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Impacts of Sand Mining Activities on the Wetland Ecosystem of Poyang Lake (China)

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Abstract: Increasing anthropogenic activities are threatening freshwater ecosystems worldwide. Sand mining in Poyang Lake has significantly impacted the wetland ecosystem over the past 20 years, yet a quantitative analysis of these impacts remains insufficient. Here, we used 63 Landsat images taken from 2000 to 2020 along with the support vector machine (SVM) method and a retrieval model of suspended sediment concentration (SSC) to identify sand mining vessels and areas affected by sand mining. Then, we analyzed the changes in landscape patterns in the areas affected by sand mining. The potential impact of underwater noise generated by sand mining vessels on Yangtze finless porpoises was analyzed by a sound propagation model. The number of sand mining vessels in Poyang Lake during the flood, normal, and dry seasons increased from 2000 to 2016 but rapidly decreased from 2017 to 2020. Sand mining vessels were mainly distributed in the northern channel from 2000 to 2006, moved toward the center of the lake from 2007 to 2010, then moved northward in 2017. Within the areas affected by sand mining, water and mudflats declined, grassland and sandbars increased, and the landscape discontinuity increased. The habitat of the Yangtze finless porpoise affected by underwater noise from sand mining vessels in all seasons has significantly increased overtime. The mean area of the affected habitats was 70.65% (dry), 64.48% (normal), and 63.30% (flood) of the total habitat areas. The porpoise habitats in the northern channel and the west branch of the Ganjiang River are more seriously affected by the underwater noise of sand mining vessels than the southern lake. The impact of sand mining activities on wetland landscape and aquatic species demands systematic investigation in the future.

Keywords: sand mining vessels; habitats; Yangtze finless porpoise; underwater noise; landscape

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1. Introduction

The escalating disturbance caused by anthropogenic activities has led to the decline of aquatic populations and habitat degradation, which in turn affects the biodiversity and functional completeness of freshwater ecosystems [1]. Sand mining is one of the main anthropogenic activities that disturb freshwater ecosystems. As the demand for building materials increases with socio-economic development, sand mining keeps threatening the functional completeness and biodiversity of freshwater ecosystems around the world [2,3].

Sand mining can reshape river terrain, alter fish habitats, destroy benthic animal habitats and fish spawning grounds, and is one of the main drivers of freshwater wetland ecosystem degradation and biodiversity decline in the basin [4–7]. Ecological problems caused by irregular sand mining exist in river basins around the world, such as the Chalakudy, Periyar, and Muvattupuzha river basins in India, the shrinkage of Tonlé Sap Lake in Southeast Asia, and the degradation of fish habitats in California River basin in the United States [8–10]. Due to such ecological problems caused by sand mining in rivers, numerous advanced countries have completely banned the practice [11]. Sand mining activities in the Yangtze River basin induce serious impacts on the survival and propagation of aquatic species [12–14]. Sand mining in the main channel of the Yangtze River was banned in 2000, which led to an influx of sand mining vessels into Poyang Lake [15], after which the local government also issued relevant policies to control sand mining.

Poyang Lake receives water from five tributaries: the Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui. The lake is divided into two parts by the position of Songmen Mountain; the northern part is a narrow outflow channel, and the southern part is the main lake, which is an overwater and highly seasonal lake (Figure 1e). Seasonal water level changes give this wetland landscape dynamic characteristics, being a true lake in the flood season and exhibiting a variety of wetland landscapes (such as water, mudflats, sandbars, and grassland) in the dry season, forming a multi-type composite wetland ecosystem [13]. Inter-annual changes in water levels yield different landscape patterns which sustain different aquatic populations after submersion, such as the grassland and sand submerged by shallow water that provides spawning grounds for some fish species [16]. Poyang Lake is also an important habitat for the Yangtze finless porpoise (*Neophocaena asiaeorientalis asiaeorientalis*); about 50% of the global population is found in Poyang Lake [17]. Sand mining activities can damage porpoise habitat and the underwater noise from sand mining vessels can also directly impact the Yangtze finless porpoise, which is highly dependent on echolocation systems for detection, identification, navigation, and feeding [18,19]. Accordingly, quantitative analysis of the landscape changes and the porpoise habitat area affected by underwater noise from sand mining are critical for maintaining the health of the wetland ecosystem in Poyang Lake. Satellite missions such as Landsat, Aster, and HJ-1A/B CCD are used to identify and monitor sand mining vessels [20–22]. Few quantitative studies have been conducted on the relationship between spatiotemporal changes in sand mining activities and ecosystems. This provides the motivation for this work: to quantify the long-term impact of sand mining on the aquatic ecology of Poyang Lake.

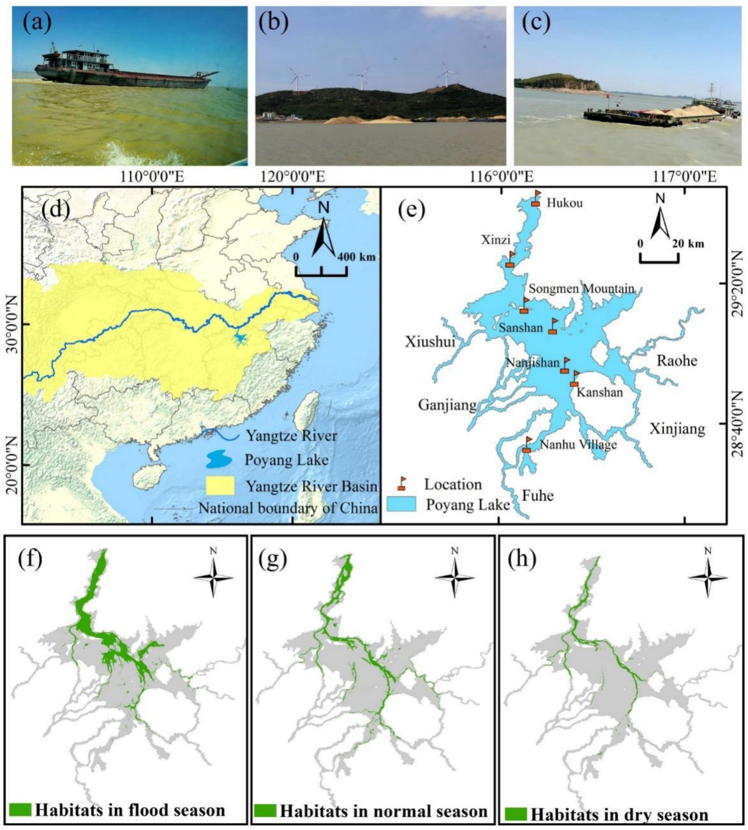

Figure 1. (**a**–**c**) Sand mining in Poyang Lake; (**d**) Yangtze River basin and location of Poyang Lake; (**e**) Tributaries of lake and locations marked; (**f**–**h**) Habitat configuration of the Yangtze finless porpoise in flood, normal and dry seasons [23].

We take the wetland landscape and Yangtze finless porpoise habitats to represent the wetland ecosystem biodiversity of Poyang Lake. Data from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) missions from 2000 to 2020 are employed, along with a support vector machine (SVM) method, a retrieval model of suspended sediment concentration (SSC), and a landscape metrics and sound propagation model to investigate the spatiotemporal distribution of sand mining vessels in Poyang Lake and the change of wetland landscape in the area affected by sand mining activities over the past 20 years. We additionally quantify the spatiotemporal changes of Yangtze finless porpoise habitats affected by the underwater noise of sand mining vessels in Poyang Lake. Our work can yield guidance for future control measures in Poyang Lake and provide research methods for other basins threatened by sand mining.

2. Materials and Methods

2.1. Dataset and Preprocessing

This study selected a total of 63 scenes of Landsat TM/ETM+/OLI images at a spatial resolution of 30 m (http://glovis.usgs.gov/, accessed on 1 September 2021) from 2000 to 2020 acquired under a cloudless or light cloud (<10%) conditions. Images in each year cover the flood (June to August), normal (March to May and October to November), and dry (December to February) seasons of Poyang Lake. All images were preprocessed in ENVI 5.3, including radiation calibration, atmospheric correction based on the FLASH module, destriping, and clipping [24].

2.2. Likely Habitats of the Yangtze Finless Porpoise

This study defines the Yangtze finless porpoise habitat in the flood, normal, and dry seasons of Poyang Lake from 2000 to 2020 based on species distribution model exercises (Figure 1f–h) [23]. In the flood season, the likely habitat is widespread, with an area of 695.36 km^2, continuously distributed from the tributaries to the outflow channel connected with the Yangtze River and expanding towards the center of the lake. In the normal season, the likely habitat areas are 415.01 km^2, still continuously distributed from the tributaries to the outflow channel, but the habitat range in the north and south lakes decreases towards the center of the river channel. In the dry season, the likely habitat area is 210.96 km^2 and limited to tributaries and narrow channels.

2.3. Detect Sand Mining Vessels and Generate Impact Areas for Sand Mining Activities

This study used supervised classification to extract water bodies and mitigate the interference by other objects in vessel extraction. Landsat TM/ETM+ bands 5, 4, 1 and OLI bands 6, 5, and 1 were performed on the water body images to improve the identification of vessels [25]. Three types of training samples (sand mining vessel, water, and others) were established for the water images and used SVM was used to extract sand mining vessels. However, it is difficult to distinguish between sand mining vessels and sand transport vessels from the Landsat images; thus, the two types of vessels are both denoted as sand mining vessels in this article.

The SSC can reflect the turbid waters formed by sand mining operations [26] and is used for the accurate detection of sand mining vessels. Here, a retrieval model of SSC used in Poyang Lake was constructed via Landsat images (Table 1) [27]. The turbid waters (SSC > 0.01082 g/L) [28] of Poyang Lake in flood, normal, and dry seasons from 2000 to 2020 were overlaid with sand mining vessels to discard erroneous data, which were located in the clear water region. Sand mining vessel data were analyzed after correction by the standard deviation ellipse and the mean center for their spatiotemporal change [29].

Sand mining activities can affect the surrounding 1 km aquatic environment [30]; accordingly, the extracted sand mining vessel point data was used to generate a 1 km radius buffer for areas potentially affected by sand mining. To avoid the randomness of image data, the sand mining buffer areas obtained every three years in each season were interlaced (except in 2000) to obtain the areas impacted by sand mining over the past 20 years.

Table 1. The retrieval model of SSC in Poyang Lake; B1-B4 represents the band1-band4 of Landsat images (following Table 2).

	Index of Model	The Retrieval Model
Landsat TM/ETM+	x = (B1 + B3)/(B1/B3)	SSC = $0.1954x^2 + 0.072x - 0.0041$
Landsat OLI	x = (B1 + B4)/(B1/B4)	SSC = $0.1523x^2 + 0.085x - 0.0041$

Table 2. Introduction to Landsat bands and spectral indices are used here.

	Landsat TM/ETM+	Landsat OLI
Coastal		B1
Blue	B1	B2
Green	B2	B3
Red	B3	B4
NIR	B4	B5
SWIR1	B5	B6
NDVI	(B4 − B3)/(B4 + B3)	(B5 − B3)/(B5 + B4)
NDWI	(B2 − B4)/(B2 + B4)	(B3 − B5)/(B3 + B5)
BSI	[(B3 + B5) − (B4 + B1)]/[(B3 + B5) + (B4 + B1)]	[(B4 + B6) − (B5 + B2)]/[(B4 + B6) + (B5 + B2)]

2.4. Analysis of Landscape Changes Based on Landscape Metrics

This study classifies the wetland landscape to analyze the changes in the landscape in the areas affected by sand mining. This research uses an SVM classifier to classify the Poyang Lake wetland landscape [31]. The samples of four wetland types (water, grassland, sandbars, and mudflats) were generated in Google Earth Engine (GEE) using Landsat images in the dry season; each landscape type was evenly selected with 400 or more samples. The samples were randomly divided into training and test samples at the ratio of 7:3. In the feature selection stage, Blue, Green, Red, NIR, and SWIR1 were selected as the spectral features of Landsat images (Table 2), and the spectral indices selected to be involved in the classification included the normalized differenced vegetation index (NDVI), the normalized differenced water body index (NDWI), and the bare soil index (BSI).

Next, this study converted the landscape classification vector data within the area affected by sand mining over the past 20 years to raster data and imported it into Fragstats 4.2 software [32], which calculates the landscape indices. The number of patch (NP) and landscape shape index (LSI) were selected to represent the number and shape of patches in the landscape to study the changes in the landscape in the areas affected by sand mining [33].

2.5. Underwater Noise Transmission Loss Calculation and Impact Area Generation

The absolute sound pressure level (SPL) was calculated using the standard Equation (1) [34]:

$$\mathrm{SPL} = 20\log_{10}(P/P_0) \tag{1}$$

where P_0 is the reference pressure (the standard being 1 µPa in underwater acoustics) and P is the sound pressure measured in (µPa). The SPL unit is dB re 1 µPa. The root-mean-square sound pressure level ($\mathrm{SPL_{rms}}$) can be used to represent the underwater noise intensity. The SPL as used in this paper refers to the $\mathrm{SPL_{rms}}$.

The source level (SL, dB re 1 µPa@1 m) is the sound pressure level of the sound at 1 m from the source [35]. Transmission loss (TL) is the sound pressure level of the source in the propagation process that will gradually decay due to transmission loss and absorption loss (which is typically negligible). The transmission loss in the shallow waters of Poyang Lake be expressed as [36]:

$$\mathrm{TL} = 15\log_{10}r \tag{2}$$

where r represents the distance from the sound source (m).

SPL be estimated from SL and TL:

$$\mathrm{SPL}(r) = \mathrm{SL} - \mathrm{TL} \tag{3}$$

There are various types of sand mining vessels in Poyang Lake, mainly including pump suction types and chain bucket types. The SL of sand mining vessels is about 160.56 dB re 1 Pa@1 m, and the frequency is typically below 1 kHz (low-frequency noise) [37]. The parameter r was calculated using the Euclidean distance toolkit of the spatial analysis extension in ArcGIS10.2. Finally, Equation (3) was used to calculate the transmission loss of underwater noise from sand mining vessels.

The Yangtze finless porpoise underwater acoustic threshold is 80~100 dB re 1 μPa at frequencies below 10 kHz [38,39]. Noise greater than 120 dB re 1 μPa can cause behavioral responses in Yangtze finless porpoise [34]. The habitat data in the flood, normal and dry seasons were interlaced with the audible area of underwater noise from sand mining vessels, and the results were expressed as the area impacted by underwater noise from sand mining vessels.

3. Results

3.1. Spatiotemporal Distribution of Sand Mining Vessels in the Past 20 Years

Sand mining vessels in the flood, normal, and dry seasons were sporadically distributed in the northern outflow channel of Poyang Lake in 2000 (Figure 2a,e,i) and were mainly seen to the north of Songmen Mountain from 2001 to 2006. The distribution expanded to the southern lake after 2007, enlarged to the center of the lake in 2010, and then spread to the southern lake, with the southernmost point found near the Kangshan dyke (Figure 2b,f,j). After 2017, the distribution of sand mining vessels began to contract northward (Figure 2c,g,k). In the flood season, the standard deviation ellipse and the mean center position of sand mining vessels move from north to south and then southeast, eventually contracting to the north (Figure 2d). In the normal season, the standard deviation ellipse and the mean center position of sand mining vessels move to the southeast (Figure 2h). The spatial variation tendency of the standard deviation ellipse and the mean center position of sand mining vessels in the dry season was not significant, which mainly moved near the northern outflow channel (Figure 2l).

The number of sand mining vessels in all seasons was less than 30 in 2000 but increased significantly in 2001, followed by an increase that peaked in 2014, 2015, and 2016 (Figure 3a). The number of sand mining vessels rapidly declined after 2017 and was drastically reduced by 2020 (Figure 3a). The mean number of sand mining vessels in the flood, normal, and dry seasons are 445 ± 135 (standard deviation), 435 ± 131, and 409 ± 112, respectively; the number in the flood season is greater than in the normal season and least in the dry season (Figure 3a). Quadratic fits for each season were calculated, with second-order fitting coefficients of 0.633, 0.443, and 0.502, respectively (Figure 3a).

3.2. Areas Affected by Sand Mining Activities over the Past 20 Years

The areas affected by sand mining activities were 352.46 km^2 (flood condition), 243.44 km^2 (normal condition), and 201.78 km^2 (dry condition). The total area affected by sand mining activities is 408.66 km^2, which are continuously distributed from the west branch of Ganjiang River to the north outflow channel and spreads to the center of the lake, with the southernmost point reaching the Kangshan dyke (Figure 3b). Sand mining activities are significantly more intensive in the north (the average number of sand mining vessels in the northern is 80% of the total) of Songmen Mountain than in the southern lake area (20%), and the southwestern lake area are unaffected by sand mining activities (Figure 3b).

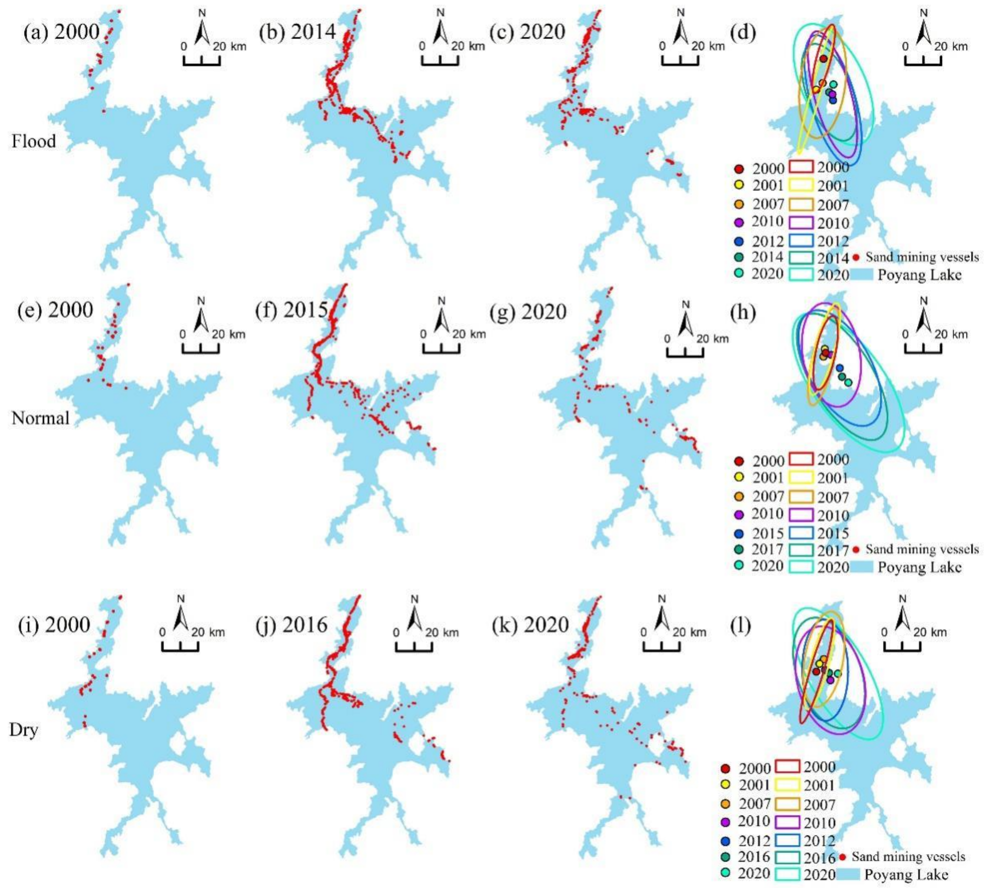

Figure 2. (**a**–**c**) Distribution of sand mining vessels during the flood season; (**d**) The standard deviation ellipse and mean center in flood season; (**e**–**g**) Distribution of sand mining vessels during the normal season; (**h**) The standard deviation ellipse and mean center in normal season; (**i**–**k**) Distribution of sand mining vessels during the dry season; (**l**) The standard deviation ellipse and mean center in the dry season.

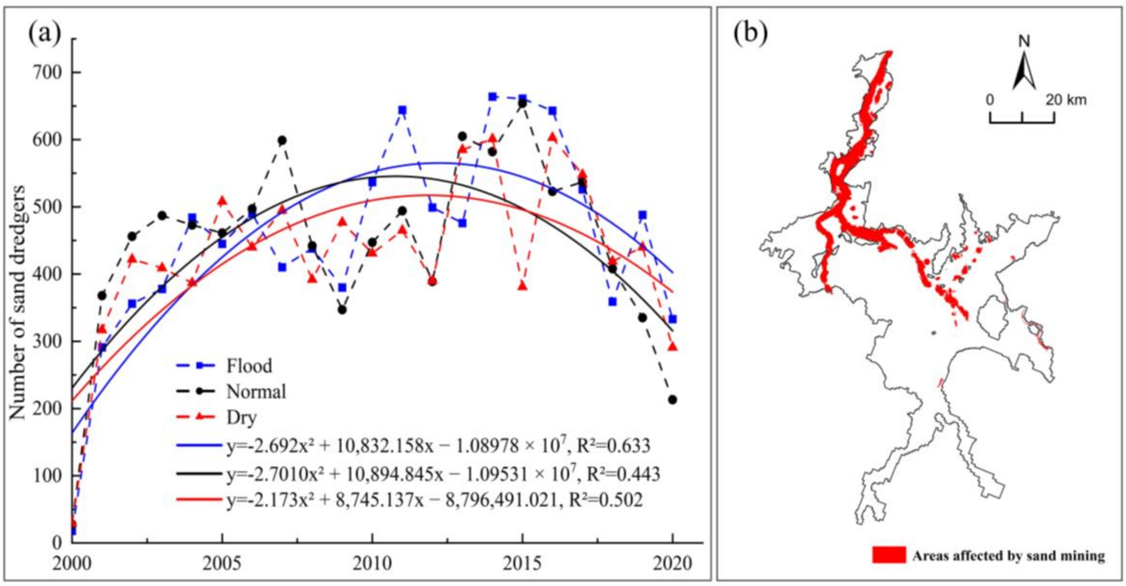

Figure 3. (**a**) Quadratic fits to the number of sand mining vessels in the past 20 years in each season; (**b**) Areas affected by sand mining activities.

3.3. Landscape Classification and Landscape Changes in Areas Affected by Sand Mining

In the region affected by sand mining activities, the mudflat area declined, water area decreased, and grassland and sandbars area increased, though the increase in sandbar area was small (Figure 4g). The long-term NP and LSI indices in the areas affected by sand mining activities increased, with correlation coefficients of 0.67 ($p < 0.01$) and 0.49 ($p < 0.05$), respectively (Table 3). Additionally, sand mining activities over the past 20 years has led to increased landscape patches and boundary complexity.

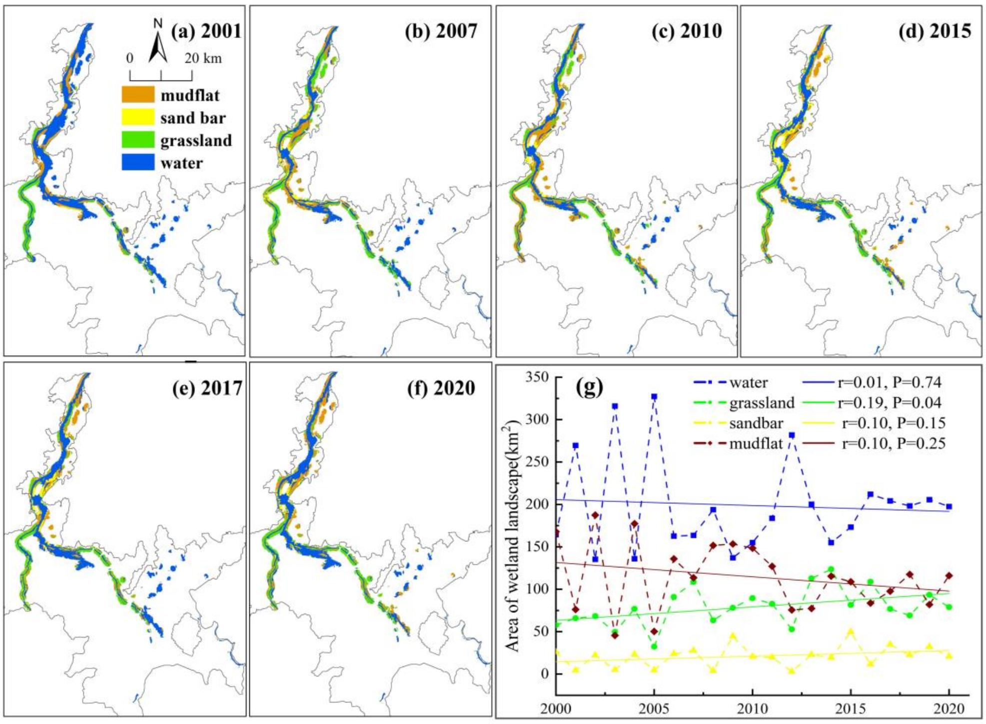

Figure 4. Results of landscape classification in the area of sand mining activities. (**a**–**f**) Multi-year wetland landscape classification; (**g**) Changes in wetland landscape area from 2000 to 2020.

Table 3. Landscape indices within the area affected by sand mining activities during the dry season from 2000 to 2020.

	NP	LSI
2003	410	13.81
2004	1092	25.15
2006	1156	25.97
2007	1301	26.57
2008	877	22.66
2009	1106	25.60
2010	1162	26.72
2011	1029	23.66
2012	886	20.36
2013	1298	24.81
2014	1290	27.18
2015	1470	27.46
2016	1698	25.68
2017	1802	28.96
2018	2530	32.36
2019	2730	33.19
r	0.67	0.49
p	<0.01	<0.05

3.4. The Impact of Underwater Noise of Sand Mining Vessels on the Yangtze Finless Porpoise

During the flood season, the area of the Yangtze finless porpoise habitat affected by underwater noise from sand mining vessels was between 178 km^2 and 617.58 km^2 (Figure 5a,b). The multi-year mean area was 440.18 $\pm$ 133.20 km^2, accounting for 63.30% of the total porpoise habitat area. Over the past 20 years, the area of porpoise habitat affected by underwater noise significantly increased, $p < 0.01$ (Figure 5h). The habitat area affected by underwater noise from 2001 to 2007 was mainly distributed in the northern outflow channel and moved to the south of Songmen Mountain in 2007 and enlarged to the southern main lake region in 2010. The area of affected porpoise habitat accounts for 88% of the total habitat area in 2018, with the proportion decreasing to 60% in 2020.

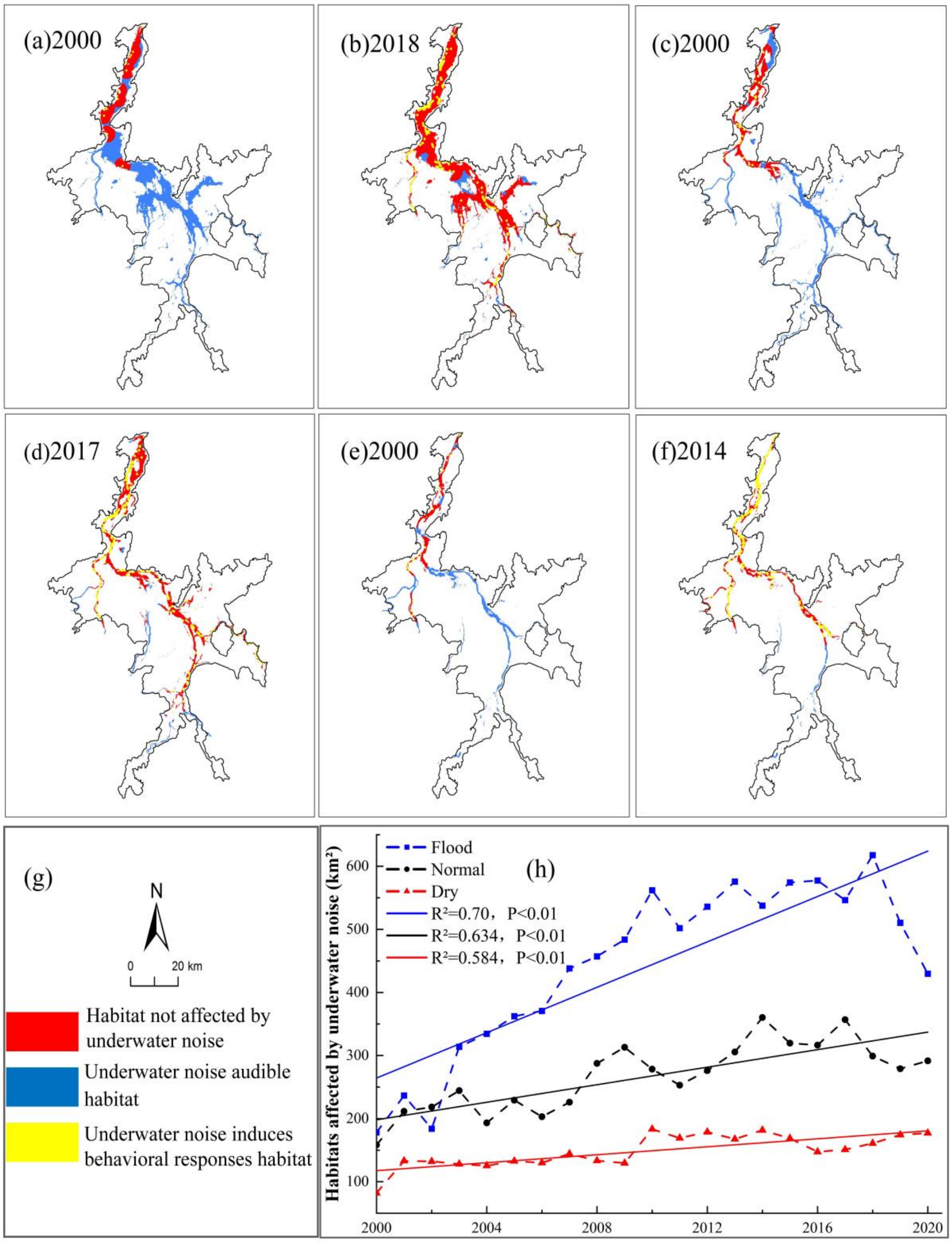

Figure 5. Distribution of porpoise habitats affected by underwater noise from sand mining vessels over the past 20 years. (**a**,**b**) Minimum and maximum impact areas in the flood season; (**c**,**d**) Minimum and maximum impact areas in the normal season; (**e**,**f**) Minimum and maximum impact areas in the dry season; (**g**,**h**) Area change of porpoise habitat affected by underwater noise.

In the normal season, the habitat area affected by underwater noise from sand mining vessels was between 158.27 km^2 and 359.91 km^2 (Figure 5c,d), the multi-year mean area was 267.62 ± 52.84 km^2, accounting for 64.48% of the total porpoise habitat area. The area of the porpoise habitat affected by underwater noise drastically increased, $p < 0.01$ (Figure 5h). The habitat area affected by underwater noise expanded rapidly since 2001, moving to the south of Songmen Mountain and rapidly spreading to the main lake region after 2007, with the area affected in 2017 being 86% of the total, decreasing to 69% in 2020.

In the dry season, the habitat area affected by underwater noise from sand mining vessels was between 82.03 km^2 and 181.75 km^2 (Figure 5e,f), the multi-year mean area was 149.04 ± 25.02 km^2, accounting for 70.65% of the total porpoise habitat area. The area of the porpoise habitat affected by underwater noise largely increased, $p < 0.01$ (Figure 5h). The habitat area affected by underwater noise before 2006 was concentrated in the northern outflow channel and expanded south of the Songmen Mountain after 2007, but the movement range to the south was small. During the dry season, the lake channel was narrow, and the habitats affected by underwater noise were mainly distributed in the northern outflow channel and the west branch of the Ganjiang River.

4. Discussion

4.1. Spatiotemporal Changes in Sand Mining Activities in Poyang Lake

Our results show that sand mining vessels in all seasons from 2000 to 2006 were concentrated in the northern outflow channel. Sand mining operations expanded to the south of Songmen Mountain in 2007 and reduced in 2008 and 2009 with a significant decrease in sand mining vessels. This is mainly due to the issue and implementation of related policies: the "Administrative Measures for River Sand Mining in Jiangxi Province" in 2006, the comprehensive prohibition of mining, and the "Comments on Strengthening the Management of Sand Mining in the Middle and Lower reach of the Ganjiang River and Poyang Lake" in 2008 [40]. The number of sand mining vessels continued to increase after 2010, and the number of sand mining vessels in the flood, normal, and dry seasons reached peaks in 2014, 2015, and 2016, respectively. The distribution of sand mining vessels has been enlarged to the southeast lake region since 2010. These peaks were greater than the limits of the sand mining plan of Poyang Lake and are consistent with the results of related studies [20]. The local government issued the latest relevant regulation to manage sand mining in 2017, and the rapid decline in the number of sand mining vessels since 2017 confirms the effectiveness of this regulation [41], with the number of sand mining vessels having been significantly reduced by 2020 and the operating region contracting northward.

Different numbers of sand mining vessels in all seasons (Figure 3a) are due to the seasonal variation of lake level and, more importantly, the lake area, which is nearly three times as large in the flood season (about 3000 km^2) than the dry season (about 1000 km^2) [13]. It is also difficult for sand mining vessels to reach the southern lake in dry seasons due to draught depth limitations.

4.2. Impact of Sand Mining Activities on Wetland Landscape

Sand mining activities intensified the wetland landscape, causing an increase in landscape fragmentation within the impacted area. Human activities are an important factor causing landscape fragmentation in Poyang Lake [42].

In addition, sand mining can enhance the discharge capacity of the lake, resulting in a decrease in water level in the dry season [43]. A decline in water level can cause a change in the distribution of the landscape, with grassland expanding towards the center of the lake [16]. Sand mining strips the lake bottom silt and the growth of grassland on the beach changes in the dry season, sensitive aquatic plant communities have become more fragmented and the growth space narrows, while the area of drought-tolerant and other vegetation expands [44].

Sand mining activity is one of the significant driving factors of landscape change in Poyang Lake. The management of the complex wetland ecosystem of Poyang Lake requires constant monitoring of human activities such as sand mining and also the monitoring of other factors such as hydrological processes, climate change, and soil moisture [45–47].

4.3. Impact of Sand Mining Activities on Yangtze Finless Porpoise

The effects of underwater noise pollution on the Yangtze finless porpoise are ranked in order of severity as audible, behavioral response, masking, temporal threshold shift (TTS), and permanent threshold shift (PTS) [48]. TTS and PTS are relatively serious damage to animal auditory. The sound exposure level of cetacean TTS is 195 dB re 1 μPa^2 s; theoretically, 1 h of continuous exposure within 1 m of sand mining vessels could result in TTS; causing PTS requires 215 dB re 1 μPa^2 s [49], which exceeds the source level intensity of underwater noise from sand mining vessels.

In the past 20 years, the area of porpoise habitat affected by the underwater noise of sand mining vessels has expanded in Poyang Lake during all seasons. The porpoise habitat in the southern lake was affected by underwater noise since 2007 and enlarged to the southern tributaries of the lake at the peak of sand mining in mid-2010. The porpoise habitats in the northern outflow channel and the Ganjiang River western branch of the lake are more seriously polluted by underwater noise. Sand mining vessels are mainly distributed in the northern outflow channel, particularly during the dry season, due to draught depth limitations; when multiple sand mining vessels work at the same time, the risk of porpoise TTS will increase [50]. Meanwhile, the watercourse is narrow in the dry season, and thus the porpoise habitat is even narrower. Sand mining vessels occupy the activity space of porpoises; the underwater noise disturbs the sonar detection of porpoises and increases the risk of porpoises being injured or killed by sand mining vessels [18]. Managers should strictly supervise sand mining vessels in the lake, and sand mining should be prohibited in the north outflow channel during the dry season.

Sand mining can also directly affect the quality of porpoise habitats. The distance to sand mining vessels is one of the primary environmental factors for the habitat configuration of the Yangtze finless porpoise [23]. Sand mining changes the lake benthic topography of the lake and creates sand bunkers, which can easily cause porpoise stranding during the receding period of the lake, and increases the larger stranding risk area [24]. Quantitative interrelationships between sand mining and porpoise habitat quality, as well as assessments of the impact of sand mining behavior on the stranding risk of porpoises, will be the subject of future studies.

4.4. Conservation of the Poyang Lake Wetland Ecosystem

Long-term remote sensing data can be used to monitor spatiotemporal changes in entire ecosystems, such as landscape, habitats, and climate change [51]. We here considered the impact on wetland landscapes and porpoise habitat from sand mining based on remote sensing data, showing that remote sensing methods provide effective parameters for monitoring the impact of human activities on wetland ecology. The calculation of the propagation of underwater noise is combined with geographic information technology to quantify it at multiple spatiotemporal scales, providing an effective method for the study of underwater acoustic environment pollution of lake wetlands. The rapid development of high spatial resolution satellites and unmanned aerial vehicle remote sensing monitoring increasingly provides high-precision data sources for research on the distribution of sand mining activities and wetland landscapes distribution, which should quantify the impact of sand mining on the landscape in future studies.

Regulation of sand mining in Poyang Lake and the implementation of a recent ten-year fishing ban has provided opportunities for the conservation and habitat restoration of the Yangtze finless porpoise. The protection of future wetland ecosystems can be achieved via high-precision remote sensing data utilized to monitor human activities such as sand mining effectively to protect and restore the Yangtze finless porpoise habitat.

5. Conclusions

Our main conclusions are:

(1) The number of sand mining vessels in Poyang Lake during the flood, normal, and dry seasons increased from 2000 to 2016 and rapidly decreased from 2017 to 2020. Sand mining vessels were mainly distributed in the northern outflow channel from 2000 to 2006 and moved southward since 2007. The distribution of sand mining vessels enlarged to the center and southern lake in 2010, with the distribution gradually contracting northward since 2017.

(2) In the areas affected by sand mining, water and mudflats declined, grassland and sandbars increased, and landscape patches increased, and landscape discontinuity increased.

(3) The porpoise habitat affected by underwater noise from sand mining vessels in all seasons significantly increased; the mean area of the affected habitats as a proportion of the total habitat area was 70.65% (dry), 64.48% (normal), and 63.30% (flood).

(4) The porpoise habitat in the northern outflow channel and the west branch of the Ganjiang River is more seriously affected by the underwater noise of sand mining vessels than those in the southern lake.

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