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Is There Any Correlation Between Landscape Characteristics and Total Nitrogen in Wetlands Receiving Agricultural Drainages?

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Abstract: In the case of increasing fragmentation of wetlands, the study of the relationship between wetland landscape characteristics and total nitrogen (TN) in water is of great significance to reveal the mechanism of wetland water purification. Taking the Naoli River (NR) wetlands in Northeast China as the research object, 10 uniformly distributed sampling sites in the study area were sampled in August 2015 to test the TN concentration and interpret the images of NR wetlands in the same period. Taking the sampling site as the control point, the whole wetlands were divided into 10 regions, and the landscape index of each region was extracted. In order to reveal whether the landscape characteristics are related to the TN concentration in the wetlands water body, the landscape index and the TN concentration in the control point water body were analyzed by correlation analysis, step-by-step elimination analysis and path analysis to reveal whether the landscape characteristics are related to the TN concentration under wetlands receiving agricultural drainages. The results showed that the correlation coefficients between four area indexes or eight shape indexes and TN concentration did not reach a significant correlation level ($P > 0.05$), indicating that TN removal was not only determined by a single landscape index. The path coefficient of edge density (ED) index is –0.41, indicating that wetland patch connectivity is the primary factor of TN removal, and there is no relationship between the larger patch area and the higher TN removal. The removal of TN in wetlands is restricted by the synergistic effect of landscape area and shape characteristics.

Keywords: Naoli River wetlands; total nitrogen removal; spatial pattern; step-by-step elimination analysis; agricultural drainages

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1 Introduction

As large areas of wetlands have been developed as farmlands (Guo et al., 2014), fragmentation of previously concentrated wetlands can be observed, resulting in a significant change of landscape pattern (Yu et al., 2011). Agricultural drainages may then enter the wetland, making it as a purification zone for wastewater

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containing nitrogen (Gao et al., 2018). Studies on the correlation between total nitrogen (TN) removal in the wastewater and the wetland landscape pattern, as well as the influence of landscape characteristics on water quality, have attracted considerable attention (Niu et al., 2009; Liu et al., 2013; Miller et al., 2016). The heterogeneity of the Taihu Lake wetland landscape had a great impact on water quality when it accommodated agricultural drainages from farmland (Zhong et al., 2014). Using spatial analysis and regression equations, Shiels (2010) found that the wetland landscape indices of the Mississisinewa River watershed and East-Central Indiana were related to the river water quality and that the impact of landscape patterns on the water quality was extremely complex (Shiels, 2010). In the Weishui River Basin, as the intensity of agricultural development continued to increase, the wetland landscape pattern had a significant impact on water quality and there was a significant correlation between landscape indices and water quality indicators (Jiao et al., 2014). Liu et al. (2018) used multivariate statistical regression analysis to link water quality data of 11 years with landscape change data and found that the water quality of the Great Barrier Reef catchments was changed temporally and spatially by the landscape pattern (Liu et al., 2018). There is a close relationship between the landscape pattern of the Miyun wetland and the water eutrophication in China. Although the amount of agricultural drainage accommodated in different wetland locations was similar, the spatial difference of water quality was significant owing to different landscape patterns (Xu and Zhang, 2016).

At present, studies on the relationship between landscape characteristics and water quality are based on the context of the wetlands receiving agricultural drainages to analyse the impacts of wetland landscape characteristics change on water quality. However, very few studies have considered the case of wetland partly reclaimed as farmland with fragmentation trends and reported the impacts of patch area and shape characteristics on TN removal in the water body. Therefore, the Naoli River wetlands of China were taken as the research object in this study. In the context of water return from an accommodated surrounding farmland, image interpretation and water quality of sampling sites were used to carry out a statistical analysis of the relationship between wetland landscape indices and TN in the water body. The influence of wetland landscape characteristics on TN removal was elucidated, which serves as a reference for comprehensive mechanistic studies of landscape pattern on ecological processes.

2 Materials and Methods

2.1 Study area

The Naoli River (NR) wetlands (132°22'41"E–134°10'21"E, 46°30'10"N–47°22'17"N) is located in the hinterland of the Sanjiang Plain, China (Jiang et al., 2011), are typical wetlands in China (Jiang et al., 2011). The watershed is low and flat, and the surface runoff is not smooth, forming a large area of marsh wetlands (Wang et al., 2018b). The main channel of the river is extended by 165 km, the widest part is 13.5 km, and the narrowest part is 4 km (Liu et al., 2016). The annual average annual runoff is 6.4×10^8 m^3 (Yin et al., 2017). The wetland area in the NR Basin decreased from 1.15×10^6 ha in 1954, to 7.57×10^5 ha in 1976, 2.78×10^5 ha in 2000, and 2.08×10^5 ha in 2015, with a loss of nearly 82% (Zou et al., 2018). At the same time, the area of cultivated land increased more than six fold. It increased from 2.06×10^5 ha in 1954, to 6.87×10^5 ha in 1976, 1.21×10^6 ha in 2000, and 1.28×10^6 ha in 2015 (Zou et al., 2018). The increase of cultivated land led to the increase of chemical fertilizer use, and the annual use of nitrogen fertilizer reached 16.5 t/km^2 in 2012 (Zhang, 2013). Subsequently, the fragmentation of the river basin landscape intensified, the wetlands were gradually surrounded by farmland, and accommodated a large number of agricultural drainages. Only the Qixing River, a tributary of NR, contained 7.6×10^7 m^3 (Ouyang et al., 2018) in 2011, the TN concentration in wetland water increased rapidly.

2.2 Water sampling and determination

From 20–27, August in 2015 (summer), water sampling was performed at 10 sampling sites distributed as evenly as possible from upstream to downstream along the NR wetlands. Sampling site order from upstream to downstream, were respectively numbered as 1, 2, 3⋯10 (Fig. 1, Table 1). At each sampling site, water in the wetlands was sampled three times; at each time, 250 mL of water was sampled with a polyethylene sampling bottle, which was previously cleaned with deionized water, at the water surface (0.5 m). A total of 30 samples were

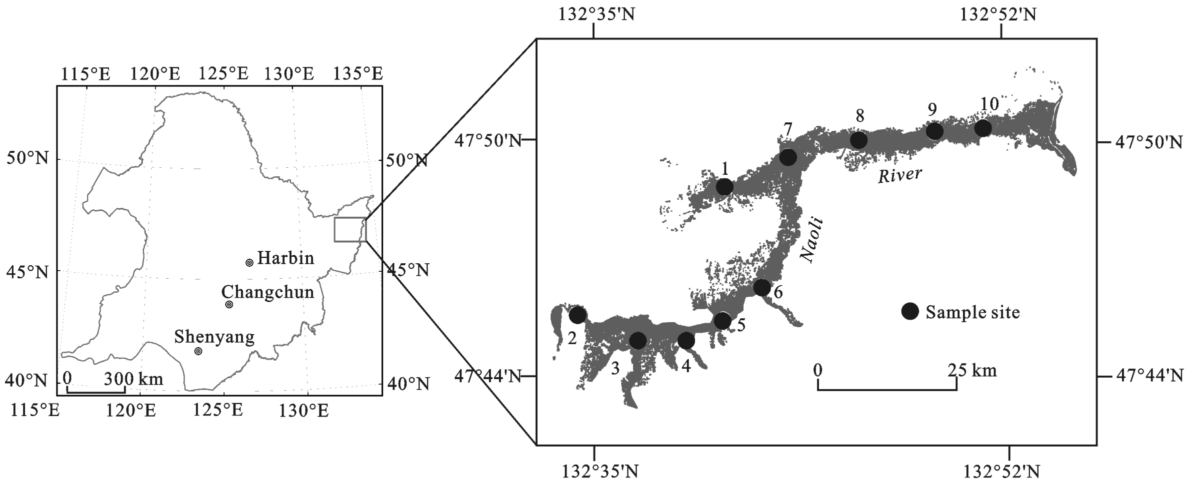

Fig. 1 Sampling sites of water quality in the Naoli River (NR) wetlands, Northeast China

Table 1 Location of sampling sites in the NR wetlands, Northeast China

Sampling site	Longitude (E)	Latitude (N)	Altitude (m)	Length from the estuary (km)
1	132°57′57″	47°08′32″	73	96
2	132°31′17″	46°40′35″	83	168
3	132°39′4″	46°44′58″	81	150
4	132°49′39″	46°45′17″	77	136
5	132°59′45″	46°48′45″	73	124
6	133°08′35″	46°53′17″	69	109
7	133°09′49″	47°12′34″	64	74
8	133°26′57″	47°16′13″	61	55
9	133°43′9″	47°17′24″	58	33
10	133°54′37″	47°14′24″	57	21

collected, and TN concentration of each sample was measured by alkaline potassium persulphate digestion-UV spectrophotometric method (Du et al., 2018). At each sampling site, the average TN concentration value of the three samples was calculated.

2.3 Remote sensing interpretation and landscape index extraction

The mesoscale Landsat 8 Operational Land Imager (OLI) data were selected as the main remote sensing data. The imaging period was during August 2015, which coincided with the water quality sampling period. At this time of year, the vegetation is vigorous, making it the best time to capture the vegetation coverage of the wetland. After geometric correction, the remote sensing data were pre-processed, which included data import, colour synthesis of multi-band images (Utilities), image cropping (Subset), and geometric correction of images. Next, the Gram-Schmidt Pan Sharp Algorithm was used in the environment to enhance the spatial resolution of the multi-spectral bands. The spatial resolution was increased to 15 m. Other supplemental data included Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (Aster DEM) V2 data at 30 m resolution and Normalised Difference Vegetation Index (NDVI) data.

The random forest method was used as the classification method for object-oriented segmentation, which extracts data based on the type and target weight and integrates the terrain data, NDVI data, and remote sensing data into raster datasets. The classification of the wetlands vegetation community was performed by the random forest method. An accuracy test was carried out by comparing the field observation results of sample sites with the interpretation of corresponding indoor samples. The overall accuracy was 77.03%. Water had the highest accuracy of 100%, and marsh wetlands had the lowest overall classification accuracy of 71.92% (Table 2), which was mainly due to the close similarity of spectral and shape characteristics of various types of vegetation in the marsh wetlands.

The NR wetlands were divided into 10 regions by the river section of each sampling site. Fragstats 3.3 was used to calculate various landscape indices in each control area of sampling site, including areal indices and

Table 2 Classification accuracy of all types of remote sensing images in the NR wetlands

Type		Sample number	Number of error sample	Accuracy of type (%)	Overall classification accuracy (%)
Building site		31	1	96.77	77.03
Paddy field		24	3	87.50	
Forest land		28	4	85.71	
Unvegetated surface water		17	0	100.00	
Dry land		14	2	85.71	
marsh community of wetlands	*Zizania latifolia*	34	11	67.65	
	Phragmites australis	41	13	68.29	
	Acorus calamus	55	9	83.64	
	Calamogrostis angustifolia	39	15	61.54	
	Carex appendiculata	38	9	76.32	
	Carex tato	47	12	74.47	
	Nymphoides peltatum	35	11	68.57	
	Weeds	28	9	67.86	

shape indices. The areal indices included wetland area per km of river length (WA), patch number per km of river length (PN), mean patch size (MPZ), and largest patch index (LPI). The shape indices included total patch perimeter per river length (TPP), mean patch perimeter (MPP), average weighted shape index (AWSI), total edge density (TED), edge density (ED), fractal double-logged (FDL), landscape shape index (LSI), and patch stretch index (PSI).

2.4 Data analysis

The TN concentration in the water body of the wetlands comes mainly from nitrogen-containing wastewater from the surrounding farmland (Wang et al., 2008). The low TN concentration in a sampling site indicates that the TN was largely removed from the water body. The landscape characteristics of the sampling control area can be very favourable to the TN removal (Tuboi et al., 2018). Therefore, The TN concentration may represent TN removal productivity. Thus, the correlation coefficients between TN and landscape indices were used to analyse the effect of the landscape factors on TN at NR wetlands. Next, based on principal component analysis, the impact indices of landscape area and shape characteristics on TN removal were obtained in each sampling site by the step-by-step elimination analysis, and then the impact indices and landscape indices were fitted by functions. The function with the greatest increase of R^2 value was selected, and the impact of each landscape index on TN was analysed in the significance range according to the change characteristics of the function curve. Stepwise regression and path coefficients were used to integrate various landscape indices into the overall equation to analyse the effect of landscape area and shape characteristics on TN removal comprehensively.

3 Results

The TN concentration at the 10 sampling sites varied from 4.53 to 8.85 mg/L (Table 3). The independent samples-T test showed a significant difference ($P < 0.01$) among TN concentrations of the sites, indicating that the TN removal in the sampling control areas was different. In addition, the landscape indices of different control areas of sampling sites were also different (Table 3), and independent samples-T test also showed a significant difference ($P < 0.01$), indicating that the landscape characteristics of different control areas of sampling sites varied.

3.1 Influence of landscape area on TN removal

3.1.1 Correlation between areal indices and TN concentration

The correlation coefficient between TN and the PN index was −0.29 (Fig. 2), indicating that where there was a large number of patches, there was a low concentration of TN. The correlation coefficient between TN and the WA index was −0.13 and that between TN and the LPI index was −0.15 (Fig. 2), indicating that wherepatch area was large and the area difference between patches

Table 3 Total Nitrogen concentration in the water body at each sampling site and landscape indices in the 10 sampling control areas

Sampling site	1	2	3	4	5	6	7	8	9	10
TN (mg/L)	6.94	5.50	7.22	5.79	6.41	6.57	8.85	4.53	5.24	5.13
WA (km^2/km)	27	1	91	125	45	72	173	95	95	48
PN (N/km)	340	61	505	1357	720	1425	1991	1027	1930	712
MPZ (km^2)	0.08	0.01	0.18	0.09	0.06	0.05	0.09	0.09	0.05	0.07
LPI	0.37	0.44	0.42	0.25	0.22	0.16	0.16	0.18	0.23	0.37
TPP (km/km)	2446	79	8498	11548	4307	7453	13845	7706	10474	4875
MPP (km)	7.19	1.30	16.83	8.51	5.98	5.23	6.95	7.50	5.43	6.85
AWSI	12	43	392	390	228	295	336	228	353	259
TED (m/m)	31	4	82	138	60	82	113	115	155	112
ED (m/km^2)	0.09	0.12	0.09	0.09	0.10	0.10	0.08	0.08	0.11	0.10
FDL	0.82	1.00	0.92	0.68	0.71	0.67	0.65	0.68	0.65	0.72
LSI	2.39	2.31	2.84	2.02	2.14	1.92	1.87	2.16	1.87	2.24
PSI	8.46	8.18	10.08	7.17	7.59	6.80	6.62	7.67	6.63	7.96

Notes: TN, total nitrogen; WA, wetland area per km of river length; PN, patch number per km of river length; MPZ, mean patch size; LPI, largest patch index; TPP, total patch perimeter per river length; MPP, mean patch perimeter; AWSI, average weighted shape index; TED, total edge density; ED, edge density; FDL, fractal double-logged; LSI, landscape shape index; PSI, patch stretch index

was large, TN concentration was relatively low and TN removal was relatively high. However, the correlation coefficient between TN and the areal indices did not reach statistical significance ($P > 0.05$), and the correlation magnitude was low.

3.1.2 Relationship between areal indices and TN removal

(1) Dimension reduction of areal indices. Four area indices were reduced to one index (areal index) by principal component analysis. The contribution rate of the first principal component was 55.68%, and that of the second principal component was 32.52%. According to their respective contribution rates, the first two principal components of the 10 sampling sites were weighted, and each sampling site was given a total areal index score representing the landscape areal characteristics of each sampling control area of sampling site.

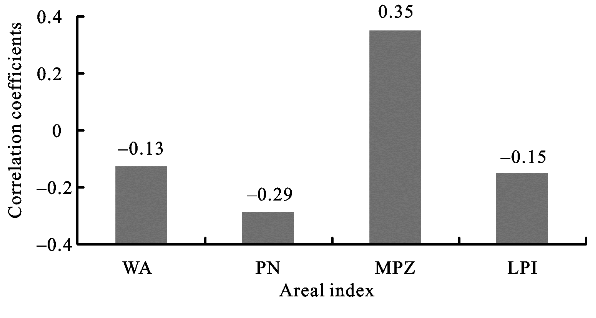

Fig. 2 Correlation coefficients between areal indices and total Nitrogon. WA, wetland area per km of river length; PN, patch number per km of river length; MPZ, mean patch size; LPI, largest patch index

(2) Calculation of the impact index of areal characteristics to TN removal. The impact index of areal characteristics on TN removal (IIACTR) was calculated by the step-by-step elimination analysis. The data of 10 sampling sites are eliminated in turn. The calculation process is as follows: taking out the data of site No. 1, calculating the correlation coefficients between landscape indices and TN of the 2nd to 10th sampling sites. Then taking out data of site No. 2, calculating the correlation coefficients between landscape indices and TN of the remaining nine sampling points. The rest can be done in the same manner. When all the 10 coefficients were calculated, the first round of calculations is complete and the smallest correlation coefficient means that the correlation between the landscape characteristics and the TN concentration of the site which was taken out is the worst. Therefore, it is eliminated in the first round. Then the second round of elimination is carried out by using the same method, and the remaining 9 sampling sites are screened in turn, and so on, one sampling site is eliminated in each round, and one sampling site is left until the last round to complete the screening (Table 4). In the process of elimination, there was a significant negative correlation between TN concentration and the total score of area indices in the sixth round ($P < 0.05$).

The number of each sampling site was reordered according to the order of elimination, and the ranking result was 7, 3, 2, 10, 4, 6, 8, 9, 5, 1 (Table 4). According to these results, the IIACTR of each sampling site was calculated, with the first eliminated sampling site ranked as 1 and the IIACTR assigned as 1. In our case, the IIACTR of sampling site number 7 was ranked as 1. The next sampling site eliminated was ranked as 2, and the IIACTR was assigned as 2. In this case, the IIACTR of sampling site number 3 was ranked as 2. Following the same process, the IIACTR of the last sampling site was assigned 10, which was sampling site number 1 (Table 4). The IIACTR is small; the removal ability is relatively weak. The IIACTR is large; the removal ability is relatively strong.

(3) Selection of fitting function between IIACTR and areal indices. Taking the IIACTR as an independent variable and each areal index as a dependent variable to establish a function, regression fitting was carried out from the first function to the sixth function. After each fitting, the R^2 value of the equation was calculated, and then the R^2 value of the last fitting was subtracted to obtain the added value of R^2 (Table 5). The function with the greatest added value of R^2 was selected. The result showed that when the fitting function between the IIACTR and the WA index was at the 6th time, the added value of R^2 was the greatest (0.25) (Table 5). Therefore, the 6th-time function was selected for analysis. According to this method, the 2nd function was selected between the IIACTR and the PN index based on the added value of R^2, the 6th function was selected between the IIACTR and the MPZ index, and the 3rd function was selected between the IIACTR and LPI index (Table 5). The change characteristics of the function curve were analysed in the significant range (IIACTR 6 to 10) to reveal the relationship between each areal index and the TN removal.

Table 4 Sampling sites eliminated and correlation coefficients between TN and the total score for landscape areal indices after step-by-step elimination of the sites

Elimination step	Sampling site eliminated	Impact index of areal characteristics to total nitrogen removal (IIACTR)	Correlation coefficient after sampling site data elimination
1	7	1	0.03
2	3	2	–0.20
3	2	3	–0.48
4	10	4	–0.74
5	4	5	–0.85
6	**6**	6	–0.94*
7	8	7	–0.97*
8	9	8	–0.98*
9	5	9	–0.99*
10	1	10	–0.99*

Notes: The order of the first column is the number of rounds in the process of elimination, the number 1 represents the first round, 2 represents the second round, and so on; and the second column is the numbers of sampling sites that are eliminated in each round. For example, the number 7 in the first row is the sampling site numbered 7 that was deleted in the first round, and the third column is based on the elimination process

Table 5 The R^2 values and added values of R^2 (R^{2+})of regression functions between areal indices (dependent variable) and impact index of areal characteristics to TN removal (IIACTR) (independent variable)

Equation times	WA		PN		MPZ		LPI	
	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}
1	0.01	0.00	0.05	0.00	0.09	0.00	0.04	0.00
2	0.24	0.24	0.46	0.41	0.15	0.06	0.06	0.02
3	0.32	0.07	0.64	0.18	0.15	0.00	0.79	0.73
4	0.39	0.07	0.71	0.07	0.16	0.01	0.95	0.16
5	0.39	0.00	0.76	0.05	0.38	0.22	0.96	0.01
6	0.64	0.25	0.83	0.07	0.65	0.27	0.99	0.03

Notes: R^{2+}, added value of R^2; WA, wetland area per km of river length; PN, patch number per km of river length; MPZ, mean patch size; LPI, largest patch index

(4) Change characteristics of the fitting function curves between IIACTR and areal indices. The fitting curve of function between IIACTR and the WA index fluctuated and decreased in the significant range (the solid line in the figure) (Fig. 3a), indicating that in a certain area range, the TN removal capacity decreased with the increase of wetland area.The fitting curve of function between IIACTR and the PN index showed a downward trend in the significant range (Fig. 3b), indicating that when the number of PN exceeded 33.91 per km, the TN removal capacity decreased and adverse effects of landscape fragmentation began to appear. The correlation between IIACTR and the MPZ index showed a fluctuating trend (Fig. 3c), indicating that the TN removal capacity did not increase with the increase of patch area.The correlation between the IIACTR and the LPI indices showed an overall upward trend in the significant range (Fig. 3d), indicating that larger area of single patch was related to stronger TN removal capacity. However, there was a small concave fluctuation in the curve, which indicates that the removal of TN in wetlands does not only rely on a few large patches but that a certain number of small patches are also needed.

3.2 Influence of landscape shape on TN removal

3.2.1 Correlation between shape indices and TN concentration

The correlation coefficient of TN and TPP index was −0.17, that of TN and TED index was −0.16, and that between TN and ED index was −0.41 (Fig. 4). This results show that when wetland has strong connectivity with other landscapes and internal patches, TN concentration is low and TN removal is large. The correlation coefficient of TN and AWSI index was 0.15, that of TN and FDL index was 0.11, and those of TN with LSI and PSI were 0.22 and 0.22, respectively (Fig. 4), indicating that whether in the entire wetland or in internal patches, the more regular the patch shape, the smaller the TN concentration and the larger the TN removal. However, all correlation coefficients did not reach a significant level ($P > 0.05$).

3.2.2 Relationship between shape indices and TN removal

(1) Dimension reduction of shape indices. Eight shape indices were reduced to one index (shape index) by

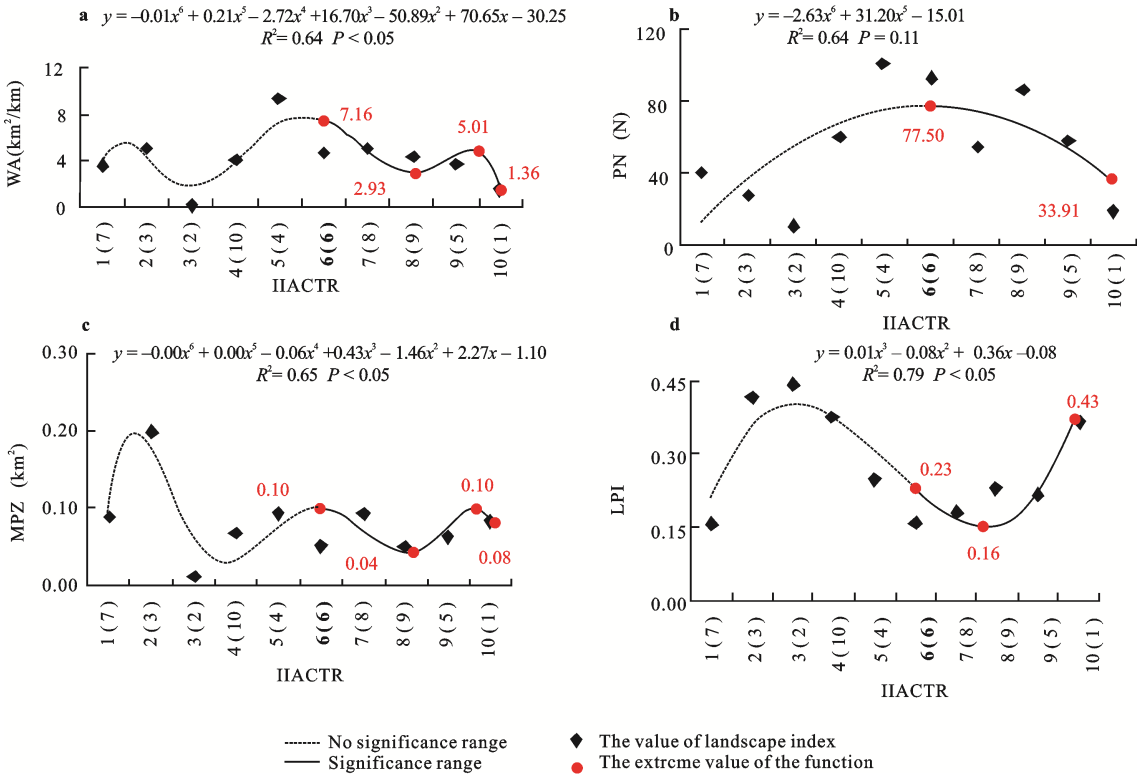

Fig. 3 Fitting functions between areal indices (dependent variables) and IIACTR (independent variable). IIACTR, The impact index of areal characteristics on TN removal; Number in bracket of horizontal axle title represents sampling site number; WA, wetland area per km of river length; PN, patch number per km of river length; MPZ, mean patch size; LPI, largest patch index

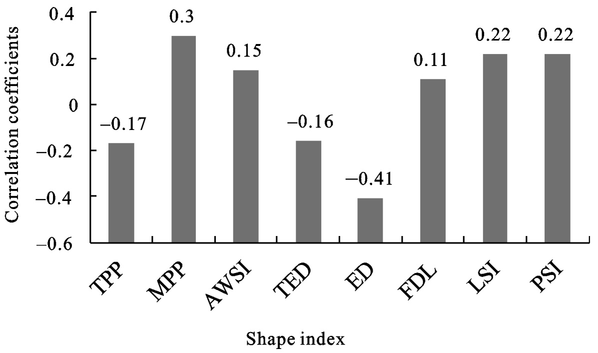

Fig. 4 Correlation coefficients between TN and shape indices.TPP, total patch perimeter per river length; MPP, mean patch perimeter; AWSI, average weighted shape index; PED, patch edge density; ED, edge density; FDL, fractal double-logged; LSI, landscape shape index; PSI, patch stretch index

using principal component analysis. The contribution rate of the first principal component was 51.68%, that of the second principal component was 30.38%, and that of the third principal component was 11.43%. According to their respective contribution rates, the first three principal components of the 10 sampling sites were weighted, and a total score of the shape index was obtained for each sampling site.

(2) Calculation of the impact index of shape characteristics to total nitrogen removal. Similarly, the step-by-step elimination analysis used for IIACTR calculation was applied to the impact index of shape characteristics toTN removal (IISCTR). The ranking result of the sampling site numbers was 3, 1, 2, 9, 5, 10, 6, 4, 8, 7 (Table 6). After six rounds, the TN concentration showed a significant and negative correlation with the total score of the shape indices ($P < 0.05$). According to the order of elimination, the IISCTR of each sampling site was obtained (Table 6).

(3) Selection of fitting function between IISCTR and shape indices. Similarly, the regression equations between the IISCTR (independent variable) and the shape indices (dependent variables) were established using the function regression fitting method. Based on step-by-step increasing, the equation with the largest added value of R^2 was selected to reveal the influence of each shape index on TN removal (Table 7). The results showed that when the fitting function between IISCTR and TPP index was at the 3rd time, the added value of R^2 was the greatest (0.46). Therefore, the 3rd-time function was selected for analysis. The 3rd function was also selected between the IISCTR and MPP index, the 4th function was selected between the IISCTR and AWSI index, the 5th function was selected between the IISCTR and TED index, and the 2nd function was selected between the IISCTR and ED index, FDL index, LSI index, and PSI index, respectively (Table 7).

(4) Change characteristics of the fitting function curves between IISCTR and shape indices. The correlation between IISCTR and TPP index, as well as IISCTR and MPP index, both showed a concave down feature (Figs. 5a, 5b) in the significant range (the solid line in the figure), indicating that stronger connectivity favours greater TN removal. However, when a certain extreme value is reached, the opposite situation occurs, namely the stronger the connectivity, the faster the wetlands receiving agricultural drainages and the lower the

Table 6 Sampling sites eliminated and the correlation coefficients between TN and total score for shape indices after step-by-step elimination of the sites

Elimination step	Sampling site eliminated	Impact index of shape characteristics to total nitrogen removal (IISCTR)	Correlation coefficient after sampling site data elimination
1	3	1	−0.25
2	1	2	−0.37
3	2	3	−0.55
4	9	4	−0.73
5	5	5	−0.83
6	10	6	-0.98^*
7	6	7	-0.99^*
8	4	8	-0.99^*
9	8	9	-0.99^*
10	7	10	-0.99^*

Note: $^* P < 0.05$

Table 7 The R^2 values and added values of R^2 of regression functions between shape indices (dependent variables) and impact index of shape characteristics to total nitrogen removal (IISCTR) (independent variable)

Equation times	TPP		MPP		AWSI		TED	
	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}
1	0.13	0.00	0.06	0.00	0.13	0.00	0.28	0.00
2	0.16	0.03	0.40	0.34	0.14	0.01	0.28	0.00
3	0.62	0.46	0.78	0.38	0.33	0.19	0.33	0.05
4	0.62	0.00	0.89	0.11	0.60	0.27	0.38	0.06
5	0.66	0.04	0.91	0.02	0.70	0.10	0.50	0.12
6	0.73	0.07	0.92	0.01	0.84	0.14	0.52	0.02

Equation times	ED		FDL		LSI		PSI	
	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}	R^2	R^{2+}
1	0.23	0.00	0.55	0.00	0.51	0.00	0.51	0.00
2	0.59	0.36	0.61	0.06	0.67	0.16	0.67	0.16
3	0.63	0.04	0.61	0.00	0.81	0.14	0.81	0.14
4	0.63	0.00	0.63	0.02	0.81	0.00	0.81	0.00
5	0.64	0.01	0.65	0.02	0.82	0.01	0.82	0.01
6	0.88	0.24	0.68	0.03	0.85	0.03	0.86	0.04

Notes: R^{2+}, added value of R^2; TPP, total patch perimeter per 1 km river length; MPP, mean patch perimeter; AWSI, average weighted shape index; TED, total edge density; ED: edge density; FDL, fractal double-logged; LSI, landscape shape index; PSI, patch stretch index

TN removal. The increased interconnection between patches can facilitate the flow of nitrogen-containing water. TN removal in wetlands is a complex process, which requires a certain time to complete (Wang et al., 2018a), and a fast influx of TN to wetlands would lead to excessive TN that cannot be removed in time, thus increasing the TN concentration. This result is also consistent with the fitting function between IISCTR and ED index in the significant range showed a downward trend slightly (Fig. 5c).

The correlation between IISCTR and AWSI index fluctuated in the significant range, indicating that a too weak or too strong edge effect is not favourable to TN removal (Fig. 5d). The fitting function between IISCTR and TED index also has the characteristics of fluctuation in the significant range (Fig. 5e), indicating that the TN removal capacity does not weaken rapidly in the process of patch fragmentation and complex shape. The correlation between IISCTR and FDL (Fig. 5f), LSI (Fig. 5g), and PSI (Fig. 5h) shape indices showed downward trend in the significant range, indicating that more regular landscape shape is associated with lower concentration of TN and greater TN removal.

3.3 Comprehensive effects of landscape area and shape on TN removal

With regression to the second step, the *F* value of the equation reached 550, and remained the same value at the third step (Table 8). At the second step, the correlation coefficient was the largest, *P* value was the smallest, residual standard deviation was the smallest, coefficient of determination was the largest, and residual path coefficient was the smallest (Table 8). This shows that the second step of the regression is the best step for interpretation and that these results can be used for statistical analysis.

The stepwise regression process showed that only the ED index was included in the equation in the first step, indicating that wetland connectivity is the primary factor for TN removal. In the second step, two areal indices (WA and PN) and five shape indices (LPI, MPP, AWSI, FDL and PSI) were simultaneously included in the equation, indicating that area and shape coordinates play a comprehensive role in TN removal.

According to the results of the path coefficients (Table 9), the path coefficient of the ED index was −0.41, which further demonstrated that wetland connectivity is the premise of TN removal. The path coefficient of the MPP index was 0.30, indicating that the TN removal process is accomplished by the accumulation of individual patches at the micro level, the patch undertakes the main function of TN removal. The path coefficient of the PN index was −0.29, showing that TN removal requires a certain number of patches. The path coefficient

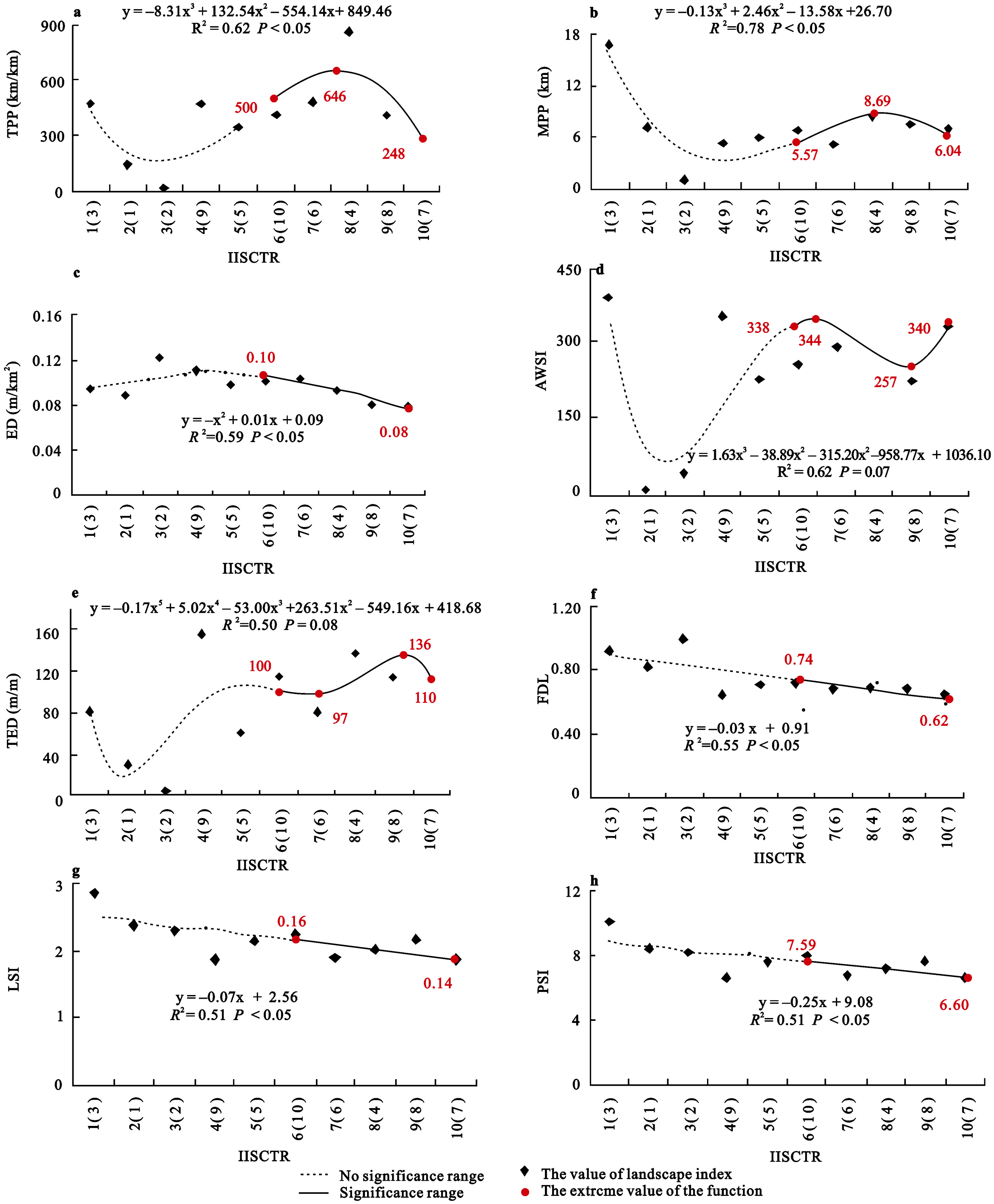

Fig. 5 Fitting functions between shape indices (dependent variables) and IISCTR (independent variable). IISCTR, the impact index of shape characteristics to total nitrogen removal, Number in bracket of horizontal axle title represents sampling site number; TPP, total patch perimeter per 1 km river length; MPP, mean patch perimeter; AWSI, average weighted shape index; TED, total edge density; ED: edge density; FDL, fractal double-logged; LSI, landscape shape index; PSI, patch stretch index

Table 8 Parameters of stepwise regression for all landscape indices

Regression step	*F*	*R*	*P*	Residual standard deviation	Adjusted *R*	Durbin-Watson	Coefficient of determination	Residual path coefficient	Incorporating factors
First	1.58	0.41	0.24	1.22	0.25	2.27	0.17	0.91	ED
Second	550	0.99	0.03	0.06	0.99	2.68	1.00	0.02	WA, PN, LPI, MPP, ED, AWSI, FDL, PSI
Third	550	0.99	0.03	0.06	0.99	2.68	1.00	0.02	WA, PN, LPI, MPP, ED, AWSI, FDL, PSI

Notes: WA, wetland area per km of river length; PN, patch number per km of river length; LPI, largest patch index; MPP, mean patch perimeter; ED, edge density; AWSI: average weighted shape index; FDL: fractal double-logged; PSI: patch stretch index

Table 9 Path coefficients of regression equation

Factor	WA	PN	LPI	MPP	ED	AWSI	FDL	PSI
Path coefficient	–0.13	–0.29	–0.14	0.3	–0.41	–0.16	0.15	0.04

Notes: WA, wetland area per km of river length; PN, patch number per km of river length; LPI, largest patch index; MPP, mean patch perimeter; ED, edge density; AWSI, average weighted shape index; FDL, fractal double-logged; PSI: patch stretch index

of the AWSI index was −0.16, and the path coefficient of the FDL index was 0.15, indicating that the impact of landscape shape on TN removal depends on patch connectivity and quantity. The path coefficient of the LPI index was −0.14, and the path coefficient of the WA index was −0.13, indicating that the impact of wetland area on TN removal is based on patch connectivity, number, and shape. The path coefficient of the PSI index was 0.04, which indicates that the regularisation of wetland patches can promote the removal of TN in the wetland.

The above analysis shows that wetland connectivity is the primary factor of TN removal and that the area and shape of wetland play a supporting and coordination role.

4 Discussion

4.1 Effect of wetland area on TN removal

The fitting function between the IIACTR and the WA index showed a wave-like downward trend (Fig. 3a) in the significant range, and the fitting function between the MPZ index and the IIACTR also showed a wave-like fluctuation (Fig. 3c) with no obvious trend. This seems to be contradictory to the assertion that larger wetland area results in stronger TN removal capacity. Other studies have reported similar findings. Wu et al. (2012) found that wetland area has a limited impact on TN removal, while the spatial pattern can contribute by more than 50% (Wu et al., 2012). Li et al. (2012) studied the effects of wetland on TN output in the Tianmu Lake watershed and found that wetland area was only one factor affecting TN removal (Li et al., 2012). Rather than a positive effect, some patches in a wetland may have an interference effect on TN removal, leading to the phenomenon that TN removal does not increase with increase of wetland area. In a comparison study, Hu et al. (2016) simulated the nitrogen removal by narrowleaf cattail (*Typha angustifolia*) and *Coix lacryma-jobi*, two wetland plants, from wetland wastewater and found that narrowleaf cattail had a very poor nitrogen removal efficiency (Hu et al., 2016). Han et al. (2017) studied the distribution characteristics of nitrogen in Caohai Lake, Guizhou, and found that submerged plants not only have poor nitrogen removal ability but also emit nitrogen into wetland water through endogenous release, which in turn increases the nitrogen content (Han et al., 2017).

4.2 Effect of wetland patch core area on TN removal

The fitting function between the IISCTR and the TED index in the significant range (solid line in Fig. 5d) showed a wave-like fluctuation, indicating that with increase of patch fragmentation in wetland, the patch core area can also participate in the TN removal process and enhance the removal ability. However, because the patch core area is small, the added TN removal ability is limited. Therefore, neither a too-large nor too-small total patch size is favourable to TN removal, and the curve only fluctuates in a small range. Moreover, once the patch core area exceeds its capacity, the whole patch is threatened. Therefore, on the premise of maintaining wetland connectivity, it is necessary to ensure the controllability of the connectivity and prevent excessive harmful substances from spreading to the core area of wetland patches. This corresponds to the finding of Deane et al. (2017) that damage to the patch core area, which accounts for only 5% of the total wetland function, would result in the loss of the entire wetland function (Deane et al., 2017).

4.3 Effect of wetland connectivity on TN removal

The ED index was incorporated into the equation at the first step of regression (Table 8), with the largest absolute value of path coefficient (Table 9). These results indicated that landscape connectivity was the primary factor for TN removal in the wetland. There was a certain degree of connectivity between patches. The wetland water carries a large amount of nitrogen, which can flow between patches, and the soil and vegetation of all adjacent patches can participate in the TN removal in the water body. The connectivity between the patches forms the foundation for TN removal, which is similar to the results of Racchetti et al. (2011), who found that the denitrification rates measured in connected wetlands (35–1888 μmol/m^2·h) are a magnitude higher than the rates measured in isolated wetlands (2–231 μmol/m^2·h) (Racchetti et al., 2011). In addition, Fan et al. (2012) verified that wetland networking plays a key role in wetland purification (Fan et al., 2012). This result is also consistent with the conclusion that the edge of wetlands is not well connected and that there is excess TN (Hille et al., 2018). Therefore, based on the impact of wetland landscape pattern on TN removal, we can conclude that the area and shape of wetlands play important roles in maintaining wetland connectivity.

According to the results of wetland landscape pattern on TN removal after the wetlands receiving agricultural drainages, it is not suitable to directly discharge agricultural drainages into wetlands without prior treatment. Buffer zones should be established before outflow water enters a wetland, and necessary pre-monitoring and pre-degradation of excess harmful substances should be carried out. Therefore, the protection of wetlands should include both protection of existing wetlands from reclamation and destruction and also proper construction and maintenance. In the process of returning farmland to wetland, it is not sufficient to emphasise only how much wetland area should be restored. It is also important to emphasise the quality of the replaced land and thus avoid fragmentation and isolation of the returned land.

5 Conclusions

TN removal from wetland water is restricted by the landscape areal and shape characteristics of the wetlands. By maintaining landscape connectivity, area and shape factors can have a synergy with each other to complete the ecological function of TN removal in the water body.

The TN removal increases with larger wetland area, higher number of patches, and larger differences between patch areas. However, the correlation coefficients between all area indices and TN concentration did not reach a significant level, and the impact of wetland area on TN did not have a standard linear relationship.

The wetland that is more regular, as a whole or as a single patch, is more favourable to nitrogen removal. The most favourable shape of the landscape for TN removal is a mixed arrangement of relatively regular circular and square patches, which make the wetland shape regular as a whole.

The comprehensive analysis of wetland landscape area and shape showed that the connectivity of wetland patches is the primary factor for TN removal and that areal and shape indices have synergistic functions. All of the different factors restrain each other in achieving TN removal in wetland water.

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