negative lower limit of confidence interval is replaced by 0.0000. - The selection ratio estimation is zero and there is no use for a habitat type.

Fig. 5. Wild red-crowned cranes active near wind farms (photo taken in Dafeng, Yancheng).

crane and the wind turbines is not high. However, the construction of wind farms on the migration routes of wild red-crowned cranes may pose a risk of collision and death for them (Fig. 5). In addition, the wintering habitat selection of wild red-crowned cranes is similar to that of reintroduced red-crowned cranes (Xie et al., 2018; Chen et al., 2024), and mixed activities of the two have also been observed (monitoring records from YNNR). The activities of research samples within the YNNR are affected by wind farms, and wild cranes that come to YNNR for wintering are obviously facing the same problem. Therefore, we could determine whether wind turbines will cause habitat loss of red-crowned cranes based on the habitat of the studied individuals, and the results are obvious. From a conservation perspective, it is essential to limit wind power development in coastal wetlands and choose sites wisely. Additionally, creating more suitable habitats for threatened bird species is crucial. Coastal wetlands are vital not only for cranes but also for other wetland birds, serving as key areas for their habitat and breeding (Sun et al., 2023). In Jiangsu Province, wind farms are primarily concentrated in the Xiangshui, Dafeng, and Dongtai regions. The establishment of these wind farms occupies land and directly disrupts the native environment, forcing red-crowned cranes and other birds residing within these areas to relocate and find alternative habitats, such as artificial wetlands (Xu et al., 2010). To address this issue, that when planning future wind energy development in coastal wetlands, preferred habitats for red-crowned cranes, such as reed wetland, should be avoided. We also reiterate the call to provide more appealing habitats in areas far from the wind farm to reduce the time birds spend in high-risk areas (Schaub et al., 2020), such as by creating diverse artificial habitats. These measures can help mitigate the impact of wind farms and provide more suitable environments for birds within these areas.

5. Conclusions

Satellite tracking studies have shown that the red-crowned crane population faces pressure from wind farms and tends to avoid wind turbines. Although the wind farm is located outside the core zone of YNNR, the habitats where the turbines are placed are similar to the suitable habitats for red-crowned cranes. With the further construction of wind farms in Yancheng coastal wetland, the suitable habitat area of red-crowned crane is gradually being compressed.

CRediT authorship contribution statement

Xinyi Hu: Writing – original draft, Methodology, Formal analysis, Data curation. **Dawei Wu:** Writing – review & editing, Writing – original draft, Methodology. **Hao Chen:** Resources, Data curation. **Weihua Chen:** Resources, Data curation. **Guoyuan Chen:** Resources, Data curation. **Wei Hu:** Writing – original draft. **Taiyu Chen:** Validation. **Changhu Lu:** Writing – review & editing, Methodology, Conceptualization.

Ethics declarations

We confirm that the present study followed international, national, and/or institutional guidelines for humane animal treatment. Also, the ethical permission was obtained from the Nanjing Forestry University Animal Ethical Committee.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 32171526). We are grateful for the Yancheng National Nature Reserve for Rare Birds for providing support to this survey.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123508.

Data availability

Satellite tracking data of wild-release red-crowned cranes in the Yancheng National Nature Reserve for Rare Birds from 2022 to 2023 https://doi.pangaea.de/10.1594/PANGAEA.968698.

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