

Changes in Landscape Ecological Risk and Driving Forces in the Sanjiang Plain, 1976-2013: Post-print

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Abstract

Affected by natural processes and human activities, the landscape ecological risk pattern in the Sanjiang Plain has undergone significant changes. This study employed GIS and RS technologies to construct a landscape risk index, combined with grid analysis and geographic detector methods to analyze the changes and driving forces of landscape ecological risk in the Sanjiang Plain from 1976 to 2013. The results indicate that temporally, from 1976 to 2013, the landscape loss degree of cropland, grassland, and wetland in the Sanjiang Plain gradually decreased, while that of forestland and residential land continuously increased, with the overall ecological risk exhibiting a decreasing trend. Spatially, high-risk areas dominated in 1976, whereas low-risk areas were predominant in 2013. From 1976 to 2013, low-risk, relatively low-risk, and medium-risk areas continuously expanded toward the western and southwestern parts of the Sanjiang Plain, while high-risk and relatively high-risk areas gradually retreated to the coasts of the Heilongjiang and Ussuri Rivers and protected areas in the north. The ecological risk overall shifted toward the southwest direction, with the risk centroid moving 37.8 km southwestward. The changes in the landscape ecological risk pattern in the Sanjiang Plain were significantly influenced by elevation, landform, distance to residential points, distance to protected areas, and human disturbance degree, among which human disturbance degree, distance to residential points, and distance to protected areas exhibited the most significant explanatory power for landscape ecological risk. In 1995, the factor explanatory power of human disturbance degree (71.2%), distance to residential points (64.6%), and distance to protected areas (43.7%) was significantly higher than that of landform type (11.2%) and watershed type (8.9%). In 2013, the explanatory power of landform type (23.5%) exceeded that of distance to protected areas (23.3%). This study provides a scientific reference for wetland protection and restoration.

Full Text

Preamble

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A Long-term Site Study for the Ecological Risk Migration of Landscapes and Its Driving Forces in the Sanjiang Plain from 1976 to 2013

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Abstract

The ecological risk pattern of landscapes in the Sanjiang Plain has experienced tremendous change in recent years due to the influence of natural processes and human activities. This study collected data in the Sanjiang Plain from 1976 to 2013. Based on GIS and RS technologies, we established a landscape risk index and simultaneously analyzed the corresponding driving forces for the ecological risk of landscapes using grid analysis and the geographic detector method. The results showed that landscape loss of farmland, grassland, and wetlands decreased slowly, whereas the loss of forest land and residential land continued to increase. Overall, the ecological risk was lower in the Sanjiang Plain from 1976 to 2013. From the spatial distribution perspective, the landscape ecosystem was primarily at high risk in 1976, whereas it was primarily at low risk in 2013. In addition, the areas with low, low-medium, and medium risks continued to expand into the vast west and southwest regions of the Sanjiang Plain, which was accompanied by a gradual retreat of the medium-high and high risk areas to the north of the Heilongjiang River and to the eastern Wusuli River along the protected areas and banks. From 1976 to 2013, ecological risk experienced a gradual migration to the southwest of the Sanjiang Plain, and the risk center of gravity migrated a distance of 37.8 km. The landscape pattern of ecological risk in the Sanjiang Plain experienced a change that was influenced by altitude, geomorphology, residential distance, distance from the reserve, and human disturbance, whereas residential distance, human disturbance, and distance from the reserve explained much of the landscape ecological risk. The explanatory power of human disturbance (71.2%), residential distance (64.6%), and distance from the reserve (43.7%) was significantly higher than that of geomorphology type (11.2%) and basin type (8.9%) in 1995, and the explanatory power of the geomorphology type (23.5%) in 2013 was also slightly greater than that of distance from the reserve (23.3%). This result could provide a scientific basis for wetland protection and restoration.

Keywords: landscape ecological risk; landscape index; geographic detectors; human disturbance; the Sanjiang Plain

Introduction

Natural ecosystems provide important material foundations and ecological services for human social development, and their sustained structural and functional stability has become a prerequisite for human social development. The continuous expansion of human society has caused most regions of the world to directly or indirectly endure pressure and stress from human activities, leading to numerous ecological risks. Ecological risk refers to a situation where the ecological functions of a population, ecosystem, or entire landscape are stressed by external pressures, thereby adversely affecting the system's health, economic value, and aesthetic value in the present and future. Landscape ecological risk refers to the potential adverse consequences arising from the interaction between landscape patterns and ecological processes under natural or human influences. Landscape ecological risk assessment, based on the coupling perspective of ecological processes and spatial patterns in landscape ecology, places greater emphasis on the spatiotemporal heterogeneity and scale effects of risk, and is committed to achieving comprehensive characterization and spatial visualization of multi-source risks. Landscape ecological risk research can provide decision-making basis for regional comprehensive risk prevention and management.

Scholars at home and abroad have conducted extensive and in-depth discussions on ecological risks in different regions. International research has mainly focused on landscape ecological risk assessment at regional scales and the exploration of methods and models. For example, Ayre and Landis used a Bayesian network model to evaluate forest landscape ecological risk in Oregon, USA. Molininos et al. studied the ecological risk of marine protected areas in Japan by measuring local climate conditions. Bayliss et al. quantitatively studied the ecological risk index on the Magela Creek floodplain in Kakadu National Park, Australia, comparing point source risks from the Ranger uranium mine with diffuse landscape-scale risks. Domestic scholars have used landscape pattern indices to compare structural characteristics between different landscapes, revealing dynamic changes and spatiotemporal patterns of landscape ecological risk. Studies by Yao Shen et al., Fan et al., and others have used landscape indices to evaluate landscape ecological risk patterns in the Taihu region, Heilongjiang River basin, and Zhoushan Zhujiajian Island, achieving good research results. These studies mainly involve land use ecological risk assessment, watershed ecological risk assessment, and sea area ecological risk assessment.

Although landscape ecological risk research has become a hot topic in China, domestic scholars have mostly analyzed driving forces of landscape ecological risk from qualitative perspectives, lacking quantitative research methods. This

paper uses geographic detectors for quantitative analysis of landscape ecological risk changes and their driving forces. Currently, geographic detectors are mainly applied in land use, remote sensing, and computer network research, but are rarely used in quantitative studies of landscape ecological risk changes and their driving factors. As China's most concentrated marsh distribution area and an important commodity grain base, the Sanjiang Plain's landscape ecological risk pattern is of great significance for regional environmental protection and national food security. This study also enriches landscape ecology theory and provides auxiliary means for planning and management decisions. Taking the Sanjiang Plain as the research area, this paper uses GIS and RS technologies to study the spatiotemporal dynamic changes of landscape ecological risk, and employs geographic detectors to quantitatively analyze the relationship between landscape ecological risk changes and driving factors, comparing the contribution of different driving factors to landscape ecological risk to provide a scientific basis for sustainable development in the Sanjiang Plain.

1 Study Area Overview

The Sanjiang Plain is located in northeastern China, in the eastern part of Heilongjiang Province, and is an alluvial low plain formed by the Heilongjiang, Songhua, and Wusuli Rivers. Geographically, it spans 43°50' -48°27' N, 129°30' -135°5' E, covering an area of 10.89×10⁴ km². The region includes Jiamusi City, the Muling County area under Mudanjiang City, and the Yilan County area under Harbin City. The Sanjiang Plain belongs to the temperate humid continental monsoon climate zone, with an average annual temperature of 2.5–3.6°C, 10°C accumulated temperature of 2300–2500°C, and annual precipitation of 500–600 mm.

The overall terrain of the Sanjiang Plain is high in the southwest and low in the northeast, with vast marsh vegetation distributed in the alluvial low plain and Xingkai Lake alluvial-lacustrine low plain. The region has high natural soil fertility. The main soil types are meadow soil, black soil, and bog soil. The economy is dominated by agricultural production, with planting and animal husbandry as the primary activities and relatively small proportions of forestry and fisheries. The grain planting structure has changed significantly, shifting from soybeans and wheat to soybeans, corn, and rice, especially with rapid development of paddy fields.

2 Data Sources and Processing

Remote sensing images for 1976, 1995, and 2013 were selected as data sources. The 1976 data came from Landsat MSS with 80 m resolution; the 1995 data came from Landsat TM with 80 m resolution; and the 2013 data came from

Landsat OLI with 30 m resolution. To reduce the impact of image resolution on landscape pattern index calculations, all remote sensing images were uniformly resampled to 80 m resolution. The images underwent geometric correction and image enhancement, and interpretation keys were established. Based on the characteristics of the study area and analysis accuracy requirements, and following the “Land Use Status Survey Technical Regulations” and “Macro Survey and Dynamic Research of China’s Resources and Environment,” the landscape types of the Sanjiang Plain were divided into farmland, woodland, grassland, water area, residential construction land, and wetland (including marshes and beaches). The accuracy rate reached over 90% after field survey verification, meeting the research needs.

Meteorological data for driving force analysis came from the China Meteorological Data Network. Soil type data came from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. DEM data came from the Earth Science Data Center of the University of Maryland. Geomorphological types were obtained through digitization and classification of the Sanjiang Plain geomorphological map. Residential points were obtained by extracting them from the Sanjiang Plain land use map, followed by buffer analysis to obtain the distance of each evaluation unit from residential points. Protected areas were obtained by digitizing the planning maps of various nature reserves in the study area.

3 Research Methods

3.1 Landscape Ecological Risk Sub-area Division

Combining the area and research scale of the Sanjiang Plain, the study area was divided into 10 km × 10 km grid units using ArcGIS, resulting in 1,089 risk sub-areas.

3.2 Construction of Landscape Ecological Risk Index

Six landscape indices were selected for analysis: landscape fragmentation, landscape separation, landscape dominance, landscape disturbance, landscape vulnerability, and landscape loss. The landscape disturbance index is obtained by superimposing landscape fragmentation, landscape separation, and landscape dominance. The vulnerability index was obtained through expert scoring. Based on this, the landscape ecological risk index was constructed through the landscape vulnerability index and landscape disturbance index.

The calculation methods are shown in Table 1. In the table: A_i is the total area of landscape type i ; n_i is the number of patches of landscape type i ; A is the total landscape area; l_i is the distance index of landscape type i ; and a , b , c are the weights of the corresponding landscape indices. According to analysis and trade-offs, combined with previous research, the three indices were assigned

values of 0.6, 0.3, and 0.1 respectively. The landscape loss degree index (R_i) and landscape ecological risk index (ERI) were calculated as follows: $R_i = S_i \times F_i$, where S_i is the landscape disturbance index and F_i is the landscape vulnerability index.

3.3 Geographic Detector

The geographic detector consists of four parts: risk detector, factor detector, ecological detector, and interaction detector. The risk detector is used to detect areas where risk exists. The factor detector is used to test whether a certain factor is the cause of the spatial distribution pattern of landscape ecological risk. The ecological detector is mainly used to detect whether different factors have significant differences in affecting the spatial distribution of landscape ecological risk. The interaction detector can identify the interaction between factors two by two. Since this paper mainly focuses on quantitative analysis of the contribution of various driving factors to landscape ecological risk changes in the Sanjiang Plain, and although the interaction detector can explain the quantitative relationship between factors, due to space limitations and the complex mechanism of interaction, this paper selects the factor detector.

The factor detector uses the explanatory power $PD_{D,H}$ of the factor to judge. The larger the explanatory power, the greater the contribution of the factor to landscape ecological risk change, and the closer the relationship; conversely, the smaller. The calculation method is: $PD_{D,H} = 1 - (1/N^2H) \sum (N_i^2H_i)$, where D is the influencing factor, H is the landscape ecological risk value, and $PD_{D,H}$ is the explanatory power of D on H (i.e., contribution).

3.4 Construction of Human Disturbance Index

To analyze the impact of human disturbance on landscape ecological risk in the Sanjiang Plain, based on previous research results and the actual situation of the study area, human disturbance index values were assigned to six landscape types. The human disturbance degree of a grid unit was calculated as: $D = (H_i \times S_i)/S$, where D is the human disturbance degree of a grid unit, H_i is the disturbance index of landscape type i , S_i is the area of landscape type i , and S is the total area of the grid unit.

The spatiotemporal differences in landscape ecological risk patterns in the Sanjiang Plain result from the combined effects of natural and socio-economic factors. This study selected altitude, geomorphological type, basin type, soil type, average temperature, and annual precipitation as natural driving factors, and human disturbance, distance from residential points, and distance from protected areas as human driving factors.

4 Results

4.1 Landscape Pattern Dynamic Changes

Using Fragstats 3.4 software, landscape pattern indices for each landscape type in 1976, 1995, and 2013 were obtained. Due to natural stress and human activity interference, changes in the area and number of patches of each landscape type led to corresponding changes in landscape type risk indices. Woodland was the main landscape type in the Sanjiang Plain, with area showing a continuous decreasing trend. Residential land was the smallest. From the perspective of landscape type area and patch number, both farmland and woodland patches showed a trend of first decreasing and then increasing. Farmland area continued to expand, leading to continuously decreasing fragmentation and separation indices, causing a decline in farmland ecological risk index. The spatial distribution characteristics of farmland landscape changed from small random scattered distribution in the early stage to concentrated contiguous distribution. Woodland area gradually decreased, leading to continuously increasing fragmentation and separation indices, causing woodland ecological risk index to rise. The spatial distribution characteristics changed from concentrated contiguous distribution to small random scattered distribution.

Wetland area and patch number continuously decreased, making wetland landscape loss index relatively high. Wetland itself has the highest vulnerability among landscape types, and accelerated wetland loss led to a decrease in its influence on landscape ecological risk. From the landscape type perspective, wetland and woodland landscape loss indices were both relatively high, while farmland was lower. Although residential land and grassland loss indices were relatively high, their influence on ecological risk was limited by their landscape area. Landscape loss indices varied across different periods, with grassland and farmland continuously decreasing, with wetland loss change being most significant (decreasing from 0.7345 to 0.2643). Woodland and residential land loss indices showed a gradual increasing trend.

4.2 Spatial Distribution of Landscape Ecological Risk

The landscape ecological risk index values of 1,089 risk sub-areas in 1976, 1995, and 2013 were calculated. Using the geostatistical analysis module Kriging in ArcGIS 10.2, the ecological risk distribution maps of the Sanjiang Plain were obtained, and the dynamic changes of ecological risk spatial characteristics were analyzed. According to the equal interval classification method, the ecological risk of the study area was divided into low risk area ($ERI < 0.12$), lower risk area ($0.12 \leq ERI < 0.17$), medium risk area ($0.17 \leq ERI < 0.22$), higher risk area ($0.22 \leq ERI < 0.27$), and high risk area ($ERI \geq 0.27$).

In 1976, the Sanjiang Plain was dominated by high risk and higher risk areas, accounting for 41.51% and 26.80% of the total study area respectively. These were mainly distributed in the northeastern, eastern, and central parts of the Sanjiang Plain, including Tongjiang City, Mishan City, and northern Fujin. These

areas contained marsh wetlands with high landscape sensitivity and vulnerability, leading to high landscape ecological risk. Medium risk areas accounted for 14.73%, mainly distributed in the southwestern Xiaoxing'anling Mountains and central Wanda Mountains in the study area. Low risk areas were sporadically distributed in the western and northern parts of the Sanjiang Plain, dominated by farmland landscape with low loss degree.

From a spatial distribution perspective, high risk and higher risk areas mainly retreated to the Naoli River basin in the central part, the Sanjiang Nature Reserve in the northeastern part, the Wusuli River coast in the eastern part, and the Xingkai Lake area in the southern part. The main reason was that with economic development and increasing population, people destroyed forests and grasslands and converted some marsh wetlands to farmland, replacing the original forest and wetland landscapes with lower ecological risk farmland landscapes, causing a sharp reduction in high risk and higher risk areas.

In 1995, lower risk and medium risk areas accounted for 32.78% and 24.26% of the total area respectively, with all three risk types showing different degrees of increase. Lower risk areas had the largest area and most obvious increase, with landscape types dominated by woodland, followed by grassland and farmland, mainly distributed in the western and southwestern parts of the study area, most prominently in northern Muling County and southern Luobei County. These areas mainly transformed from high risk and higher risk areas. Several scattered high risk areas appeared in the central, northeastern, and southeastern parts of the study area, including the Honghe and Sanjiang reserves in the northeast and the Xingkai Lake reserve in the southeast. This was mainly because under mandatory national policy regulation, wetlands in protected areas were effectively preserved, while wetlands outside protected areas were significantly affected by human activities, with large areas of marsh wetlands being reclaimed.

In 2013, high risk and higher risk areas in the study area further decreased, with high risk areas accounting for only 3.24% of the total area. Low risk and lower risk areas significantly increased, with lower risk areas increasing from 32.78% to 35.46% of the total area. Low risk areas increased from 1.5×10^4 km² to 3.2×10^4 km². At this time, low risk and lower risk became the main risk types in the study area.

4.3 Changes in Landscape Ecological Risk Spatial Pattern

From 1976 to 2013, risk values showed a gradually decreasing trend in most areas of the Sanjiang Plain. The average landscape ecological risk value decreased from 0.300 to 0.186 to 0.162. Areas with large reduction 幅度 were mainly located in the Naoli River, Bielahong River, and Yalu River basins in the northeastern part of the study area, as well as the lower reaches of the Muling River in the eastern part. These areas were mainly located where wetland loss was significant, with landscape types changing from wetland to farmland, while the

ecological risk value of farmland was much lower than that of wetland, causing a substantial decrease in ecological risk values in these areas.

Some areas in the Sanjiang Plain showed gradually increasing risk values, mainly located in the western Xiaoxing' anling Mountains, central Wanda Mountains, and Xingkai Lake area. The landscape types in these regions were mainly woodland or water areas, and the ecological risk values of woodland and water areas gradually decreased. The overall trend of landscape ecological risk in the Sanjiang Plain was gradually decreasing. This was mainly due to the continuous increase in population in the Sanjiang Plain. To ensure national food security, the state encouraged wetland development through policies, and large-scale agricultural development activities led to fragmentation of large wetland areas, reducing wetland area, fragmentation, and dominance, thereby reducing landscape ecological risk.

Using the spatial statistical tools in ArcGIS, the risk centroids and standard deviation ellipses for 1976, 1995, and 2013 were obtained. From 1976 to 2013, the ecological risk centroid showed an overall trend of moving southwestward, with a centroid shift distance of 37.8 km. The ratio of the short axis to the long axis of the standard deviation ellipse gradually increased, with both axes showing an increasing trend, indicating that landscape ecological risk in the study area extended in both east-west and north-south directions, with the short axis extension trend being stronger than the long axis extension trend. The ecological risk centroid moved 28.1 km southwestward from 1976 to 1995 and 9.8 km southwestward from 1995 to 2013, indicating that early changes were more significant than later changes. During 1976-1995, large-scale reclamation in the northeastern part of the study area significantly reduced wetland area and gradually increased farmland area. At the same time, with improved mechanization and transportation conditions, previously inconveniently developed suitable agricultural wasteland was further reclaimed. During 1995-2013, farmland area in the northeastern part of the study area increased significantly. Affected by terrain and topography, farmland area in the southwestern part was relatively small, with landscape types dominated by woodland with gradually increasing ecological risk, causing the risk index in the southwestern part of the Sanjiang Plain to exceed that in the northeastern part, thus showing an overall movement of ecological risk toward the southwest.

4.4 Analysis of Factors Influencing Dynamic Changes of Landscape Ecological Risk in the Sanjiang Plain

The factors influencing landscape ecological risk changed over time, and their influence degree also showed obvious spatial differences.

4.4.1 Topographic and Geomorphological Factors Using the spatial analysis tools of ArcGIS, combined with DEM data of the study area, landscape ecological risk in different periods showed differences at different altitudes in the Sanjiang Plain. From 1976 to 2013, landscape ecological risk and altitude

generally showed a decreasing trend. The maximum values in all periods appeared at 0–35 m. The reduction 幅度 of landscape ecological risk reached its maximum at 50–65 m, after which landscape risk values alternated. At 0–50 m, the main landscape types were wetland and water areas with high separation and vulnerability, resulting in high landscape risk. At 50–95 m, farmland and residential points mainly appeared, with relatively low separation and vulnerability, resulting in medium landscape ecological risk. At 95–800 m, the landscape type was mainly woodland, less affected by human activities, with relatively low separation and fragmentation but obvious dominance, resulting in the smallest landscape ecological risk value. From a geomorphological perspective, from 1976 to 2013, areas with higher landscape ecological risk were mainly concentrated in low-lying low floodplains, which was consistent with the concentrated distribution areas of marsh wetlands in the study area.

4.4.2 Residential Construction Residential points are settlement locations formed by humans according to production and living needs and are also important land use types affecting landscape ecological risk patterns. Using ArcGIS buffer analysis of residential points, the average landscape ecological risk values of the Sanjiang Plain under different distance conditions were statistically analyzed. From 1976 to 2013, landscape ecological risk showed a trend of first increasing and then decreasing with distance from residential points, but the location of maximum landscape ecological risk was the same across periods, at 9–10 km buffer units. Within 0–10 km, landscape ecological risk showed a gradually decreasing trend. This was mainly because near residential points, industrial and agricultural activities were frequent, wetlands and water areas had long been reclaimed into farmland, resulting in relatively low landscape ecological risk. At 11–20 km, with increasing distance from residential points, human activities were limited, and the widespread distribution of woodland allowed wetlands and water areas to be better preserved, with landscape types mainly being wetland and water areas with high separation and vulnerability, resulting in high landscape ecological risk. Beyond 17–20 km, landscape types were mainly woodland with obvious dominance but low vulnerability and loss, resulting in relatively low landscape ecological risk. Human activity is a direct driving factor of land use change and also a direct cause of ecological risk.

4.4.3 Protection Policies and Protected Area Construction Landscape ecological risk is closely related to protection policies and protected area construction. China joined the “Convention on Biological Diversity” in 1992, and the Sanjiang Plain became one of the key protected areas in China, beginning to emphasize wetland protection. In 1998, the Heilongjiang Provincial Government decided to stop any form of wetland development in the province. In 2003, the Standing Committee of Heilongjiang Provincial People’s Congress discussed and passed the “Heilongjiang Province Wetland Protection Regulations.” The state built many nature reserves, including the Sanjiang National Nature Reserve (1994), Xingkai Lake National Nature Reserve (1994), Honghe National

Nature Reserve (1996), and Naoli River National Nature Reserve. The 1990s also proposed policies for returning farmland to wetland for wetland restoration.

Under mandatory national policy regulation, wetland area changes were relatively gentle. The remaining marsh wetlands are mainly distributed in and around protected areas. Using GIS technology to statistically analyze changes in landscape ecological risk at different distances from protected areas, the closer to the protected area, the greater the landscape ecological risk. The 0-2 km area is the region nearest to the protected area and also the most strongly affected by human disturbance, so landscape ecological risk is relatively high. Due to less human disturbance impact, landscape ecological risk is relatively low beyond 15 km.

4.4.4 Human Disturbance Disturbance is a ubiquitous phenomenon in nature that directly affects ecosystem evolution processes. Human disturbance caused by human activities has dramatically increased its impact on the surface natural environment and ecosystems. Landscape type change is the most intuitive manifestation of regional human activity impact. Studying landscape ecological risk changes under human disturbance conditions is of great significance for achieving sustainable development of human society and the natural environment. Using Excel to establish the relationship between human disturbance degree and landscape ecological risk, human disturbance degree was divided into five levels, with larger values indicating greater disturbance intensity.

From 1976 to 2013, the maximum landscape ecological risk appeared at the lowest human disturbance degree, indicating that the smaller the human disturbance degree, the greater the landscape ecological risk. The minimum landscape ecological risk values in different periods all appeared at the highest human disturbance degree, indicating that with increasing human disturbance intensity, landscape ecological risk gradually decreased. This was mainly because human activities changed surface cover conditions, especially after four large-scale agricultural reclamations, which destroyed the integrity of wetland landscapes and caused gradual conversion of wetlands to farmland, thereby reducing landscape ecological risk. From 1976 to 2013, landscape ecological risk in the Sanjiang Plain continuously decreased with increasing human disturbance intensity, but each period was slightly different. In 1976, it showed an “N” -shaped distribution pattern of first increasing, then decreasing, then increasing again, while 1995 and 2013 both showed a gradually decreasing trend. The landscape ecological risk in 1976 was significantly higher than in the other two periods, and human disturbance degree showed a continuous decreasing trend, which was directly related to protection policies, establishment of protected areas, and wetland fragmentation.

4.5 Quantitative Analysis of Driving Factors of Landscape Ecological Risk Changes in 1995

Using the factor detector to detect the relative importance of each influencing factor, the contribution of each factor to risk change was calculated. From 1976 to 2013, human disturbance degree and distance from residential points ranked in the top two in contribution to landscape ecological risk change, indicating they are the main controlling factors of landscape ecological risk change in the Sanjiang Plain. Geomorphological type and basin type also had significant contributions to landscape ecological risk, indicating that natural factors also have important influence on landscape ecological risk change.

In 1995, the main factors affecting landscape ecological risk change in the Sanjiang Plain were human disturbance degree, distance from residential points, and distance from protected areas. Among them, the explanatory power of human disturbance degree (71.2%), distance from residential points (64.6%), and distance from protected areas (43.7%) was significantly higher than that of geomorphological type (11.2%) and basin type (8.9%), indicating that human factors played a dominant role in landscape ecological risk change in the Sanjiang Plain.

In 2013, the factors with greater explanatory power for landscape ecological risk were human disturbance degree (36.9%), distance from residential points (32.8%), and distance from protected areas (23.3%). However, the explanatory power of geomorphological type (23.5%) was greater than that of distance from protected areas (23.3%), indicating that not all human factors had greater explanatory power than natural factors. Because the process of wetland conversion to farmland was most intense in the Sanjiang Plain during this period, and the implementation of protection policies and improvement of protected areas still required a process, although the state formulated a series of relevant protection policies and established nature reserves, their effect was not yet obvious.

5 Conclusions

From 1976 to 2013, landscape spatial changes in the Sanjiang Plain transformed from small random distributions to concentrated contiguous distributions. The dominance of water areas and residential land increased significantly, and landscape spatial aggregation gradually increased. Wetland landscape had the highest loss degree but decreasing dominance, and landscape spatial aggregation decreased. From the perspective of ecological risk spatial distribution and pattern changes, landscape ecological risk in the Sanjiang Plain showed a gradually decreasing trend. In 1976, high risk and higher risk areas dominated, but by 2013, the area of high risk and higher risk significantly decreased. From 1976 to 2013, high risk and higher risk areas continuously retreated to protected areas within the study area, while low risk and lower risk areas gradually expanded to

the western and southwestern parts of the Sanjiang Plain, with ecological risk overall moving toward the southwest.

From the perspective of influencing factors, changes in the landscape ecological risk pattern of the Sanjiang Plain were mainly affected by altitude, distance from protected areas, and human disturbance. The maximum landscape risk appeared at altitudes of 0–35 m in low-lying low floodplains. Landscape ecological risk decreased with increasing distance from residential points and protected areas, and decreased with increasing human disturbance intensity. Human disturbance degree, distance from residential points, and distance from protected areas were key factors affecting landscape ecological risk in the Sanjiang Plain. Quantitative analysis by geographic detectors showed that in 1995, the explanatory power of human disturbance degree (71.2%), distance from residential points (64.6%), and distance from protected areas (43.7%) was significantly higher than that of geomorphological type (11.2%) and basin type (8.9%). In 2013, the explanatory power of geomorphological type (23.5%) was slightly higher than that of distance from protected areas (23.3%).

When using geographic detectors to determine the contribution of influencing factors, due to the large time span and difficulty in data collection, this study did not consider the impact of various elements on landscape risk and only conducted factor detection analysis. Future research will more deeply study the impact of various factors and factor interactions on landscape risk.

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Note: Figure translations are in progress. See original paper for figures.

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