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Effect of spatial pattern on nutrient reduction in the Liaohe Delta

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Abstract: The effect of spatial pattern on the nutrient reduction is investigated based on the spatial simulation model developed for the study area of the Liaohe Delta, China. Four scenarios are designed to test the effect of different landscape components on the nutrient reduction in the reed marsh: Canal density, reed area size, reed area shrinking pattern, and pumping station position. Based on a spatial model designed for the study area, the nutrient reduction in each case of these scenarios is simulated. The results indicate that each factor brings less than 10% change in the total nutrient reduction rate. More canals will not help much to improve nutrient reduction. Smaller areas are more efficient than larger ones. The shrinkage pattern is better than others in keeping a higher nutrient reduction rate. It is also more efficient to keep the pumping station near the border of the area to be irrigated. These conclusions provide theoretical supports to strategy makers for local land use planning, and contribute to the understanding of the relationship between landscape patterns and functions.

Landscape pattern analysis has been a major topic in landscape ecology[1-4]. Many quantitative methods have also been designed to describe the pattern, in order to get an overall idea of how the landscape is structured, and what is the effect of different patterns on large scale ecological processes[5-11]. So far this kind of research has mainly focused on habitat analysis, or site selection of wild animals, in the scope of nature conservation[12-13]. But few pattern analyses have been made on the bio-chemical process yet, though some papers have touched upon this topic[14-16]. Wetlands are increasingly thought of as landscape features that can be used to trap nutrients[17-23]. China has just noticed its importance and started working on it[24-25]. Our major concern is focused on the possibility to use the estuary wetland as a treatment system for nutrient enriched river water, in order to reduce the chances of eutrophication in the coastal seawater[26]. It is scientifically important to study the effect of spatial arrangement (pattern) of wetland features on the nutrient reduction, in order to understand further about the relationship between landscape structure and function, which has been the focus of landscape ecological research. In the mean time, the results from such kind of research will provide strong supports for sustainable landscape management and planning. 1 Methodology 1.1 Study area and spatial simulation model The study area is in Liaoning Province, China, to the north of Liaodong Bay, within the range of 121(35´-122(55´E and 40(40´-41(25´N. The world largest reed marsh (c.a. 100,000 ha) is located here. The climate is temperate monsoon, with reed (Phragmites australis), cattail (Typha spp.) and Suaeda heteroptera as main vegetation species. It is a managed natural wetland with wastewater irrigation in spring and reed harvesting in winter. The dry reed stems are moved out of the system as raw materials for paper mills, while leaves are collected as fuel or fodder. Reciprocally, in spring the wastewater from paper mills will be used to irrigate the reed (normally 3 times a year, each time lasting 15-20 days with 20 days natural drainage in between). Experiments showed that the current wastewater irrigation regime has no negative effect on the reed growth, nor is accumulation problem observed, while the nutrients and pollutants in the water can be removed by the reed marsh[27-29]. More importantly, coastal pollution from paper mill effluent is avoided. In springs of 1997 and 1998, intensive field measures were made to investigate the purification function of reed marsh and canal system in the Liaohe Delta[24]. One of the well-managed reed fields with its related pumping station and canals was selected for this study. Water sampled at the pumping station was considered to be the input into the system. In the canals, the water was collected at 500, 2000 and 6000 meters away from the pumping station, respectively. In the reed field far from the edges, surface water and ground water samples at 40, 60 and 80 cm depths were collected from Lysimeter systems specially designed for ground wa ter collection[26]. Water samples were acidified with H_2SO_4 to keep pH<2, and analyzed with standard methods provided by the State Environmental Protection Agency[30]. Our research was mainly focused on the nutrients that might cause eutrophication problems in sea, namely, TN (total nitrogen) and SRP (soluble reactive phosphorous). The spatial model has two subsystems to simulate the nutrient reduction in the canals and reed fields respectively. The field data from the canal system were good enough to fit into a non-linear regression model: where C(x, y) is the nutrient concentration (mg/l) in water at a certain point on the canal, and ´dist.´ is the distance (m) from this point to the pumping station. ´A´ and ´B´ are parameters related to the input concentration of nutrients: where C1, C2, C3 and C4 are constants obtained from linear regression of field data, and different for nitrogen and phosphorous, while ´inload´ is the input load (mg/l) of nutrient concentration at the pumping station. But the analysis results in the reed field failed to build a strong enough model to simulate the reduction in the reed bed system, mainly due to lack of measure points in the extensive area (c.a. 100,000 ha), with low accessibility. To compensate the shortage of field data, Mander and Mauring´s (1994) linear regression model was adopted for the reed system. This model was based on more than 40 wetland treatment sites around the world, most of which were located in the temperate zone as the Liaohe Delta. The main species in these wetlands are also reed or cattail as in our study area. The formulas are: where Y is removal and X is load, both in g/m2·d for N and mg/m2·d for P. There is no limitation for increasing capacity of removal as load increases[17]. The input load (X) can be decided by the daily water load (m3), area of reed (m2), and nutrient concentration (mg/l) at the source point: The above process-based models are combined with digital canal and reed distribution maps, and transformed into a spatial model with the help of GIS. The main part of the model is run in the Grid module of Arc/Info, with AML (Arc Macro Language) programs designed by Li[26]. The general idea is that, given water and nutrient concentration input at the pumping station, as well as the distribution of canals and reed fields, the model is able to predict the concentration or reduction distribution at any point (grid cell, 30 m resolution) in the simulated area. The total reduction is obtained by summing up all the reduction values in each cell, while the reduction rate is the percentage of total reduction to total input. Validation against experimental data indicates that the model is strong enough to make the above prediction (n = 12, RTN = 0.717, RSRP = 0.821, both are higher than the significant value: R = 0.708). Simulation results for the whole irrigated area at different periods and input loads indicate that the canal system and reed system compensate with each other very nicely in nutrient reduction. In other words, when the reduction in the canal system is high (at low input loads, for example), the removal efficiency in the reed system will be low, and vice versa. This made the total reduction rate more or less stable in spite of the input load, irrigation period and many other factors change. For total nitrogen (TN), it is about 66%, for soluble reactive phosphorous (SRP), it is about 88%. The reduction in the canal system is lower than in the reed system for TN, but much higher than the reed system for SRP. The whole system is more efficient to remove phosphorous than nitrogen. In the nutrient reduction model, three factors are mainly concerned: 1) nutrient concentration at the pumping station; 2) area of the reed; and 3) distance of a point on the canal to the pumping station. Simulation data has showed that the input concentration does not have much effect on total reduction rate in the system. How about the effect of different spatial arrangements of canals, reed fields and pumping stations on the reduction? Generally we expect that:* If the number or total length of canals decreases, the amount of nutrients removed by canals will decrease. As a result the total reduction rate should decrease.* If the area of reed decreases, the nutrients removed by both canals and reed should decrease. Therefore the total amount of nutrients removed should decrease.* Different reed distribution patterns should have different effects on the amount of nutrients that can be removed. But it is difficult to predict which pattern is better in its ability of nutrient reduction.* The positioning of pumping station should also affect the nutrient reduction in the reed and canal system.These predictions were analyzed via different scenarios of reed, canal and pumping station combinations. 1.2 Pattern scenarios designed for nutrient reduction simulation One of the irrigation areas in the north-western part of the Liaohe Delta was chosen for this study. To simplify the analysis procedure, some test maps with different spatial patterns were designed for this area to simulate the nutrient reduction, and some general assumptions were made: * The irrigation period is 20 days, from April 20th to May 10th, and the water pumping capacity is 21 m3/s.* The input concentration at the pumping station is 7.33 mg/l for TN (total nitrogen) and 0.14 mg/l for SRP (soluble reactive phosphorous) during this period, as measured from one of the sample periods in 1998.* The daily water and nutrients input load into the system remains stable during this period. By changing one variable while keeping the others stable, four series of testing maps were generated: canal density, reed area size, reed area shrinking pattern and pumping station position. The situation of each scenario is described in detail as follows. 1.2.1 Canal density If the present area of reed is reserved, but the density of canals is changed into one of the following situations : The canal density varies greatly in the whole irrigated area of the Liaohe

Delta. The above densities (0-34.67 m/ha) can more or less cover the variation range in the reed field part. In Figures 1-b, c and e, the canals are deleted or added until the canal density reaches the desired value. Maybe the distribution pattern of the ´designed canals´ is somewhat arbitrary, but the simulation results should provide enough information to indicate the overall trend. The relative position of canals is also considered to keep distribution balance for the whole reed field. This is also the case in the following scenarios. 1.2.2 Reed area size If the canals are kept as present, but the area of reed shrinks into one of the following situations (Figure 2): The natural wetland in the Liaohe Delta has been shrinking due to continuous land conversion from reed to paddy field or other land use types. Although the reed is also expanding on the newly created beach, the speed is not as high as that of the loss. The reed field loss in the small area chosen for our research is especially high because it is relatively far from the sea and the soil is more suitable for agricultural use. In Figure 2, the shrinking sequence from present situation to 3/4, 1/2, and 1/4 of the present area towards the pumping station is delineated, and the canals are truncated accordingly. Normally the canal segments are considered only when they are in the reed covered area. Once the reed field is converted into other land use types, the polluted water from paper mills is not allowed to apply any more, because it contains some other pollutants, which may affect the quality of crop products. For the scenario of area shrinking, two alternatives of simulation can be made:* Keep total water input load at the pumping station as present, and intensify the water load per unit area when the total reed area becomes smaller.* Keep the present water load per unit area stable, and reduce the total water input load at the pumping station when the reed area decreases. 1.2.3 Reed area shrinking pattern If the area of the reed decreases to half of the present situation, and the canals are kept as present, but the distribution pattern of reed becomes one of the following situations (Figure 3): The cases in this scenario is based on Collinge and Forman[31], who proposed the four land conversion possibilities that vary in their spatial configuration: shrinkage, bisection, fragmentation, and perforation. In the Liaohe Delta, different patterns of canals and reed are caused by land conversion from reed marsh to agricultural or other use. The change of the patterns should be based on the logical rule of local land conversion. In reality, ´shrinkage´ and ´fragmentation´ are more likely to happen within one irrigation area than ´bisection´ and ´perforation´. However, the latter two cases are theoretically as important as the other two and are also considered. The four reed area shrinking patterns in Figure 3 are delineated in GIS. The position of different reed and non-reed areas is arbitrarily assigned. As in the reed area size scenario, only those canals that might contribute to the irrigation of reed are reserved. Figure 4 Different pumping station positions in relation to the reed and canal distribution, in which, a and d are near the border, b, c and e are near the center 1.2.4 Pumping station position This scenario keeps the present reed area and canal distribution, and rearranges the position of the pumping station (Figure 4). Water and nutrients input load remains at present level. Although the pumping station in this irrigation area is located near the border of the reed field, it is not always the case in other irrigation areas. New pumping stations will also be built in the future in the newly reed occupied area as vegetation succession continues towards the sea. To study the effect of pumping station position on the nutrient reduction, the locations of pumping stations are randomly chosen in Figure 4. Figure 4-a represents the present situation with the pumping station sitting on the border of the irrigation area. Figure 4-d is similar to 4-a, with the pumping station sitting on the other end of the irrigation area. The stations are located somewhere inside the irrigation area in Figures 4-b, c and e. Based on the spatial simulation model and assumptions made earlier, the nutrient reduction is calculated for each case in the above scenarios and presented in the following part. 2 Results 2.1 The effect of canal density Figure 5 presents the different simulation results for different canal density cases (Figure 1) and nutrient elements. From Figure 5, some general conclusions concerning the canal density scenario can be drawn:* Generally speaking, the increase of canal density does not help much for the total nutrient reduction. Less than 4% more total N or P is reduced by doubling the canal density. Even the highest difference between no canal and double the present canal density is less than 10%. Therefore it is not a good idea to increase the canal density to improve the system efficiency in nutrients reduction.* With the increase of canal density, both canal and reed systems show an increase in the nutrient reduction capacity, resulting in the increase of total reduction. The exception is in the situation of no canal, where the reduction by reed is very high. Therefore, in case of canal shortage, the nutrients will be removed by reed system as compensation.* With the increase of canal density, the increase extent of nutrient reduction in the canal system is a little bit higher than that of the reed system. This is reasonable because more canals are put into use for water transportation.* The relationship between total reduction rate and canal density is a little bit higher for N (RN = 0.840, n = 5) than for P (RP = 0.811, n = 5). Although the results agree with the prediction that more canal, more reduction, the increase of total reduction quantity does not seem so obvious compared with the magnitude of canal density increase. 2.2 The effect of different reed area when total input stable

Figure 6 shows the simulation results for the reed area size scenario (Figure 2) in TN and SRP reduction, provided that the total water input at the pumping station is kept as present, and the input load per unit area is intensified when the reed area shrinks. From Figure 6, some conclusions can be drawn concerning the effect of different area sizes. If the total water and nutrients input keeps the present level at the pumping station, then:* With the decrease of reed area, the total reduction quantity for TN and SRP has both increased, if the area shrinks steadily towards the pumping station. This is contradictory to what we had expected. We will come back to this point later on in the discussion part of this paper.* With the decrease of reed area, the total canal length decreases as well. But the canal reduction quantity for N and P changes differently. For N, it increases, while for P, it decreases.* The total reduction for N (RN = - 0.997, n = 4) is a little bit more closely related to the reed area than for P (RP = - 0.990, n = 4). The simulation results prove to be contrary to our prediction that smaller area will reduce the nutrient removal ability. The reason for this has to be discovered from the way we calculate the reduction for nitrogen and phosphorous. More detailed discussion on this will be provided in the next part of this paper.

2.3 The effect of different reed area sizes when total input reduces

Figure 7 presents the simulation results for different reed area sizes (Figure 2) for TN and SRP, provided that the total input of water at the pumping station decreases with the reed area. Figure 8 provides the relative reduction rate for this scenario. In this case the input load per unit area can be kept at present level. This is more reasonable because the reed field has limited ability to accept the amount of water input into the system, even if there is no limitation for the quantity of nutrient input. Compare Figures 7 and 8, if the water and nutrient input load at the pumping station decreases with reed area, so as to keep the present input load per unit area, then:* With the shrinking of reed area, the total amount of N and P removed by the system decreases sharply. This can be understood because the total input at the pumping station decreases almost proportionally with the reed area. It also agrees with the predictions at the beginning of the paper. * Concerning the absolute quantity removed, both the canal and reed systems show a decrease in nutrient reduction, as a result of decreased total input, canal length, and reed area. * Concerning the percentage removed, smaller areas are more efficient than larger ones in nutrient removal (Figure 8). This is concordant with the results obtained when keeping the total input load at the pumping station stable.* The percentage of N removed by the canal and reed has both increased with the shrinking of reed area, resulting in an increase of total reduction rate.* The percentage of P removed by the canal decreases as the reed area shrinks, while the percentage of P removed by reed increases. After compensating with each other, the total percentage removed increases a little bit with the shrinking of reed area. * The total nutrient reduction rate is closely related to the area size of the reed (RN = - 0.983, RP = - 0.980, n = 4), though negatively. But the total reduction rate difference between the present situation and 1/4 of the present area is only about 5% for N and 2.5% for P. This group of simulation results based on stable input load per unit area agree well with the prediction that the smaller the reed area is, the lower the nutrient removal is. But this agreement is superficial because smaller areas are more efficient in terms of reduction rate. Experimental results from the Everglades Nutrient Removal Project also showed the same trend (Nungesser and Chimney, personal communication) at least for phosphorous.

2.4 The effect of different reed area shrinking patterns

Figure 9 provides the simulation results based on different reed area shrinking patterns, namely, shrinkage, perforation, fragmentation and bisection (Figure 3)[31]. The sizes of reed covered area are all half of the present situation, and the input load per unit area is also kept at the present level. It is also possible for us to keep the total input load at the pumping station at present level, but the trend of simulation results should be the same. Therefore, only one calculation scenario is provided for analysis. According to Figure 9, if the reed area decreases to half of the present area at different patterns, while the water input load per unit area is kept at the present situation, it can be concluded that:* In terms of total nutrient reduction, the sequence for different reed distribution patterns is: Shrinkage > Perforation > Fragmentation > Bisection Therefore, the shrinkage pattern of land transformation is mostly recommended than other patterns, while bisection is least recommended, if we want to keep a high nutrient reduction rate in the reed field.* Comparing the situation of perforation and fragmentation, nutrients removed by the canals in the perforation case are more than in the fragmentation case. On the other hand, nutrients removed by the reed in the fragmentation case are more than in the perforation case. For the sake of reed growth and harvesting, fragmentation is ´better´ than perforation pattern. The total reduction of these two cases does not differentiate very much. The spatial allocation of reed and non-reed areas can affect the canal distribution a lot, as well as the simulation results. None of these land transformation patterns is recommended, if we take other factors such as management and bio-conservation into consideration. * In the case of shrinkage, the reduction rate in the reed field is the highest. This is an optimistic result because the irrigation aims to bring more nutrients into the reed field as fertilizers.* Concerning the percentage of nutrients removed, the maximum difference bet

ween individual patterns is about 5% for nitrogen, and 3% for phosphorous. Therefore the effect of reed area distribution pattern is about the same level as other pattern scenarios. According to the land reclamation projects in the Liaohe Delta, the shrinkage and fragmentation patterns are more likely to happen. The former is more acceptable as far as nutrient reduction and management factors are concerned. 2.5 The effect of different pumping station positions From Figure 10, it can be concluded that:* The positioning of pumping station does have a strong effect on the nutrient reduction of both canal and reed systems. But, due to the compensation effect between the reed and canal systems, the total reduction does not change so much. Generally speaking, the total reduction rate is higher when the pumping station is far from the spatial center of the system .* When the pumping station is farther away from the spatial center of reed area, the canal reduction for nitrogen and phosphorous is higher (a, d). On the contrary, the reed reduction capacity becomes higher when the pumping station comes closer to the system center. This series of simulation result has proved the expectation that the position of pumping station has an effect on the nutrient reduction. It also points out the extent and trend of this effect.

关键词： pattern effect; nutrient reduction; wetland; canal density; area size; shrinking pattern; pumping station position