Integrating wintering waterbird movements with earth observation data of wetland dynamics

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Abstract: Wetlands are among the most productive and essential ecosystems on earth, but they are also highly sensitive and vulnerable to climate change and human disturbance. One of the current scientific challenges is to integrate high-resolution remote sensing data of wetlands with wildlife movements, a task we achieve here for dynamic waterbird movements. We demonstrate that the White-naped cranes *Antigone vipio* wintering at Poyang Lake wetlands, southeast of China, mainly used the habitats created by the dramatic hydrological variations, i. e. seasonal water level fluctuation. Our data suggest that White-naped Cranes tend to follow the water level recession process, keeping close to the boundary of water patches at most of the time. We also highlight the benefits of interdisciplinary approaches to gain a better understanding of wetland ecosystem complexity.

Key words: Poyang Lake; Sentinel-1A; interdisciplinary approach; wetland monitoring; water surface; White-naped Cranes

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1 INTRODUCTION

Wetlands offer a wide variety of essential ecosystem services, such as biodiversity support, flood control, maintaining water quality, carbon sequestration, as well as water and goods supply for surrounding human communities (Zedler & Kercher, 2005; Harris, 2017; Meng, et al., 2017). Because wetlands are so highly dynamic and heterogeneous as driven by hydrological and climatic fluctuations, they are at the same time sensitive and vulnerable to climate change, human disturbance and invasive species (Brinson & Malvárez, 2002; Zedler & Kercher, 2005; Dronova, et al., 2011; Gabrielsen, et al., 2016; Tan & Jiang, 2016). In order to contribute to the understanding of the complex ecological processes in wetlands, as well as conserve the wildlife that inhabit these areas, we propose that timely, reliable and high-quality monitoring data are crucial (Henry, et al., 2016; Li, et al., 2018). In general, the worldwide demand for such information is dramatically increasing in a variety of research fields, particularly biology, ecology, conservation and remote-sensing (Hebblewhite & Haydon, 2010; Kuenzer, et al., 2014; Dronova, et al., 2015; Gallant, 2015).

However, gathering adequate information of wetland ecosystems is often difficult due to the highly dynamic nature of the temporarily inundated areas. It is common practice to conduct field surveys, which are indeed highly informative about the changes in wetland functions and related drivers and consequences. However, on-the-ground surveys are expensive, labor-intensive, sometimes even logistically challenging and restricted in spatial scale (Li, et al., 2012; Dronova, et al., 2015; Gallant, 2015). Recent advancements in technology and methodology of animal telemetry, e. g., tracking the animal by using animal-borne Global Position System (GPS) devices, and remote sensing (Kuenzer, et al., 2014) provide sophisticated tools to gain vital insights into the interactions between animals and wetlands (Hebblewhite & Haydon, 2010; Kays, et al., 2015; Remelgado, et al., 2017). However, integrating these cutting-edge developments from both disciplines to monitor the wetland habitat alterations and the responses of animals are challenging (Kuenzer, et al., 2014). For instance, while GPS tracking technology has allowed animal ecologists to track animal movements in increasingly finer spatiotemporal scales (e. g. GPS sampling every second or minute, with location errors of less than 5m), the spatiotemporal resolution of remote sensing products that were previously publicly available and easily accessible by animal ecologists such as Landsat or MODIS (Moderate Resolution Imaging

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Spectroradiometer), were often mismatched by the scales of animal GPS tracking data (Wilmers, et al., 2015; Remelgado, et al., 2017). Therefore, this study focuses on the assessment of the potential application of satellite data provided by the recently launched Copernicus Programme which are free and open to the public, meanwhile with a good balance of spatiotemporal resolution (European Copernicus Programe, 2018).

Poyang Lake is an ideal place for addressing this interdisciplinary challenge. It is the largest freshwater lake in China and has significant value for flood control, maintenance of water quality and water supply (Harris, 2017). Due to its essential role and unique hydrological and ecological characters, it has received extensive research interests from both remote-sensing scientists and animal ecologists (Qi, et al., 2009; Yésou, et al., 2011; Wang, et al., 2013; Dronova, et al., 2016; Xia, et al., 2016; Wang, et al., 2017; Yu, et al., 2017; Ye, et al., 2018; Zhang, et al., 2018). Annually and inter-annually, water level variations create a wide range of ephemeral but unique habitats making Poyang Lake one of the most important wetlands for waterbirds in East Asian (Barter, et al., 2005; Fox, et al.,2009; Cao, et al. 2008, 2010 Harris, 2017; Wang, et al., 2017). Waterbirds are often monitored and used as a biological indicator for the health of wetland ecosystems due to their specific habitat requirements (Wang, et al., 2013; Zhang, et al., 2018). Most studies that deal with water levels and waterbird distributions at Poyang Lake used field surveys rather than telemetry data (Wang, et al., 2013; Dronova, et al., 2016; Xia, et al., 2016; Xia, et al., 2017), but see Aharon-Rotman, et al. (2017).

Over the past decade, a dam at the outlet of Poyang Lake that would be used to regulate the water levels has been proposed (Barzen, et al., 2009; Construction Office of Poyang Lake Water Control Project of Jiangxi Province, 2013; Harris, 2017). Potential implications of this water control structure on the Poyang Lake ecosystem are controversial (Wang, et al., 2013; Tang, et al., 2016; Xia, et al., 2016; Jia, et al., 2017a). It is urgent to investigate the relationships between wetland dynamics and waterbird movements under natural conditions with the aim of contributing to decision-making in conservation and management plans.

Here, we showcase how the integrated use of GPS tracking technology in combination with time series of earth observation data could benefit the study of the ecology of waterbirds and provide increasing insights into waterbird movements in their dynamic environments. We focus on the vulnerable White-naped crane *Antigone vipio*. Among crane species in Poyang Lake, White-naped cranes have been observed to use mudflat and wetland margins more frequently than other crane species (Meine & Archibald, 1996; Jia, et al., 2017b). Such habitat specializations are interesting as the mudflats and margins of the wetland are most sensitive to environmental changes in this ecotone (Wasson, et al., 2013; Gallant, 2015). The movements of White-naped Cranes are thus suitable to address the question of how waterbirds may react to wetland dynamics.

2 METHODS

2.1 Study area and species

Poyang Lake is located in the mid-Yangtze Basin, with five main tributaries draining into the lake from the south and the lake water freely connecting to the Yangtze River in the north (see Fig. 2). The water level of the lake has considerable seasonal variation, i.e. the annual mean water level and its variation are 13.27 m and 11.13 m, respectively (Xia, et al., 2016). In summer, the lake's surface area exceeds 4000km^2, while in winter it shrinks to less than 1000 km^2 and the lake basin becomes a complicated mosaic landscape of river channels, isolated sub-lakes, mudflats and submerged grasslands (Dronova, et al., 2011; Li, et al., 2012). Over 98% of the world population of critically endangered Siberian Crane *Leucogeranus leucogeranus*, as well as 90% and 50% of endangered Oriental Stork *Ciconia boyciana* and vulnerable Swan Goose *Anser cygnoides*, respectively, winter in Poyang Lake (Barter, et al., 2005; Harris, 2017).

To delineate the study area boundary, we first generated a Minimum Convex Polygon (MCP) surface of space use, by plotting all the GPS data points of wintering White-naped Cranes from 2014—2015 (see detailed information in section 2.3). Then we buffered the MCP area by 30 km as the defined study area boundary. In this way, we could include potential habitats such as rice paddy in the adjacent area of the lake, which has been reported as a type of habitat for cranes and other waterbirds (Li, et al., 2012).

The White-naped Crane, about 130cm in height and 5.6 kg in weight, is a long-distance migratory bird species (Fig. 1). White-naped Cranes breed in north-eastern Mongolia, north-eastern China and adjacent areas in Far Eastern Russia. The cranes living in the western portion of the breeding range winter at the Poyang Lake area and the eastern portion winter in the Demilitarized Zone between North and South Korea, as well as around Kyushu in Japan. Over the last two decades, the White-naped Crane population in China has experienced a rapid decline from around 3000 to 1000-1500 individuals and Poyang Lake has become their only known wintering site in China (Li, et al., 2012; Jia, et al., 2017a). The main threat is habitat loss primarily due to the changing hydrology (Meine & Archibald, 1996; Harris & Mirande, 2013). In the Poyang Lake area, the main over-winter habitats include shallow water, mudflat and sedge area. The primary food resources are tubers and roots of wetland plants, in particular, *Vallisaneria spiralis* in shallow water and mudflat habitat (Meine & Archibald, 1996), *Potentilla limprichtii* and *Amana edulis* in sedge area (personal unpublish data).

2.2 Inundation frequency from Earth Observation

Inundation frequency is a dataset generated from numerous, so-called watermasks, i.e. binary datasets derived from Synthetic Aperture Radar (SAR) satellite data. In 2014, the first satellite of the Copernicus Programme Sentinel-1A was launched, and the second Sentinel 1, i.e. 1B, in 2016. These radar data are acquired in the C-band, corresponding to a wavelength that is not hindered by atmospheric effects and therefore independent of cloud cover. The data offer a spatial resolution of 10 m. The repetition rate of Sentinel-1 is reported with 5 to 10 days, depending on a worldwide acquisition scheme (European Copernicus Programe, 2018).

Single watermask derivation from SAR data was conducted using WaMaPro (Water Mask Processor). This open-source based software tool developed at the German Aerospace Center (DLR) uses backscatter data and empirically derived thresholds to separate the image into land and water areas (Gstaiger, et al., 2012; Kuenzer, et al., 2013; Martinis, et al., 2015).

For the overlay with available bird movement data, Sentinel-1 data were selected for nine overlapping dates in November and December 2014 (see Table 1). To generate the inundation frequency map the watermasks from November 8, 2014 to December 26, 2014 were summarized. The result contains values from 0 to 9. All areas where no water was present during the nine selected dates are categorized as 0. The values from 1 to 9 describe how often a pixel (an area of 10m by 10m) was covered with water. The value 9 represents permanent water coverage from November 8 to December 26, 2014.

We used the inundation frequency value as a proxy for the changing hydrological characteristics of Poyang Lake during the study period. Because hydrological traits have been recognized as major driving forces for wetland vegetation succession (Qi, et al., 2009; Zhang, et al., 2012; Deng, et al., 2014), this could be an indirect indicator for the food resource distribution of White-naped Cranes. The inundation frequency may also influence the accessibility of food resources, i. e. habitats which have water that is too deep or areas that are too dry may prevent birds from digging for food regardless of the food abundance (Barzen, et al., 2009; Burnham, 2017). We expected that the inundation frequency value of crane GPS locations would increase over time as the birds occupy the newly emerged habitats along with decreasing water levels, until the water reaches the places where the water is too deep for *Vallisaneria spiralis* to grow during the summer.

2.3 GPS tracking

In August of 2014, 6 White-naped Cranes were captured in the Khurkh and Khuiten River Valleys of northern Mongolia by a joint team of scientists from the Mongolian Wildlife Science and Conservation Center from Mongolian Academy of Sciences, and the International Crane Foundation. The birds were then color banded and deployed with a leg-mount GPS device (60—65 g, Fig. 1). The GPS devices were programmed to get a GPS location every 30 minutes. Location error was less than 12.5 m. We only used data that were obtained during the daytime.

2.4 Movement analysis

The GPS data were sub-sampled and grouped by the observation period of two days before and after the Sentinel data were acquired (in total five days per period). For example, the last acquisition date of Sentinel-1 data was December 26, 2014, thus the last period included GPS location data that ranged from December 24 to 28 (Table 1). The GPS data which fell outside of the period window and later than December 28, 2014, were omitted in our analysis. The inundation frequency value for each GPS location was extracted from the inundation frequency map. We used histograms and heat maps to show how the White-naped Cranes used their habitats in relation to dynamically changing water extent.

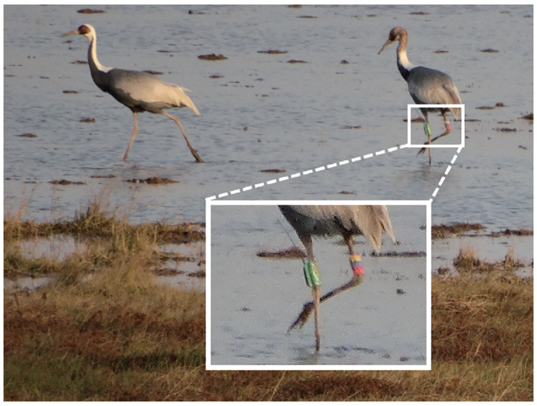
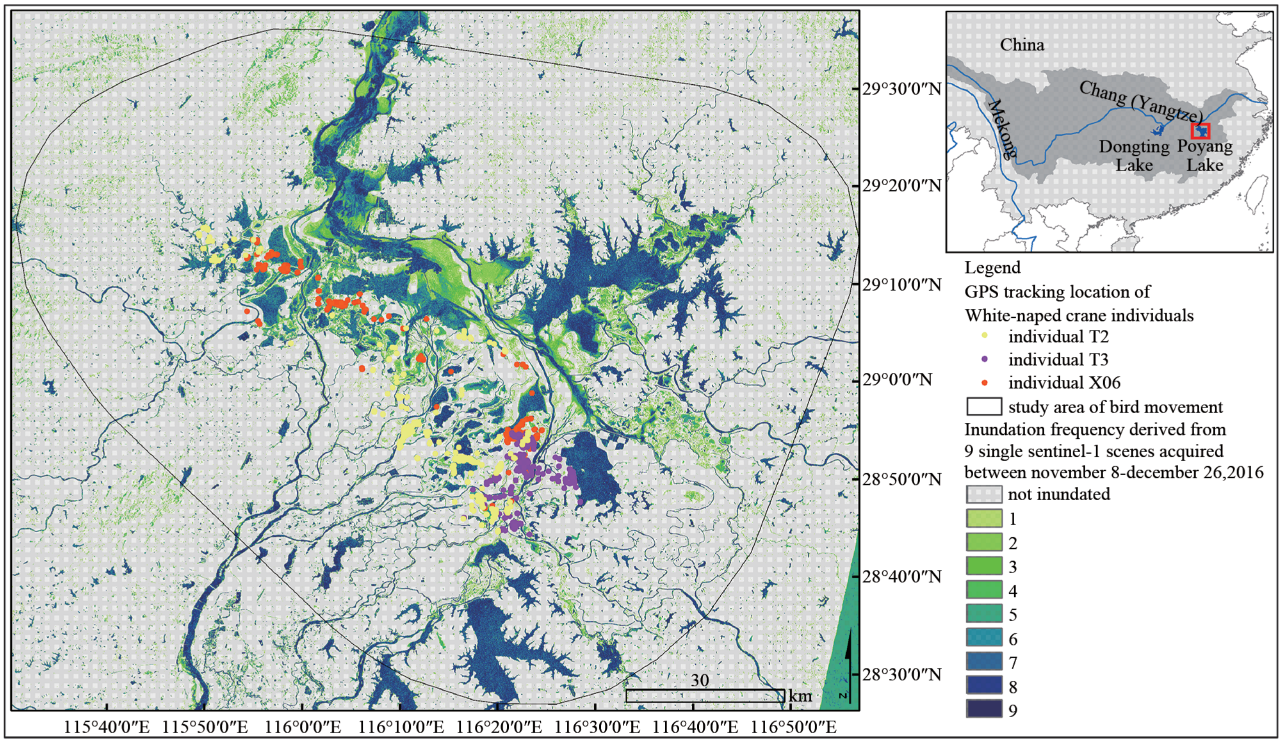
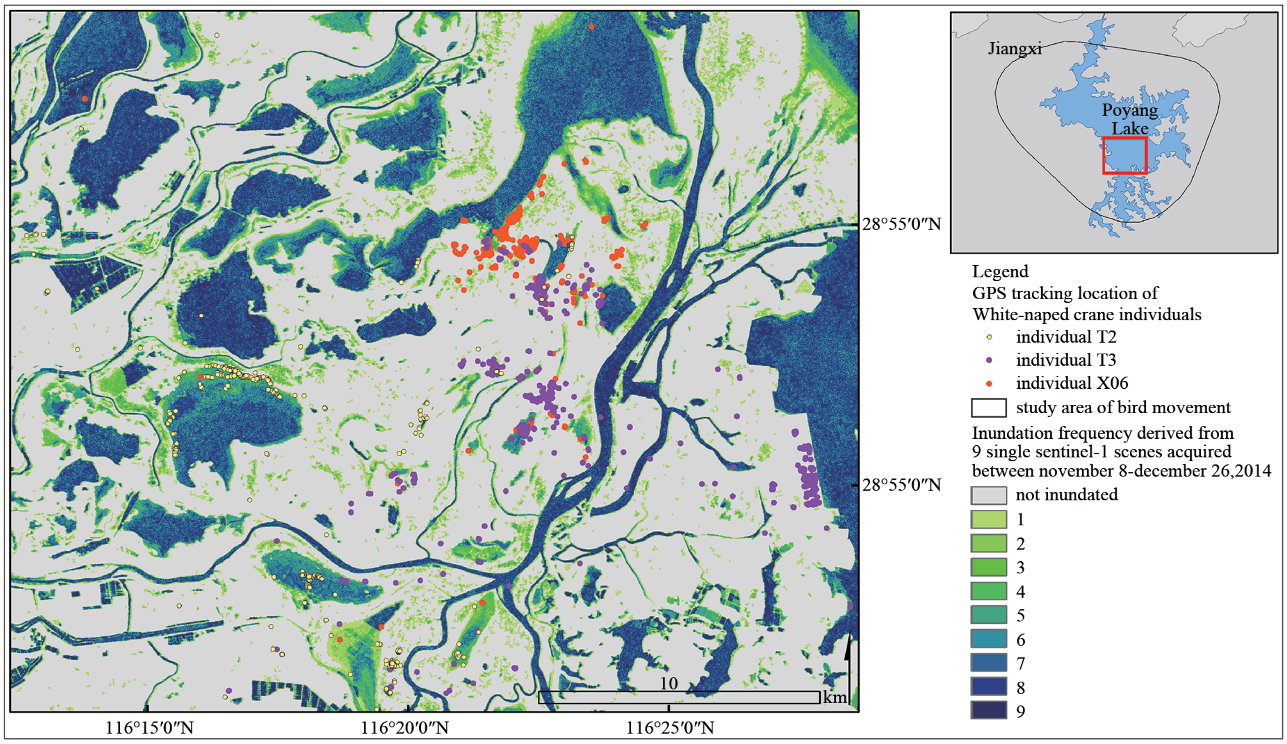


Fig. 1 A juvenile White-naped crane with a GPS tracking device and color bands on its legs at its typical habitat at the Poyang Lake area (photo by Yan Lvu)

The single binary watermask layers that created the inundation frequency map were cropped by the study area boundary separately (see Fig. 2 for study area outline). We then calculated the size of the water surface area (in km^2) to represent the hydrological regime changes.



(a) Overview of study area and distribution of tracking the location of cranes



(b) Detail view of locations in the southern part of the lake. Colors from green to blue indicate how many times a location was covered with water during 9 satellite observations in 2 months. The points in yellow, red and purple are tracking locations of 3 cranes, respectively

Fig. 2 Inundation frequency map and White–naped Cranes' diurnal locations in Poyang Lake (November and December of 2014), China

To test whether White-naped Crane movements were related to the recession of water levels, we calculated and compared the distances to water and land surfaces of each GPS location, using the corresponding period of the watermask layer. If the bird was in either the water or the land patch, the distance to each corresponding category of the patch was zero. We quantified the 'distance difference', as the distance to the nearest water patch minus the distance to the nearest land patch. In essence, this measurement corresponded to the relative position of the crane in the landscape. Negative distance difference values indicate the cranes resided in the water area, whereas positive values show cranes used land patches. We expected that the distance difference values should be slightly positive based in the assumption that the mudflat which White-naped Crane prefer, should be located between water and land patches, even if it wasn't directly classified from binary water surface layers.

The analyzing and plotting procedures were conducted in R version 3.4.3 (R Core Team, 2017), Qgis 2.18 (Quantum GIS Development Team, 2018) and ArcGIS 10.3. The mean value was reported as the mean ± standard deviation.

3 RESULTS

Three White-naped Cranes (one adult and two juveniles from different families), tracked with high-resolution GPS devices arrived in Poyang Lake area for wintering on the same day, November 2, 2014. Table 1 reports the number of diurnal GPS points in each period that had corresponding watermask layer data.

The geographical distribution of GPS locations is shown in Fig. 2. Cranes were mainly relocated at: (1) sub-lakes located in the northwest corner, particularly the Bang Lake and the Dacha Lake of the Poyang Lake National Nature Reserve; and (2) sub-lakes at the southern part of the lake, such as Liufang Lake, Linchong Lake, Bianyu Lake, Shatangchi and rice paddy near Kangshan Lake (Fig. 2(b)).

Table 1 Acquisition times of Sentinel–1 data in 2014 and numbers of GPS locations during each period.

Period	Watermask Acquired date (month–d)	GPS location time range (start/end)	Number of GPS locations
1	11–08	11–06/11–10	333
2	11–13	11–11/11–15	328
3	11–20	11–18/11–22	318
4	11–25	11–23/11–27	305
5	12–02	11–30/12–04	313
6	12–07	12–05/12–09	316
7	12–14	12–12/12–16	321
8	12–19	12–17/12–21	320
9	12–26	12–24/12–28	283

We found that 56.43% of the GPS locations the cranes visited had zero inundation frequency values, indicating that they were never inundated during the study period. The birds spent less than 10% of their time in each of the other inundation frequency categories. The highest level of inundation frequency was only chosen by the cranes in 0.07% of their time (Fig. 3). This result indicates that around half of the places that tracked White-naped Crane visited were not inundated throughout November and December 2014. In contrast, the birds barely used places that were always covered by water.

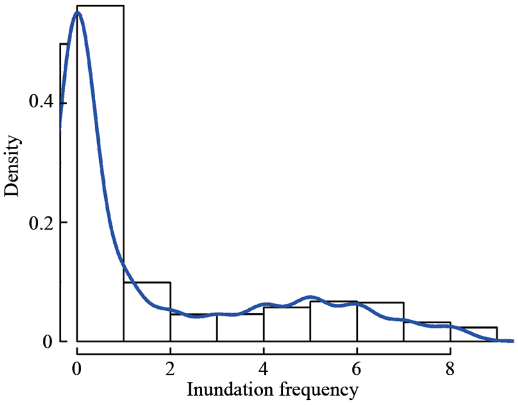


Fig. 3 Inundation frequency values of associated GPS tracking data points（The blue curve is the kernel density）

We further tested whether the bird's GPS locations with inundation value zero (dry places) were inundated after the winter recession started (Harris, 2017) and before cranes arrived. We termed this time the 'pre-winter' period and used 6 additional layers of Sentinel-1 data (along with the same procedures as described in section 2.2) acquired on October 3, 8, 15, 20, 27, and November 1. We discovered that 50.47% of these GPS locations with zero inundation values after cranes arrived, were shortly in the water during this pre-winter period (i.e., these locations were the recently dried-out, or emerged habitats when cranes arrived). If we took the pre-winter period (six additional watermask layers) into account, 71.98% of GPS locations fell into the emerged area for which the inundation value was neither zero nor fifteen (i.e., never or always covered by water from October to December 2014).

The frequency distributions of inundation values during each period were similar but not identical (Fig. 4). Beside period 9 (December 24—28, 2014), most of the White-naped Cranes were at the places of value zero, particular November 2—9, 2014 (period 5—6). There was no apparent tendency for the cranes to visit more inundated areas, i.e., increase their inundation frequency value.

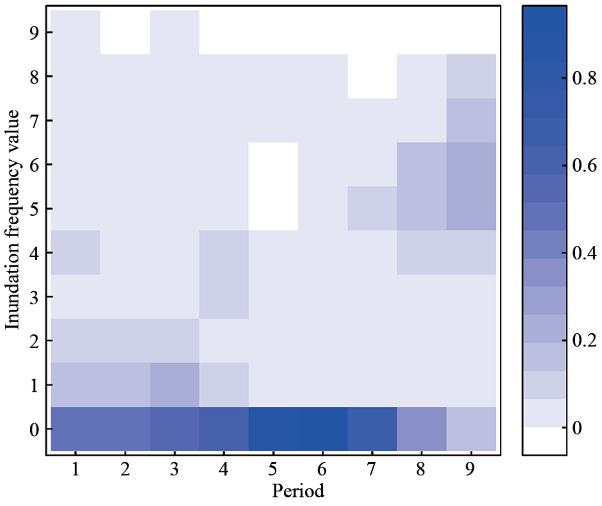


Fig. 4 The corresponding inundation frequency of GPS locations in each period. The darkness of the cell in the heat map shows the frequency of a particular inundation value for a certain period

We compared the distances to the water area and distances to the land area of each GPS location to determine the relationship of crane movements related to water surface dynamics (Fig. 5). The overall recession of water was interrupted in the last period of both November and December. In the period 4 and 9 (Fig. 5), the sizes of water surfaces increased. Cranes occupied the land patches (the positive distance difference value) at most of their time after arrived at Poyang Lake until late December. The distance differences during this period value were close to zero, indicating the birds were situated near the water edge. In the first 8 periods, the mean distance difference was 185.35 ± 202.94 m. However, in the last period (December 24—28, 2014), the mean distance difference was 576.15 ± 418.35 m, in accordance with the increased water level.

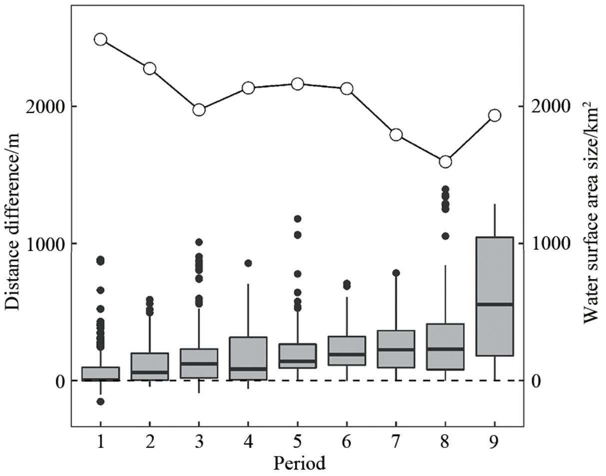


Fig. 5 Boxplot of distance difference（distance to water minus distance to land in meters）for each period, showing the first or third quartiles and median value and outlier as black points. The white circles on the top connected by a line show the respective size of the water surface area（km^2）for each period.

4 DISCUSSION

Integrating the time series of earth observation data and animal movement data reveal some interesting aspects regarding the mechanism of how animals respond to their dynamic environments over fine spatiotemporal scales. First, the result of inundation frequency (Fig. 3) suggests that over-wintering White-naped Cranes mostly used emerged habitats in the Poyang Lake area, which is consistent with previous studies (Barter, et al., 2005; Harris, 2017; Wang, et al., 2017). Second, the cranes kept relatively close to the border of water patches at most of the time (Fig. 5). The slight increase of the cranes' distance from water over time (Fig. 5) might indicate that suitable habitats such as mudflats expanded, thus giving cranes a larger area to find food farther from the water. It is also possible the cranes foraged in sedge areas which were less influenced by the inundation level over a short time span (Barzen, et al., 2009). Further studies regarding the time variation of White-naped Crane habitat selection are required to explain the pattern that we observed.

In the last observation period (December 24—28, 2014), the expansion of water surface likely indicates a winter flood, which is unusual because December is generally the driest months in the Poyang Lake area (Harris, 2017). This unexpected hydrological event might have lead the cranes to move away from places with zero inundation frequency towards more flooded areas (Fig. 4), but only those areas that are slightly flooded and thus even further away from the water (Fig. 5). A less pronounced rise in water level also occurred during period 4 (November 23—27, 2014), but did not trigger a strong response from the cranes (Fig. 5). We do not yet understand whether there is a threshold level of inundation or a seasonal effect of habitat requirement that is responsible for the difference in the cranes' response.

We like to highlight that our investigations should only be interpreted as a pilot study, due to the short time span and the small sample sizes. Nevertheless, it is challenging to pursue a larger sample size for endangered species. One important shortcoming in the interpretation of our data is the individual difference among birds, as well as the large interannual variations in inundation levels at the Poyang Lake area. Other biotic or environmental factors, which were deliberately not included in our pilot study, may influence the patterns we observed. Furthermore, we currently only correlated wetland dynamics and bird movements in a descriptive way. To determine whether hydrology dynamics truly drive the movements of the cranes, longer time series and more natural experiments need to be included. As a further limitation, the accuracy of watermasks is estimated in the range of 1—3 pixels (10—30 m), depending on picture quality. Similarly, mobile GPS devices may err by about 10 m. Moreover, the land cover category 'mudflat', as one of the most important land cover classes of interest for bird monitoring, likely to situated at the land side of the water patches border (Fig. 2b). The categorizations carried out with WaMaPro aimed at the detection of surface water only, which is not optimized a priori. Thus, the mudflat is a mixed land cover class with pixels of conjunctive water and land patches in watermask layers. Future analyses might combine the respective inundation frequencies with the mapping of land cover types derived from earth observation data e.g. Sentinel-2 time series.

Despite the shortcomings of our analyses, the current results offer insights into the complexity of dynamic wetland ecosystems. White-naped Cranes which over-winter in the Poyang Lake area are highly reliant on the emerged habitats created by seasonal variation in water levels. Our analyses confirm that the functioning of wetlands is linked to the diversity of the hydrological regime (Kingsford, et al., 2004; Barzen, et al., 2009). Therefore, we urge caution when introducing new human interventions which could reduce the natural character of the dynamics (Kingsford, et al., 2004; Wasson, et al., 2013; Guan, et al., 2014).

Previous studies assessing the relationship between wetland dynamics and waterbirds mainly focused on general habitat suitability, or on the abundance and diversity of wintering waterbirds under different water level conditions (Chen, et al., 2016; Dronova, et al., 2016; Xia, et al., 2016; Aharon-Rotman, et al., 2017). Our study advances these valuable approaches by exploring the relationships between a dynamic wetland landscape and waterbird distributions and individual movements, allowing for a deep, mechanistic understanding of the decisions of the birds. We could only achieve this goal due to a time series of cloud-independent earth observation data available for the Poyang Lake area. Sentinel-1 data provide a spatiotemporal high-resolution data source with the great potential to support similar analyses of birds tracking data across the globe.

In summary, we integrated animal tracking and earth observation data to understand how waterbird movements are affected by wetland dynamics. We highly recommend the further collaboration between remote sensing scientists and animal ecologists, which could be beneficial for both fields, as well as nature conservation and management.

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