IOP Publishing Environ. Res. Lett. 15 (2020) 125013 https://doi.org/10.1088/1748-9326/abc6d0

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
7 August 2019

REVISED
19 August 2020

ACCEPTED FOR PUBLICATION
2 November 2020

PUBLISHED
16 December 2020

LETTER

Protection effect of overwintering water bird habitat and defining the conservation priority area in Poyang Lake wetland, China

Chuanzhun Sun[1,2], Hannes J König[2], Sandra Uthes[2], Cheng Chen[2,3], Peng Li[4,5] and Karoline Hemminger[2,3]

[1] College of Public Management, South China Agricultural University, No. 483, Wushan Road, Tianhe District, Guangzhou 510642, People's Republic of China
[2] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, Müncheberg D-15374, Germany
[3] Department of Agricultural Economics, Humboldt-Universität zu Berlin, Invalidentr. 42, 10115 Berlin, Germany
[4] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China
[5] Graduate University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

E-mail: hkoenig@zalf.de

Keywords: biodiversity conservation, protected area, composite biodiversity index, biodiversity hotspot, Poyang Lake wetland

Supplementary material for this article is available online

Abstract

Biodiversity conservation is one of the most important objectives of protected areas. Most biodiversity assessment-related studies use the change in species abundance data to measure the level of biodiversity conservation. Yet for many areas, long-term species data are not available and thus it is necessary to use biodiversity indices to monitor the effect of land use (LU) changes or the impact of protected area establishment. Poyang Lake wetland is one of the most important wintering sites for migratory water birds on the East Asian–Australasian flyway. To protect this habitat, 14 nature reserves were created in the region between 1997 and 2003. This paper aims to assess the effect of nature reserve creation on the status of habitat for overwintering water birds in Poyang Lake wetland by analysing LU and land cover data from 1995, 2005 and 2015. We developed a composite biodiversity index to search for current biodiversity hotspots (conservation priority) in the study area. An integrated approach consisting of the Integrated Valuation of Ecosystem Services and Trade-offs model, GIS, fragment analysis and hotspot analysis was used to realize our objective. Our results showed that the creation of the nature reserve had positive effects on overwintering water bird habitat. However, tremendous changes (such as change of habitat area, quality and fragmentation) within and outside the nature reserve showed that the role of protected area still needs to be further discussed. Moreover, regional synthesis LU management plans such as ecological restoration should be carried out. The results of the habitat assessment also indicate that a comprehensive biodiversity index framework based on net primary productivity, habitat connectivity and habitat quality could be more efficient in assessing biodiversity and defining a reasonable protected area, from data obtain in large scale perspective.

1. Introduction

Approximately 75% of the earth's land surface is exposed to severe human pressures (Venter *et al* 2016). Combined with climate change, there are globally unprecedented rates of biodiversity loss (Riordan and Rundel 2014). Currently, pressures are becoming increasingly extensive and widespread, and pressures are rapidly intensifying in places with high biodiversity (Venter *et al* 2016). Wetlands harbour significant biodiversity (Secretariat 2004) and supply crucial ecosystem services (ES) (Costanza *et al* 1997). However, the area of wetlands has been reduced by 50% worldwide, while the quality of wetland wildlife habitat has been declining as a result of different types of human activities (Fraser and Keddy 2005). Many countries and regions have developed policies to address these degradation problems, e.g. the establishment of restoration projects (Sun *et al* 2015) and the construction of nature reserves (Harris 2016).

Maintaining biodiversity in regional ecosystems may be a high-priority goal because this issue involves many other conditions and ecosystem health responses (Erwin 2009). Therefore, enhancing biodiversity is an important target and success criterion of wetland restoration and protection (Matthews and Endress 2008, Ma *et al* 2010). The biodiversity level is one of the most essential research hotspots in assessing protection efforts and future conservation planning.

To assess the effects of protection efforts, biodiversity maps have been widely used. Some research studies use the species–area relationship (SAR) method to determine the species capacity of land use/land cover (LU/LC) maps and then derive biodiversity at the landscape scale (Pereira and Daily 2006, Polasky *et al* 2008, Nelson *et al* 2009, Kennedy *et al* 2016). Other researchers used empirical equations to assess the biodiversity level of different types of vegetation; then, these studies have derived biodiversity maps for a landscape (Li 2007, Yi *et al* 2014). Tools to model the spatial distribution of biodiversity have been developed, including the Integrated Valuation of Ecosystem Services (InVEST) model (Sharp *et al* 2018), the GLObal BIOdiversity model for policy support (GLOBIO) (Alkemade *et al* 2009, Chaplin-Kramer *et al* 2015) and Artificial Intelligence for Ecosystem Services (ARIES) (Villa *et al* 2014). Most research related to biodiversity assessments has focused on using species abundance data to obtain the spatial distribution at regional and global scales (Maes *et al* 2012, Chaplin-Kramer *et al* 2015). Habitats with a favourable conservation status usually have richer biodiversity and vice versa (Maes *et al* 2012). Therefore, some research assessing the effects protection efforts focusses on assessing habitat area, quality and fragmentation (Hodgson *et al* 2011, Doerr *et al* 2011, Ke *et al* 2011, Sun *et al* 2015, Tang *et al* 2016). Biodiversity hotspots are widely used for conservation priority and planning, while recent studies are mostly based on species abundance and diversity (Myers *et al* 2000, Aben *et al* 2016, Cai *et al* 2018).

Regarding wetland restoration and protection, especially in areas where overwintering bird gather, research tends to use water bird species and their density or abundance to reflect the biodiversity status (Cui *et al* 2009, Xia *et al* 2016, Wang *et al* 2017, Hagy *et al* 2017), while only a few studies focus on the bird habitat status (Ke *et al* 2011, Xia *et al* 2016). Meanwhile, research has developed some habitat indices that reflect changes in biodiversity in wetland areas. For example, Zhao *et al* (2018) explored an efficient habitat index for assessing the population and abundance of overwintering water birds in the Poyang Lake wetland, South China, where a large protected area has been established.

Biodiversity assessments and conservation based on the abundance and diversity of species are increasingly used to reveal human-wildlife conflicts (König *et al* 2020) and possible trade-offs that may occur bewteen the different stakeholder groups (König *et al* 2015). Additionally, a conservation strategy cannot be based merely on the number of taxa present in an ecosystem (Marchese 2015). There is considerable controversy regarding the definition of species-rich. Currently, data on species distributions are usually scarce, and it is difficult to obtain long-term biological data. Moreover, as there is obvious biological heterogeneity among different regions it is difficult to choose the most representative and sensitive species in each region. All of these data quality issues cause biodiversity assessments and the development of conservation strategies to be unreliable (Marchese 2015). Therefore, we need a more comprehensive understanding of the complex biodiversity process, and we must consider additional factors, such as human activities and climate change (Marchese 2015). Although some methodological studies include factors such as habitat area, quality, fragmentation, human activities and climate (Ke *et al* 2011, Doerr *et al* 2011, Polasky *et al* 2011, Baral *et al* 2014, Tang *et al* 2016, Sallustio *et al* 2017, Cai *et al* 2018), these studies tend to consider only one or two factors and seldom use a combination of several factors; furthermore, these studies are rarely conducted using a combination of systematic, functional, dynamic and spatial perspectives. There is also controversy regarding whether protected areas optimally protect biodiversity (Liu *et al* 2001, Pimm *et al* 2014, Gray *et al* 2016). Therefore, more comprehensive assessments and more reasonable protection area planning are needed.

The objective of this paper is to assess the status of habitat for overwintering waterbirds in the Poyang Lake wetland considering the effect of nature reserves; then, based on a composite biodiversity index, we search for current biodiversity hotspots (i.e. sites of conservation priority) in this area.

1.1. Study area

We performed a case study in the Poyang Lake wetland located in the Jiangxi Province in Southeast China, as this is one of the most important international wetlands identified in the Ramsar convention and has several hundred thousand overwintering water birds (Ji *et al* 2007). Overwintering water birds here refers to birds that travel from their breeding places (mostly in Northeast Eurasia) to Poyang lake wetland every winter (Harris 2016). Poyang lake wetland is one of the most important stopover sites for water birds on the East Asian-Australasian flyway network (Xu *et al* 2019). Winter surveys at Poyang have recorded an average of 425 000 overwintering water birds (Harris 2016), these include four species of cranes, two stork species and several geese (Zhao *et al* 2018). Especially for the critically endangered Siberian crane (*Grus leucogeranus*) Poyang lake is a crucial site. 98% of the global population of

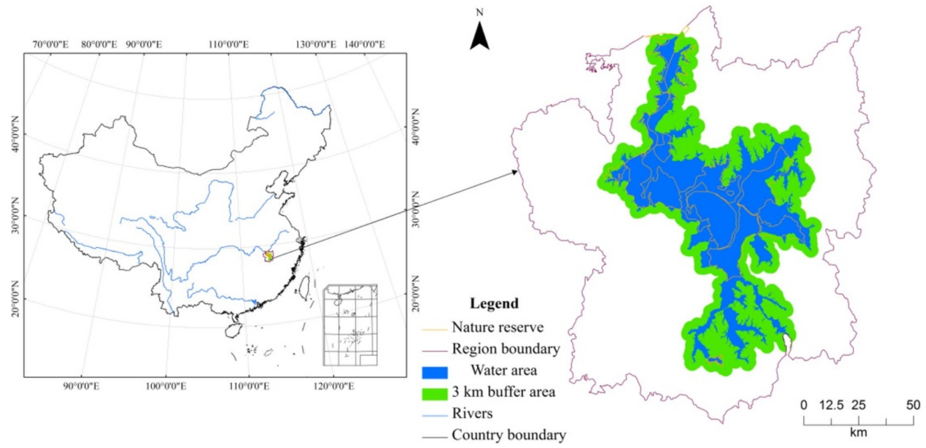


Figure 1. Maps of the study area.

3800–4000 birds overwinter here. They are specialised to forage on Vallisneria tubers in shallow water areas, whose occurrence is threatened by crab farms as well as major flood events (Burnham *et al* 2017). But also 50% of the vulnerable white-naped cranes (*Grus vipio*), 60% of the swan geese (*Anser cygnoid*) and 42% of the oriental white storks (*Ciconia boyciana*) in the world overwinter in Poyang Lake wetland (Xia *et al* 2010). In the past ten more years, some species increased, such as Common Cranes (*Grus grus*), Siberian crane (*Grus leucogeranus*), and some decreased, such as Swan goose (*Anser cygnoides*) (Shan *et al* 2014, Li *et al* 2014, An *et al* 2019). Another reason that we chose this sight is that there are eight overwintering water bird natural reserves in this area, which cover approximately 50% of the wetland area (Harris 2016). Moreover this region is a grain production area and has many kinds of human activities that threaten wildlife (Li *et al* 2016, 2018). In addition LU has changed substantially during the last two decades (Sun *et al* 2017).

Poyang Lake connects with the Yangtze River and the five other rivers in Jiangxi Province, and it is the largest freshwater lake in China (figure 1). Water exchanges between the rivers and the lake because of the monsoonal climate; thus, the water levels in this lake vary with season. These dramatic hydrological changes lead to equally dramatic ecological processes in Poyang Lake and directly affect the characteristics of its different habitats and rich biological diversity (Harris 2016, Xia *et al* 2016). The Poyang Lake wetland is rich in aquatic plants, plankton, benthic animals, fish and insects, and the wetland provides superior habitat and food for overwintering water birds. Mud area, shallow water area, and wet grassland area are the best habitats for overwintering water birds (Xia *et al* 2016).

This study area had three areas (figure 1): the wetland area, a 3 km buffer area from the wetland edge, and the Poyang Lake wetland region. The wetland land area is the area occupied by the highest water level. The buffer area was defined by ecological planning of the Poyang Lake region in 2009[6]. It is considered a transitional area with overwintering water birds and human activities. The Poyang Lake wetland region includes two county-level cities and ten counties. In our study, the habitats of overwintering water birds are all within the wetland area and buffer area. However, the human-induced factors are present in the entire Poyang Lake region.

A total of 14 wetland nature reserves have been established in the Poyang Lake region (Harris 2016), and eight of them are overwintering water bird nature reserves (figure 1). Most of the nature reserve was established approximately 1997–2003 with the exception of the Poyang national nature reserve. Here, we used the boundaries of all the nature reserves together to determine the statistics of the average habitat quality within or outside the nature reserve range. When analysing the years 1995/2005, the statistics refer to the habitat comparison before and after the nature reserves were established. When analysing the years 2005/2015, the statistics refer to the habitat change after the nature reserves were established.

2. Material and methods

2.1. Methods

To realize the object of our study, we first carried out a spatial and temporal habitat change analysis in and outside the nature reserve for the 3 years in the time period 1995–2015, during which most of the nature reserve was established. Our assessment was based on three dimensions: habitat quality (figure 2), threats and landscape fragmentation. Complementary to this, the InVEST model was used to evaluate the habitat quality for overwintering water birds. Second, we generated a composite biodiversity map and obtained the biodiversity hotspots based on a

[6]http://finance.ifeng.com/news/20 100 226/1 863 953.shtml

- Habitat quality: Refers to the ability of the environment to provide resource, it can be express by the land use land cover type and its degradation (Forman 2003; Sharp *et al* 2018).
- Habitat connectivity: The degree of the landscape facilitates the movement of species and other ecological flows (Taylor *et al* 1993).
- NPP: The net primary production of vegetation, which can reflect the status and the flexibility of the ecosystem; NPP is the basic condition of survival for all kinds of living beings in an ecosystem.

Figure 2. Definitions of habitat quality, connectivity and NPP.

composite biodiversity index, in which human activities, climate and ecosystem process factors were considered.

2.1.1. Habitat quality

We used the InVEST model (3.6.0, Sharp *et al* 2018) to evaluate the overwintering water bird habitat quality for the years 1995, 2005 and 2015 in the Poyang Lake wetland. The InVEST approach was originally developed to assess ES in a quantifiable and spatial way. This approach is particularly suitable for studying wildlife habitat quality and has been proven to be effective in characterizing biodiversity (Sallustio *et al* 2017). Compared to other methods, the InVEST method offers the advantage of considering the human impacts on wildlife habitat. For habitat quality evaluation, InVEST considers several parameters, including habitat suitability and threat types (e.g. urban, transportation, and industry), threat intensity, distance between the habitat and the threat, habitat sensitivity to a threat and accessibility of the habitat (Sharp *et al* 2018). In our study, we chose urban areas, village areas, other construction land (construction land outside urban and village areas such as mining area, airport area and industry area), farmland, fish ponds and transportation systems (including different types of roads) as the threat factors. We define mud area, shallow water, and wet grass land within the nature lake area and paddy field, sparse shrub area, grassland area within the 3 km buffer area as the habitat for overwintering water birds (Xia *et al* 2010, Sun *et al* 2015).

The output of the InVEST model for habitat quality is grid format data, and the value of the grid map ranges from 0 to 1; higher values represent high habitat quality, and vice versa. More recent studies have used InVEST to evaluate habitat quality (Terrado *et al* 2016, Kennedy *et al* 2016, Lin *et al* 2017, Sallustio *et al* 2017). InVEST has great advantages in evaluating habitat quality based on LU/LC data on a large scale. However, one of the biggest disadvantages of the habitat quality evaluation application is that the threat of the study area boundary has been ignored. To minimize this disadvantage, we consider not only the threats within the wetland area but also the threats from the area outside of the wetland, namely the entire Poyang lake region. For more information on the theory of how InVEST evaluates habitat quality and how we defined the parameters in our study case, please see the appendix (available online at stacks.iop.org/ERL/15/125013/mmedia).

2.1.2. Landscape fragmentation

FRAGSTATS 3.4 (software package) was used to calculate the landscape metrics for each LU map in the Poyang Lake wetland. Five commonly used landscape-scale landscape fragmentation metrics were selected (Ke *et al* 2011), including the number of patches (NP), patch density (PD), splitting index (SPLIT), landscape division index (DIVISION) and aggregation index (AI). The definitions and descriptions of these landscape metrics in FRAGSTATS are given in the FRAGSTATS user's guide (Mcgarigal and Marks 1995).

2.1.3. Connectivity index

Pascual Hortal and Saura developed the connectivity index 'probability of connectivity' (PC) to represent the habitat connectivity conditions at the landscape scale (Hanski 1998, Pascual-Hortal and Saura 2006, Saura and Josep 2009). The PC index can be expressed by following formula:

$$I_{\mathrm{PC}} = \frac{\sum_{i=0}^{n}\sum_{j=0}^{n} a_i \cdot a_j \cdot P_{ij}^{*}}{A_{\mathrm{L}}^{2}} \quad (1)$$

where n is the patch amount at the landscape scale, and a_i and $\mathrm{a_j}$ are the areas of the patches i and j, respectively. A_{L} indicates the total area of the study area. P_{ij}^{*} refers to the expanding probability between patch i and j. In this study, PC is used to assess the connectivity ability of each habitat patch. Conefor Inputs for ArcGIS 10.0 (software package) and ConeforSensinode 2.6 (software package) were integrated to calculate the PC index.

2.1.4. Biodiversity index

From the landscape-scale perspective, high-level biodiversity can be defined from three aspects (Yu

1999, Yu *et al* 2009): First, it can support high-level ES. Second, it can reflect the connectivity of habitat patches. Third, it can prevent habitat degradation. Specifically, energy is the basis of survival for all kinds of living beings, and net primary productivity (NPP, figure 2) is an appropriate index that can be used to represent the energy produced by vegetation. Habitats with high productivity have more available sources and sustain more individual populations, increasing the survival probability of species (Wright 1983, Evans *et al* 2005, Liu *et al* 2015, Lausch *et al* 2016, Cai *et al* 2018). Habitat connectivity (figure 2) is crucial for maintaining ecological processes in good condition. Habitat connectivity is also a key factor in maintaining the stability of biodiversity and ecosystems (Taylor *et al* 1993, Matlack and Monde 2004). Habitat degradation determines habitat quality, and habitat quality depends on LU structure and the level of intensity in the surrounding area (Sharp *et al* 2018).

According to many related studies (Xie *et al* 2018), in this paper, we established a composite biodiversity index at the landscape scale by integrating NPP, habitat connectivity and habitat quality (Formula 2), in which each aspect was considered to be equally important because they are all crucial for biodiversity protection and ecological stability.

$$\mathrm{BI} = \mathrm{NPP} + \mathrm{CON} + \mathrm{HQ} \tag{2}$$

In this formula, BI (biodiversity index) represents the biodiversity level at the landscape scale. In our study, we calculated the average NPP of December, January and February from 2000 to 2010 as the NPP level of the Poyang Lake wetland and then standardized the NPP value into the range of 0–1. These 3 months were chosen because all kinds of overwintering water birds stay in the Poyang Lake wetland during this period. CON (connectivity) represents the connectivity of each habitat patch, ranging from 0 to 1. HQ (habitat quality) refers to the habitat quality, which is obtained from the InVEST model and ranges from 0 to 1

We make principle components analysis before we use formula 2. 5000 points were randomly chosen in the study area and they were assigned the value of NPP, CON and HQ. The principle components analysis shows that the initial Eigen values of NPP and HQ is 1.793 and 1.005 respectively, and they explain 93.24% of the variations. Therefore, we keep NPP and HQ and change formula 2 into formula 3. In our study we use formula 3 to calculate biodiversity on landscape scale:

$$\mathrm{BI} = \mathrm{NPP} + \mathrm{HQ} \tag{3}$$

It is feasible to reflect the potential threat and biodiversity spatial distribution when integrating GIS and ecological models to evaluate biodiversity at the landscape scale (Polasky *et al* 2011, Baral *et al* 2014, Chaplin-Kramer *et al* 2015, Su *et al* 2016). By integrating these two types of biodiversity indicator, we can obtain grid format maps (30 m) of the composite biodiversity index, and its final value was transformed into the range of 0–1, with higher values representing higher biodiversity levels.

2.1.5. Biodiversity hotspot

Areas with high concentrations of endemic species and with high habitat losses are often referred to as 'biodiversity hotspots' (Myers 1988). A broad definition refers to any area or region with exceptionally high biodiversity at the ecosystem, species and genetic levels (Marchese 2015). Spatial autocorrelation analysis can be used to identify biodiversity hotspots at landscape scale (Aben *et al* 2016, Cai *et al* 2018). The G_i^* index is the most commonly used coefficient for spatial autocorrelation analysis. It is based on partial spatial autocorrelation using a distance weighted matrix, which can detect aggregates of high-value areas and low-value areas. The G_i^* index was proposed by Getis and Ord (1992), and it is expressed by the following equation:

$$G_i^* = \frac{\sum_j^n W_{ij} x_j}{\sum_j^n x_j} \tag{4}$$

G_i^* can be standardized to $Z\left(G_i^*\right)$ (Getis and Ord 1992):

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{\mathrm{VAR}(G_i^*)}} \tag{5}$$

In these two equation, n is the total amount of spatial unit. x_j is the attribute value of the spatial unit in a partial spatial area. W_{ij} is the distance weight between unit i and j; W_i is the sum of all the distance weights; $\bar{x}$ is the average of all the attribute values in the study area. $E(G_i^*)$ is the mathematical expectation of G_i^* and $\mathrm{VAR}(G_i^*)$ is the variance of G_i^*.

When $Z(G_i^*) > 0$, the value of the unit is higher than that of the neighbour unit; $Z(G_i^*) > 0$ means the opposite. When $Z(G_i^*) > 1.96$, it is a high-value area, namely, a hotspot area (Fen and Ying 2005). When $Z(G_i^*) < -1.96$, it is a low-value area, namely, a cold spot area. In our study, based on the grid maps of the biodiversity index, we used ArcGIS spatial autocorrelation tools to conduct the hotspot analysis.

2.2. Data resources

We obtained LU/LC and transportation data for 1995, 2005 and 2015 from the Resource and Environment Data Cloud platform of China (www.resdc.cn/). The LU/LC data have a spatial resolution of 30 m, with 25 LC classes. The transportation data were in GIS shapefile format, including data for railways, high-speed roads, primary roads, secondary roads and ordinary roads. NPP data were obtained from the

Table 1. Habitat change during the two study phases within and outside nature reserve.

	1995–2005				2005–2015			
	Area (ha)		Average quality		Area (ha)		Average quality	
Habitat change type	Within	Outside	Within	Outside	Within	Outside	Within	Outside
Newly created habitat	1014	5928	0.76	0.58	2801	6532	0.86	0.67
Lost habitat	459	6340	−0.69	−0.57	2611	10 988	−0.90	−0.54

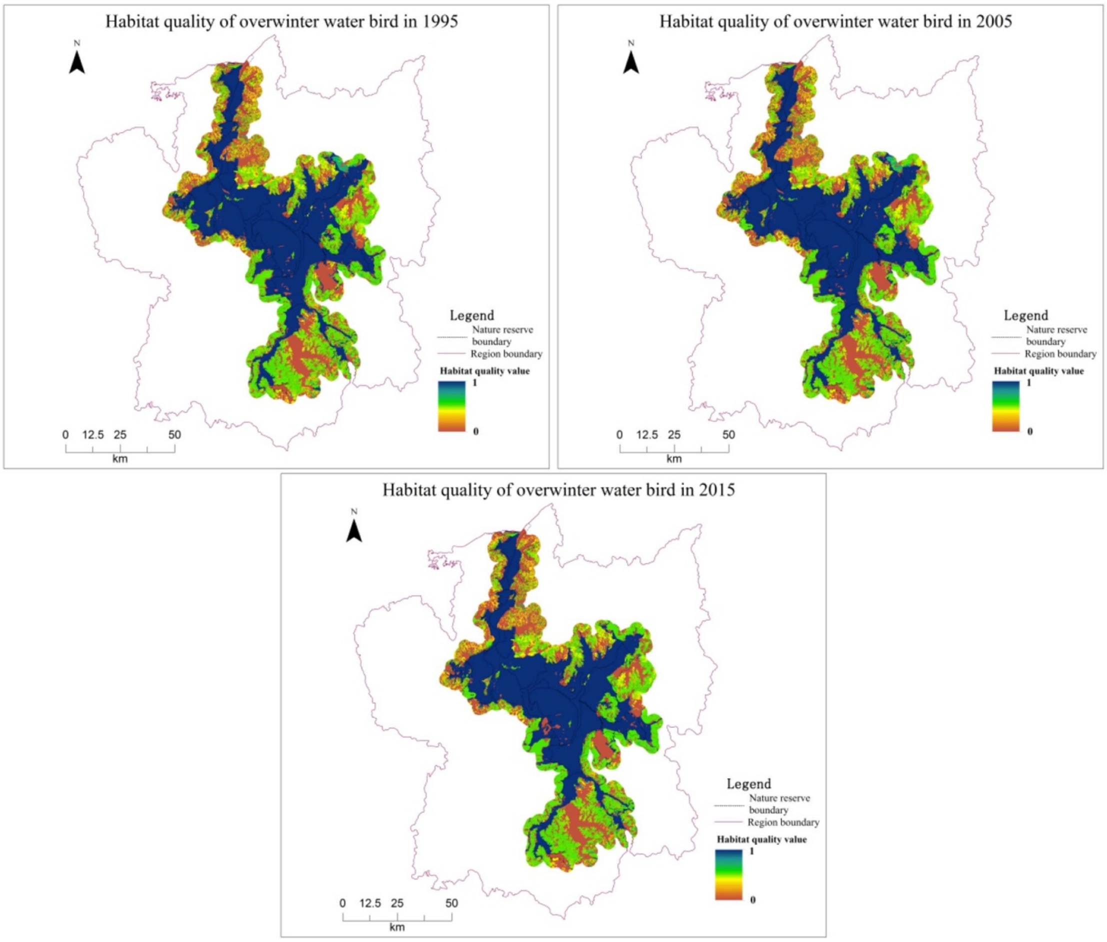


Figure 3. Spatial distribution of habitat quality of overwintering water birds in 1995, 2005 and 2015.

'National ecosystem remote sensing survey of the year 2000–2010' project (Ouyang *et al* 2014). These data are in grid format with a resolution of 250 m.

The nature reserve boundary was obtained from each nature reserve administration. The overwintering water bird natural habitat extents of Poyang Lake were obtained from a project called the National Key Basic Research Program (973 Program). The name of this project is the National Main Terrene Ecosystem Service Function and Ecosystem Security of China. These habitat ranges were reinterpreted from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) remote sensing images (30 m resolution) at different water levels. By combining all of the interpreted results, the final overwintering water bird natural habitat ranges could be obtained.

3. Results

3.1. Habitat area and quality changes within and outside the nature reserve

The habitat of overwintering water bird experienced big change during both study periods. From 1995 to 2005, habitat within the nature reserve showed a positive change. The area of newly created habitat (none habitat changed into habitat) within the nature reserve is about twice the area of lost habitat (habitat changed into none habitat) (table 1). The absolute value of average habitat quality in new habitat areas is higher than in the lost habitat area. However, in this phase, habitat change outside the nature reserve showed a similar change amount both on habitat area and absolute value of average habitat quality. From 2005 to 2015, the habitat area experienced larger

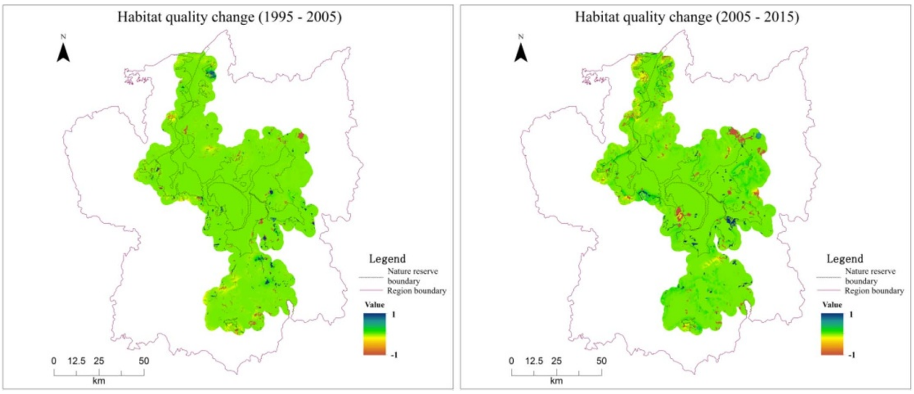


Figure 4. Habitat quality change during 1995–2005 and 2005–2015.

Table 2. Change ratios of human occupied area (for 'roads' calculated by length).

	Change (outside nature reserve)		Change (within nature reserve)	
Threat	1995–2005	2005–2015	1995–2005	2005–2015
Farmland	−2.25%	−3.48%	−7.19%	−3.10%
Fish farm	−1.27%	2.59%	−2.86%	8.09%
City area	16.98%	35.80%	0.00%	43.50%
Village area	1.37%	2.49%	−3.21%	−8.90%
Other construction	21.77%	156.52%	−15.33%	−56.12%
Road (km)	8.10%	28.08%	13.93%	28.52%

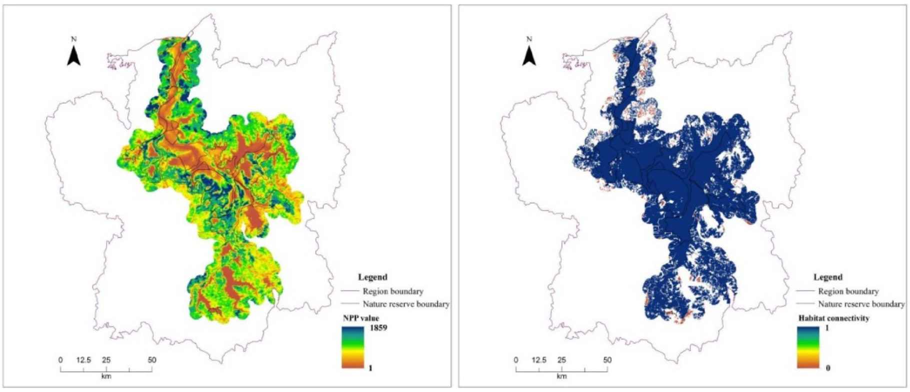
Table 3. Landscape change during 1995–2015.

	Change outside nature reserve		Change within nature reserve	
Indicator	1995–2005	2005–2015	1995–2005	2005–2015
NP	1.85%	−0.14%	5.62%	0.37%
PD	1.84%	−0.14%	5.63%	0.37%
SPLIT	0.69%	6.34%	−1.38%	1.37%
DIVISION	0.01%	0.08%	−2.70%	2.68%
AI	0.03%	0.08%	0.01%	0.04%

NP: number of patches; PD: patch density; SPLIT: splitting index; DIVISION: landscape division index; AI: aggregation index.

change than in the first phase. Within the nature reserve, the change area of new habitat and lost habitat was very close, as well as their absolute habitat quality change. Referring to the habitat change outside nature reserve, there was a large amount of habitat area change. A lot of habitat (10 988 ha) turned into another kind LU type, about twice as large as the newly created habitat. The main reason is that a very large area of paddy fields turned into another kind of none habitat such as fish farming (1463 ha), urban area (377 ha), village area (591 ha) and other construction area (1568 ha). Additionally, there was also a large amount of sparse forest area (1822 ha) turned into high coverage forest which is not suitable for overwintering water birds. For the habitat quality outside the nature reserve, the absolute value of average habitat quality in newly created habitat areas was higher than the lost habitat area. The reason is that the lost habitat area was mostly paddy field and sparse shrub area, with a comparatively low habitat quality.

From the habitat quality maps of 1995, 2005 and 2015 (figure 3), most of the high quality habitats were distributed in the wetland area, while the low quality habitat was distributed in the buffer area. In 1995, there was only one nature reserve (Poyang national nature reserve); in this nature reserve, almost the entire area was of high quality. By 2005, all the overwintering water bird nature reserves had been created, and most nature reserves had high habitat quality. However, some parts of the nature reserve in the north, east and south of the Poyang Lake wetland had low quality. During 1995–2005, most of the habitat change area was outside the nature reserve range, and its areas that increased and decreased were approximately equal (figure 4). However, within the nature reserve area, changes were much less. In 2015, all nature reserves had already existed for a long time, and most nature reserve areas still had high-quality habitats. During 2005–2015, there were large areas of habitat quality change both inside and outside the nature reserve, and most of the



(a) (b)

Figure 5. Spatial distribution of the long-term average NPP value (left, gC/($m^2 \cdot a$)) and habitat connectivity value in 2015 (right) in the Poyang Lake wetland.

change occurred around the edge of the nature reserve (figure 4).

3.2. Change ratios of human occupied area (threats) within and outside the nature reserve

Generally, in both stages, the human-related LU/LC type experienced a decreasing trend within the natural reserve range while increasing in the area outside the nature reserve range. Regarding the threats within the nature reserve range, most of the threats decreased during both stages (table 2). During 1995–2005, nearly all threats experienced a large decrease except for the roads. Compared to the first stage, half of the threats during 2005–2015 decreased, while the others increased obviously. In this stage, fish farms were the most obvious increasing threat, increasing by 729 ha, which was nearly 65% of the total change in threats within the nature reserves. Many paddy fields and natural wetlands changed into fish farms during this stage.

As for threats outside the nature reserve, almost all of the threats increased in both study stages, except for farmland reduction in both stages and fish farm reduction in the first stage. Specifically, the farmland decreased (1116.67 ha) and the fish farm decreased (815.15 ha) were the most important threat changes during 1995–2015. However, during 2005–2015, the most important changes were the farmland decrease (1685.63 ha), the fish farm increase (1636.64 ha) and other construction land increases (2735.61 ha).

3.3. Fragmentation change in landscape within and outside the nature reserve

The change trends from fragmentation were not completely constant with the change trends of habitat quality and its threats. Generally, the NP and PD increased during the study period, especially within the range of the nature reserves (table 3). However, the main reason for these trends was that water-related LC types (such as rivers, lakes, muds and marshlands) changed into each other because of the frequent increase and decrease of the water level in Poyang Lake. These habitats are all natural habitats for overwintering water birds; they change into each other but still connect together, which does not have an obvious impact on habitat quality.

Other landscape indicators showed an improvement in landscape quality within the range of the nature reserves in the first study stage, but there was a decrease in the second stage. The SPLIT and DIVISION indicators decreased during 1995–2005. Meanwhile, the AI slightly increased in the same period. However, the landscape split and division increased during 2005–2015, which means, from the perspective of the whole landscape, different types of landscape patches were created after the nature reserve has existed for many years. However, the same type of landscape patches became slightly aggregated in this stage. As for outside the nature reserve, different types of landscape patches split and the same type of landscape patches aggregated in both study stages; however, these trends were more apparent in the second stage.

3.4. Biodiversity index and biodiversity hotspot analysis

According to equation (4), we combined the long-term average NPP map (figure 5(a)) and the habitat quality map (figure 3), we obtained the current biodiversity index value map of overwintering water birds (figure 6). This map is consistent with the natural reserve range. From this figure, we also know that most of the high biodiversity values were distributed in the southwest portion of the Poyang Lake area, especially within the Poyang Lake national nature reserve, the Nanjishan national nature reserve and the Kangshan nature reserve.

Considering the importance of habitat connectivity, we kicked out the area where habitat connectivity

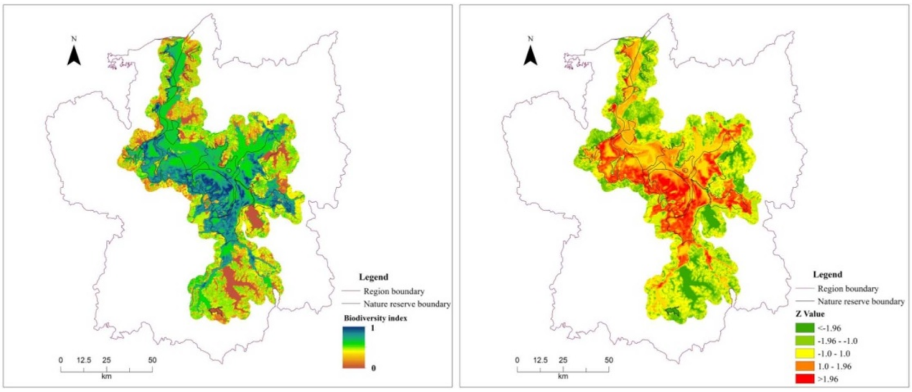


Figure 6. Current spatial distribution of the biodiversity index (left) and spatial distribution of Z(G_i^*) in the Poyang Lake wetland (right).

Table 4. Current areas of hotspots and coldspots in the Poyang Lake wetland.

	Hotspot		Coldspot	
	Within nature reserve	Outside nature reserve	Within nature reserve	Outside nature reserve
Area (Ha)	96 205	36 341	10 277	112 852
Ratio	72.58%	27.42%	8.35%	91.65%

is under 0.5, namely biodiversity value in these area was assigned as 0. Then using spatial autocorrelation analysis, we obtained the current spatial distribution of Z (G_i^*) in the Poyang Lake wetland (figure 6). According to this map, the biodiversity hotspot area is 132 546 ha (table 4), which is 17.89% of the entire habitat area. By comparing the biodiversity hotspot distribution inside and outside the nature reserve, we find that 72.58% of the hotspot area is within the nature reserve. However, the other 27.42% of the hotspot area represents the potential biodiversity abundance area, which can be included in the nature reserves in the future. Meanwhile, there are 123 130 ha of coldspot area in the overwintering bird habitat area, accounting for 16.61% of the entire habitat area. For these coldspots, 8.35% are in the nature reserve, and these sites are inappropriate for biodiversity protection.

4. Discussion

4.1. Nature reserve protection effects and policy implication

In this study, we assessed the protection effects of overwintering bird habitat from three dimensions: habitat quality, threats and landscape fragmentation. The results showed that habitat represented by these indicators had similar change tendencies during the study phases, but presented a lot of differences as well. Previous studies tended to either focus on habitat and threats (e.g. Polasky *et al* 2011, Sun *et al* 2015, Tang *et al* 2016) or on landscape fragmentation (e.g. Ke *et al* 2011, Wang *et al* 2013). This approach can lead to inaccurate results. Our assessment method not only considers the landscape structure but also includes the human impact factors. Moreover, the interaction between human impact factors and habitat itself is considered.

Regarding the final protection effect of the nature reserve, our results showed that the nature reserve had a positive effect on biodiversity conservation when compared to habitat change outside the nature reserve. However, there are also tremendous changes in the Poyang lake wetland, including a lot of changes within the nature reserve, which shows that the role of the protected area still needs to be discussed, as many previous studies have noted (Liu *et al* 2001, Pimm *et al* 2014, Gray *et al* 2016). Sun *et al* (2015) conducted some village-scale studies in the Poyang Lake wetland and showed a more obvious improvement in overwintering water bird habitat as a result of ecological restoration projects, such as returning farmland to lake and returning farmland to forest in some villages (Sun *et al* 2015). Our study also showed similar improvements during 1995–2005, when tremendous ecological restoration projects were implemented. However, after that stage, although there were still some ecological restoration projects, a lot of restored ecological land turned back into cultivated land because of economic reasons (Jiang 2006, Harris 2016). And also large amounts of paddy field turned into fish farming, in there, overwintering water birds were hardly visited (Sun *et al* 2015). Moreover, as showed before, there were many constructions during 2005–2015, especially outside the nature reserve, which not only occupied some habitat, but also made great pressure on the habitat. Habitat conditions during migration can influence bird survival (Hewson *et al* 2016). All the degradation in Poyang lake wetland might impede movement and thereby reduce migration success and survival. Finally, it will breakdown migration networks and impact the bird survival in the breeding place in Northeast Eurasia. In fact, the connectivity of East Asian–Australasian flyway migration networks decreased continuously over the past 15 years because of deteriorating environmental conditions (Xu *et al* 2019). For example wetlands has been decrease obviously during the past ten more years in Yangtze river basin in China (Xu *et al* 2019). Some of the stop sites no longer being utilized by migrants (Verkuil *et al* 2012). Therefore, as the most important overwintering bird area in east Asia, the conservation effects in Poyang lake wetland has great influence on protection of overwintering birds in Northeast Eurasia. The nature reserve conservation policy should also be combined with restoration engineering measures for the threats from human being. For example, we should be aware that by 2015, there were still 1238 ha of human settlements and farms and154.41 km of road within the nature reserve, and these should be eliminated gradually, except for some infrastructure for protection. Even if they cannot be removed, human-related LU management should be more strictly implemented. A priority for conservation efforts should be to develop whole-lake management plans for wetland systems (Wang *et al* 2017).

4.2. Framework of biodiversity index

We have built a biodiversity index to determine the spatial distribution of biodiversity in the Poyang Lake wetland. The NPP, habitat connectivity and habitat quality are considered in this index. These three indices are crucial to keeping the biodiversity and ecosystem stable and integrated (Yu 1999, Yu *et al* 2009, Wu *et al* 2013, Xie *et al* 2018), as these factors represent the source basis, ecosystem process and interaction of habitat and human factors at the same time. However, before using the comprehensive biodiversity index, principle components analysis should be used to reduce colinearity.

For the three indicators, firstly, habitats with high productivity provide more available sources and energy to sustain more individuals and viable populations, increasing the survival probability and decreasing the extinction risk of species (Wright 1983, Evans *et al* 2005). Some case studies have shown that species richness is highly related to NPP (Wu *et al* 2014, Cai *et al* 2018). However, it is difficult to obtain long-term biological data in field studies, yet with the rapid development of remote sensing technology, building a regional NPP dataset is feasible and realistic. Therefore, NPP is an ideal data type for biodiversity assessments. Species data limitations call for the further exploration of the potential of remote to characterize habitat features related to diversity and abundance at spatial scales relevant to conservation and management (Dronova *et al* 2016). NPP is determined by photosynthesis, temperature, precipitation and evaporation (Cramer *et al* 1999, Liu *et al* 2015). Therefore, climate factors are also included in our biodiversity index. Climate factors are likely to have a large impact on biodiversity, from organisms to biomes (Céline *et al* 2012). In our study, in order to avoid the climate fluctuate impact on currently biodiversity status, we used a long period (2000–2010) of average monthly (from December to February) NPP values to express the current NPP spatial distribution in the Poyang Lake wetland.

Second, habitat quality assessments consider habitat suitability and human activities (threats), but if a patch of high quality is isolated from other habitats, it will not exchange with others. Our results also indicated that the habitat quality change tendency is not completely in agreement with the change in landscape fragmentation. Therefore, both habitat quality and habitat connectivity should be included in the biodiversity index. Habitat connectivity is an important indicator for measuring ecosystem processes (Xiong *et al* 2008). Habitat connectivity is one of the key factors for biodiversity conservation and maintains the stability and integration of ecosystems (Taylor *et al* 1993). Highly connected patches are more efficient in realizing ecosystem function, and a higher connectivity value indicates a higher capability for ecosystem circulation (Matlack and Monde 2004). For the wetland area, an individual wetland seldom meets all the requirements (e.g. foraging, resting, roosting, and nesting sites Thus, connectivity can provide the resources required by diverse waterbirds (Kelly *et al* 2008, Ma *et al* 2010), and connectivity also increases the potential food availability for water birds. However, hydrological fluctuations are important features in wetland areas; thus, hydrological connectivity should be included in future studies (Xia *et al* 2016, Hagy *et al* 2017).

Except for climate change, LU is the most important factor expected to drive unprecedented rates of biodiversity degradation (Riordan and Rundel2014). Habitat quality assessments by InVEST are based on LU/LC data, and InVEST has great advantages in terms of quantifying the impact of spatial human activities on habitat. It has also been proven to be reliable in large-scale assessments (Sallustio *et al* 2017) and has been widely used in many case studies (Terrado *et al* 2016, Kennedy *et al* 2016, Lin *et al* 2017, Sallustio *et al* 2017). However, there are some concerns about InVEST regarding its oversimplification and tendency to smooth habitat complexity over the landscape (Sallustio *et al* 2017), especially in the high biodiversity portion of the study area. To reduce this problem in our study, we used the long-term (2000–2010) average biomass amount of each habitat type to represent the relative habitat suitability in the Poyang Lake wetland. Another limitation of the InVEST model application is that most current studies do not consider the threats outside the study area; however, these threats also have a large impact on habitat quality (Baral *et al* 2014, Sharp *et al* 2018). In our study, we included all the threats from the entire Poyang Lake wetland region, which minimized this problem.

4.3. Biodiversity hotspot for conservation priority area

Biodiversity hotspots have become a tool for setting conservation priorities to minimize human-wildlife conflicts (König *et al* 2020) and play an important role in biodiversity preserve decision-making (Marchese 2015). In addition, biodiversity hotspots should be used in a more comprehensive way (e.g. Marchese 2015). Our study obtained biodiversity hotspots based on the biodiversity index from a broad sense of biodiversity hotspot definition. Since Myers (1988) built up the concept of biodiversity hotspots, vulnerability and irreplaceability are the core measure for conservation planning (Margules and Pressey 2000). Most related studies focus on high concentrations of endemic species and high habitat loss. However, the species-related hotspot approach ignores some important biodiversity dimensions because the ecosystem is a complicated and dynamic system (Pereira *et al* 2013). For example, wetlands are considered one of the largest unknown element dynamics and matter flux ecosystems (IPCC (International Panel on Climate Change) 2001), and even the water birds that use the habitats might not correctly reflect the quality of the wetland habitats (Horne 1983). Therefore, hotspot analysis based on the bottom of the ecosystem impact factors, such as NPP, habitat connectivity and habitat quality, might be a feasible and effective method that can be used for biodiversity hotspot analysis. We should also emphasize that there are obvious spatial autocorrelations among species and among the different habitat patches (Liu *et al* 2010). Previous species-related biodiversity hotspot analysis seems to neglect this aspect. In our study, we included spatial autocorrelation analysis in the biodiversity hotspot approach. For biodiversity conservation, normally, current biodiversity hotspots in our study could be used as conservation priority area. However, there are also some other areas that need to be protected, for example, during last several decades, there were tremendous high quality habitat areas lost, which could be restored and be included in the conservation priority area.

5. Conclusion

The overall objective of this paper was to assess the protective effect of overwintering water bird habitat quality by considering nature reserves and searching for conservation priority areas in the Poyang Lake wetland. By comparing the habitat, threats and landscape fragmentation change within and outside the nature reserve, we concluded that the nature reserve had a positive effect on the habitat of overwintering water birds. However, tremendous changes indicate that the effect of the protection area still needs to be discussed, as many previous studies have noted. In the future, nature reserve conservation policy should also be combined with restoration engineering measures and regional synthesis LU management plans should be carried out.

The results of the habitat assessment also indicated that the built biodiversity index should not consider only habitat quality or only landscape fragmentation. A comprehensive biodiversity index framework based on NPP, habitat connectivity and habitat quality needs to be built for habitat assessment and for identifying areas of protection priority. This biodiversity index should represent the ecosystem source basis, ecosystem process and human activity impact on ecosystems. Finally, biodiversity hotspot analysis based on the biodiversity spatial distribution showed that the protected areas should be re-planned and redesigned in the near future in our study area.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This research was supported by National Key Research and Development Program of China (No. 2019YFC0507802); The Natural Sciences Foundation of China (No. 41601575); Youth Innovation Promotion Association of the Chinese Academy of Sciences (No. 2020055).

Funding was also provided by the Marianne und Dr Fritz Walter Fischer- Foundation for the junior research group LandSTRAT (Human-Wildlife Conflicts and Coexistence in Agricultural Landscapes) as well as from the Leibniz Centre for Agricultural Landscape Research (ZALF).

ORCID iDs

Chuanzhun Sun https://orcid.org/0000-0003-2642-4269
Hannes J König https://orcid.org/0000-0002-4980-7388
Sandra Uthes https://orcid.org/0000-0002-2527-7052
Cheng Chen https://orcid.org/0000-0003-1318-2854
Peng Li https://orcid.org/0000-0002-0849-5955
Karoline Hemminger https://orcid.org/0000-0003-1321-2224

References

Aben J, Bocedi G, Palmer S C F, Pellikka P, Strubbe D, Hallmann C, Travis J M J, Lens L and Matthysen E 2016 The importance of realistic dispersal models in conservation planning: application of a novel modelling platform to evaluate management scenarios in an afrotropical biodiversity hotspot *J. Appl. Ecol.* **53** 1055–65

Alkemade R, Oorschot M V, Miles L, Nellemann C, Bakkenes M and Brink B T 2009 Globio3: a framework to investigate options for reducing global terrestrial biodiversity loss *Ecosystems* **12** 374–90

An A, Cao L and Jia Q 2019 Changing abundance and distribution of the wintering Swan Goose Anser cygnoides in the middle and lower Yangtze River floodplain: an investigation combining a field survey with satellite telemetry *Sustainability* **11** 1398

Baral H, Keenan R J, Sharma S K, Stork N E and Kasel S 2014 Spatial assessment and mapping of biodiversity and conservation priorities in a heavily modified and fragmented production landscape in north-central Victoria, Australia *Ecol. Indic.* **36** 552–62

Burnham J, Barzen J, Pidgeon A M, Sun B T, Wu J D, Liu G H and Jiang H X 2017 Novel foraging by wintering Siberian cranes *Leucogeranus leucogeranus* at China's Poyang Lake indicates broader changes in the ecosystem and raises new challenges for a critically endangered species *Bird Conserv. Int.* **27** 204–23

Cai T *et al* 2018 What makes the Sino-Himalayan mountains the major diversity hotspots for pheasants? *J. Biogeogr.* **45** 640–51

Céline B, Bertelsmeier C, Leadley P, Thuiller W and Courchamp F 2012 Impacts of climate change on the future of biodiversity *Ecol. Lett.* **15** 365–77

Chaplin-Kramer R *et al* 2015 Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage *Proc. Natl Acad. Sci.* **112** 7402–7

Costanza R *et al* 1997 The value of the world's ecosystem services and natural capital *World Environ.* **387** 253–60

Cramer W, Kicklighter D, Bondeau A, Iii B M, Churkina G, Nemry B, Ruimy A and Schloss A L The Participants of The Potsdam NPP Model Intercomparison 1999 Comparing global models of terrestrial net primary productivity (NPP): overview and key results *Glob. Change Biol.* **5** iii–iv

Cui B, Yang Q, Yang Z and Zhang K 2009 Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China *Ecol. Eng.* **35** 1090–103

Doerr V A J, Barrett T and Doerr E D 2011 Connectivity, dispersal behaviour and conservation under climate change: a response to Hodgson *et al J. Appl. Ecol.* **48** 143–7

Dronova I, Beissinger S R, Burnham J W and Peng G 2016 Landscape-level associations of overwinter water bird diversity and abundance from remotely sensed wetland characteristics of Poyang Lake *Remote Sens.* **8** 462

Erwin K L 2009 Wetlands and global climate change: the role of wetland restoration in a changing world *Wetlands Ecol. Manage.* **17** 71–84

Evans K L, Warren P H and Gaston K J 2005 Species-energy relationships at the macroecological scale: a review of the mechanisms *Biol. Rev.* **80** 1–25

Fen X S and Ying L G 2005 An exploratory spatial data analysis of SARS epidemic in China *Adv. Earth Sci.* **20** 282–91

Forman R 2003 *Road Ecology: Science and Solutions* (New York: Island Press)

Fraser L H and Keddy P A 2005 *The World's Largest Wetlands: Ecology and Conservation* (Cambridge: Cambridge University Press)

Getis A and Ord J K 1992 The analysis of spatial association by use of distance statistics *Geogr. Anal.* **24** 189–206

Gray C L, Hill S L L, Newbold T, Hudson L N, Borger L, Contu S, Hoskins A J, Ferrier S, Purvis A and Scharlemann J P W 2016 Local biodiversity is higher inside than outside terrestrial protected areas worldwide *Nat. Commun.* **7** 12306

Hagy H M, Hine C S, Horath M M, Yetter A P, Smith R V and Stafford J D 2017 Waterbird response indicates floodplain wetland restoration *Hydrobiologia* **804** 119–37

Hanski I, 1998 Connecting the parameters of local extinction and metapopulation dynamics *Oikos* **83** 390–6

Harris J 2016 Poyang Lake, Yangtze River Basin, China *The Wetland Book* (Berlin: Springer) (https://doi.org/10.1007/978-94-007-6173-5_34-2)

Hewson C M, K. Thorup J W, Pearce–Higgins and Atkinson P W 2016 Population decline is linked to migration route in the Common Cuckoo *Nat. Commun.* **7** 12296

Hodgson J A, Moilanen A, Wintle B A and Thomas C D 2011 Habitat area, quality and connectivity: striking the balance for efficient conservation *J. Appl. Ecol.* **48** 148–52

Horne B V 1983 Density as a misleading indicator of habitat quality *J. Wildl. Manage.* **47** 893–901

IPCC (International Panel on Climate Change) 2001 Climate change 2001: impacts, adaptation, and vulnerability. Technical summary, and summary for policymakers. Third assessment report of working group I of the intergovernmental panel on climatic change

Ji W, Zeng N, Wang Y, Gong P, Xu B and Bao S 2007 Analysis on the waterbirds community survey of Poyang lake in winter *Ann. GIS* **13** 51–64

Jiang L G 2006. Flood risk and land-use change in the Wetland restoration area around Poyang Lake China, PhD diss. (Beijing, China: Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences) (in Chinese)

Ke C Q, Zhang D, Wang F Q, Chen S X, Schmullius C, Boerner W M and Wan H 2011 Analyzing coastal wetland change in the Yancheng national nature reserve, China *Reg. Environ. Change* **11** 161–73

Kelly J P, Stralberg D, Etienne K and Mccaustland M 2008 Landscape influence on the quality of heron and egret colony sites *Wetlands* **28** 257–75

Kennedy C M *et al* 2016 Optimizing land use decision-making to sustain Brazilian agricultural profits, biodiversity and ecosystem services *Biol. Conserv.* **204** 221–30

König H J, Kiffner C, Kramer-Schadt S, Fürst C, Keuling O and Ford A T 2020 Human–wildlife coexistence in a changing world *Conserv. Biol.* **34** 786–94

König H J, Podhora A, Zhen L, Helming K, Yan H, Du B, Wübbeke J, Wang C, Klinger J, Chen C and Uthes S 2015 Knowledge brokerage for impact assessment of land use scenarios in inner Mongolia, China: extending and testing the FoPIA approach *Sustainability* **7** 5027–49

Lausch A *et al* 2016 Linking earth observation and taxonomic, structural and functional biodiversity: local to ecosystem perspectives *Ecol. Indic.* **70** 317–39

Li P, Jiang L, Feng Z, Sheldon S and Xiao X 2016 Mapping rice cropping systems using Landsat-derived renormalized index of normalized difference vegetation index (RNDVI) in the Poyang lake region, China *Frontiers Earth Sci.* **10** 303–14

Li P, Xiao C and Feng Z 2018 Mapping rice planted area using a new normalized EVI and SAVI (NVI) derived from Landsat-8 oli *IEEE Geosci. Remote Sens. Lett.* **15** 1822–1826

Li Y K, Qian F W, Shan J H, Li J, Yuan F K, Miao L J and Xie G Y 2014 The effect of climate change on the population fluctuation of the Siberian crane in Poyang Lake *Acta Ecol. Sin.* **34** 2645–53

Li Y 2007 Exploitation and utilization of land resources in Xishuangbanna: rubber tree and water *Trop. Agric. Sci. Technol.* **30** 38–44

Lin Y P, Lin W C, Wang Y C, Lien W Y, Huang T, Hsu C C, Schmeller D S and Crossman N D 2017 Systematically designating conservation areas for protecting habitat quality and multiple ecosystem services *Environ. Modell. Software* **90** 126–46

Liu C Y, Dong X F and Liu Y Y 2015 Changes of NPP and their relationship to climate factors based on the transformation of different scales in Gansu, China *Catena* **125** 190–9

Liu J G, Linderman M, Ouyang Z Y, An L, Yang J and Zhang H M 2001 Ecological degradation in protected areas: the case of Wolong nature reserve for giant pandas *Science* **292** 98–101

Liu J, Lü X, Liu Q and Gao J 2010 Spatial autocorrelation analysis of wetland bird diversity in Bielahong Basin *Acta Ecol. Sin.* **30** 2647–55

Ma Z, Cai Y, Li B and Chen J K 2010 Managing wetland habitats for waterbirds: an international perspective *Wetlands* **30** 15–27

Maes J, Paracchini M L, Zulian G, Dunbar M B and Alkemade R 2012 Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe *Biol. Conserv.* **155** 1–12

Marchese C 2015 Biodiversity hotspots: a shortcut for a more complicated concept *Glob. Ecol. Conserv.* **3** 297–309

Margules C R and Pressey R L 2000 Systematic conservation planning *Nature* **405** 243–53

Matlack G R and Monde J 2004 Consequences of low mobility in spatially and temporally heterogeneous ecosystems *J. Ecol.* **92** 1025–35

Matthews J W and Endress A G 2008 Performance criteria, compliance success, and vegetation development in compensatory mitigation wetlands *Environ. Manage.* **41** 130–41

Mcgarigal K and Marks B J 1995 Fragstats: spatial pattern analysis program for quantifying landscape structure *Gen. Tech. Rep. PNW* **351** (US Department of Agriculture, Forest Service, Pacific Northwest Research Station)

Myers N 1988 Threatened biotas: hotspots in tropical forests *Environmentalist* **8** 118–208

Myers N, Mittermeier R A, Mittermeier C G, Fonseca G A B D and Kent J 2000 Biodiversity hotspot for conservation priorities *Nature* **403** 853–8

Nelson E *et al* 2009 Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales *Frontiers Ecol. Environ.* **7** 4–11

Ouyang Z Y, Wang Q, Zheng H, Zhang F and Hou P 2014 National ecosystem survey and assessment of China (2000-2010) *Bull. Chin. Acad. Sci.* **29** 462–6

Pascual-Hortal L and Saura S 2006 Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation *Landsc. Ecol.* **21** 959–67

Pereira H M *et al* 2013 Ecology. Essential biodiversity variables *Science* **339** 277–8

Pereira H M and Daily G C 2006 Modeling biodiversity dynamics in countryside landscapes *Ecology* **87** 1877–85

Pimm S L, Jenkins C N, Abell R, Brooks T M, Gittleman J L, Joppa L N, Raven P H, Roberts C M and Sexton J O 2014 The biodiversity of species and their rates of extinction, distribution, and protection *Science* **344** 1246752

Polasky S *et al* 2008 Where to put things? Spatial land management to sustain biodiversity and economic returns *Biol. Conserv.* **141** 1505–24

Polasky S, Nelson E, Pennington D and Johnson K A 2011 The impact of land-use change on ecosystem services, biodiversity and returns to landowners: a case study in the state of Minnesota *Environ. Resour. Econ.* **48** 219–42

Riordan E C and Rundel P W 2014 Land use compounds habitat losses under projected climate change in a threatened California ecosystem *PLoS One* **9** e86487

Sallustio L, De Toni A, Strollo A, Di Febbraro M, Gissi E, Casella L, Geneletti D, Munafò M, Vizzarri M and Marchetti M 2017 Assessing habitat quality in relation to the spatial distribution of protected areas in Italy *J. Environ. Manage.* **201** 129–37

Saura S and Josep T 2009 Conefor sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity *Environ. Modell. Software* **24** 135–9

Secretariat R C 2004 *The Ramsar Convention Manual: A Guide to the Convention on Wetlands(Ramsar, Iran, 1971)* 3rd edn (Gland, Switzerland: Ramsar Convention Secretariat)

Shan J H, Ma J Z, Li Y K, Qian F W and Tu X B 2014 The dynamics and determinants of population size and spatial distribution of common cranes wintering in Poyang Lake *Acta Ecol. Sin.* **34** 2050–60

Sharp R, *et al.* 2018 InVEST 3.6.0 User's Guide *The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund*

Su Y, Guo Q, Xue B, Hu T, Alvarez O, Tao S and Fang J 2016 Spatial distribution of forest aboveground biomass in china: estimation through combination of spaceborne lidar, optical imagery, and forest inventory data *Remote Sensors Environ.* **173** 187–99

Sun C Z, Zhen L, Wang C, Yan B Y, Cao X C and Wu R Z 2015 Impacts of ecological restoration and human activities on habitat of overwintering migratory birds in the wetland of Poyang lake, Jiangxi province, China *J. Mt. Sci.* **12** 1302–14

Sun C Z, Zhen L and Miah M G 2017 Comparison of the ecosystem services provided by China's Poyang Lake wetland and Bangladesh's Tanguar Haor wetland *Ecosyst. Serv.* **26** 411–21

Tang X, Li H, Xu X, Yang G, Liu G, Li X and Chen D 2016 Changing land use and its impact on the habitat suitability for wintering Anseriformes in China's Poyang lake region *Sci. Total Environ.* **557** 296–306

Taylor P D, Fahrig L and Merriam H G 1993 Connectivity is a vital element of landscape structure *Oikos* **68** 571–3

Terrado M, Sabater S, Chaplin-Kramer B, Ziv G and Acuña V 2016 Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning *Sci. Total Environ.* **540** 63–70

Venter O *et al* 2016 Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation *Nat. Commun.* **7** 12558

Verkuil Y I, N. Karlionova E N, Rakhimberdiev J, Jukema J J, Wijmenga J, Hooijmeijer P, Pinchuk E, Wymenga A J, Baker and Piersma T 2012 Losing a staging area: eastward redistribution of Afro-Eurasian ruffs is associated with deteriorating fuelling conditions along the western flyway *Biol. Conserv.* **149** 51–9

Villa F, Bagstad K J, Voigt B, Johnson G W, Portela R, Miroslav H and David B 2014 A methodology for adaptable and robust ecosystem services assessment *PLoS One* **9**

Wang H, Gao J, Ren L L, Kong Y, Li H and Li L 2013 Assessment of the red-crowned crane habitat in the Yellow River Delta Nature Reserve, East China *Reg. Environ. Change* **13** 115–23

Wang W, Fraser J D and Chen J 2017 Overwinter water birds in the middle and lower Yangtze River floodplain: changes in abundance and distribution *Bird Conserv. Int.* **27** 167–86

Wright D H 1983 Species-energy theory: an extension of species-area theory *Oikos* **41** 496–506

Wu J S, Zhang L Q, Peng J, Feng Z, Liu H M and He S B 2013 The integrated recognition of the source area of the urban ecological security pattern in Shenzhen *Acta Ecol. Sin.* **33** 4125–33

Wu Y, Colwell R K, Han N, Zhang R, Wang W, Quan Q, Zhang C, Song G, Qu Y and Lei F 2014 Understanding historical and current patterns of species richness of babblers along a 5000-m subtropical elevational gradient *Glob. Ecol. Biogeogr.* **23** 1167–76

Xia S X, Yu X B and Fan N 2010 The wintering habitats of migratory birds and their relationship with water levels in Poyang Lake, China *Resour. Sci.* **32** 2072–8

Xia S, Liu Y, Wang Y, Chen B, Jia Y, Liu G, Yu X and Wen L 2016 Wintering waterbirds in a large river floodplain: hydrological connectivity is the key for reconciling development and conservation *Sci. Total Environ.* **573** 645–60

Xie Y, Gong J, Zhang S, Ma X and Hu B 2018 Spatiotemporal change of landscape biodiversity based on InVEST model and remote sensing technology in the Bailong river watershed *Sci. Geog. Sin.* **38** 979–86

Xiong C N, Wei H and Lan M J 2008 Analysis of connectivity on greenland landscape in metropolitan region of Chongqing City *Acta Ecol. Sin.* **28** 2237–44

Xu J J, Si Y L, Wang Y Y, Zhang Y, Prins H H T, Cao L and Boer W F 2019 Loss of functional connectivity in migration networks induces population decline in migratory birds *Ecol. Appl.* **29** e01960

Yi Z, Cannon C H, Chen J, Ye C and Swetnam R 2014 Developing indicators of economic value and biodiversity loss for rubber plantations in Xishuangbanna, southwest China: a case study from Menglun township *Ecol. Indic.* **36** 788–97

Yu K J 1999 Landscape ecological security patterns in biological conservation *Acta Ecol. Sin.* **19** 8–15

Yu K J, Wang S S, Li D H and Li C B 2009 The function of ecological security patterns as an urban growth framework in Beijing *Acta Ecol. Sin.* **29** 1189–204

Zhao H, Wang Y, Xu B, Chen X and Jiang Z 2018 Exploring an efficient habitat index for predicting population and abundance of migratory birds in Poyang lake wetland, south China *Acta Ecol. Sin.* **38** 381–90