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Investigating the Dynamic Change and Driving Force of Isolated Marsh Wetland in Sanjiang Plain, Northeast China

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Abstract: Isolated marsh wetlands are crucial for maintaining regional hydrological connectivity and biological contiguity. The Sanjiang Plain is the most typical area of marsh wetland change in China. A large number of isolated marshy wetlands have been formed here due to natural and anthropogenic influences. However, there have been few quantitative studies of the dynamics of isolated marsh wetlands and their drivers at the regional scale. This study used Landsat series image data provided by the Google Earth Engine. Through field surveys, combined with visual interpretation and the Random Forest Algorithm, the distributional changes in isolated marsh wetlands, non-isolated marsh wetlands, and natural marsh wetlands in the Sanjiang Plain from 1975 to 2020 were identified and extracted. The dynamic change characteristics as well as the patch importance values (dIIC) of isolated and non-isolated marsh wetlands were analyzed using the dynamic degree, standard deviation ellipse model, and the integral index of connectivity (IIC). Finally, the driving factors and interactions affecting the distribution of isolated marsh wetlands were analyzed by the Geodetector model. The results show that (1) the temporal dynamics of the three types of marsh wetlands are less than 0 from 1975 to 2020, and the temporal dynamics of isolated marsh wetlands are the largest. The lost wetlands were concentrated in the northeastern and east–central regions of the Sanjiang Plain. The center of mass of the standard deviation ellipse moved from northeast to southwest, and the isolated marsh wetlands moved the most. (2) The IIC of non-isolated marsh wetlands and natural marsh wetlands decreased and then increased, and the non-isolated marsh wetlands with high-grade connectivity were mainly distributed in the northeastern and east–central regions. On the other hand, the IIC of isolated marsh wetlands increased and then decreased, and the isolated marsh wetlands with high-grade connectivity were mainly distributed in the northeastern region. (3) The elevation is the most important driving factor affecting the distribution of isolated marsh wetlands in the Sanjiang Plain. The interaction between the driving factors had a significantly higher effect on the distribution of isolated marsh wetlands than that of a single driving factor, with the strongest interaction between aspect and elevation in 1975, 1986, 2000, and 2010, and between aspect and slope in 2020.

Keywords: isolated marsh wetlands; dynamic change; geodetector; driving forces

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1. Introduction

The wetlands are one of the most important ecosystems on earth, with high ecological service value per unit area and multiple functions such as biodiversity conservation, carbon sequestration, and hydrological regulation [1–3]. The dynamics of wetlands not only significantly affect ecosystem services, but also alter their ecological functions [4,5]. However, global wetlands are experiencing fragmentation due to natural and human activities [6], creating many isolated marsh wetlands [7]. Currently, there is no consensus on the definition of an isolated marsh wetland [8,9]. Isolated wetlands are officially defined in the United States as wetlands that are not contiguous with a flowing body of water or connected by surface water [10]; whereas, from a geographic and landscape ecology perspective, isolated wetlands are wetlands that are considered to be surrounded by uplands [11,12]. Drawing on the above definition of isolated wetlands and taking into account the actual situation of the Sanjiang Plain, this study defines isolated marsh wetlands as marsh wetlands that lack a relative connection with other water bodies and are isolated in the landscape [13], and we use this to identify the isolated marsh wetlands from non-isolated marsh wetlands.

Isolated marsh wetlands are sensitive to climate change due to their unique location and environmental conditions [14]. Although these wetlands play an important role in supporting specialized biological communities, species conservation, the maintenance of genetic diversity, and the provision of ecosystem services [15–17], their long-term dynamics and mechanisms for coping with climate change have not been well studied by academics. In addition, isolated marsh wetlands are closely hydrologically linked to the surrounding environment, and research on functions such as groundwater recharge, flood regulation, and water purification is relatively weak [18–21]. These research limitations have somewhat restricted our overall understanding of wetland hydrologic function and ecosystem health.

The Sanjiang Plain is the most typical marsh wetland transformation area and the largest freshwater marsh wetland aggregation area in China [22]. Wetland fragmentation has been exacerbated by changes in natural conditions and human activities, such as wetland development, drainage, and the construction of flood control embankments, so that the originally concentrated and continuous wetlands have been isolated from the rest of the landscape, and only wetlands with a lower topography remain, forming the typical landscape of isolated marsh wetlands [10]. The ecological effects of isolated marsh wetlands are very significant, and the full realization of their ecological effects is closely related to their long-term dynamic changes [10]. Currently, studies on wetlands are mostly limited to the dynamic changes in marsh wetlands and their functional roles [23–25] and spatial changes in landscape patterns of isolated marsh wetlands in a certain period [13], whereas the lack of monitoring of long-term dynamic changes in isolated marsh wetlands leads to the difficulty of capturing the changes in the status of isolated marsh wetlands promptly, which limits the effective assessment of the health of regional wetlands and the effectiveness of their conservation. This limits the effective assessment of the health of regional wetlands and the accurate measurement of their conservation effectiveness. Therefore, studying the dynamic changes in isolated marsh wetlands and quantitatively analyzing their driving factors is an urgent factor that can help conserve and restore wetland ecosystems and the full play of their ecological effects [26].

Data acquisition methods are the main limiting factor in the study of dynamic changes in isolated marsh wetlands on long-time scales. Traditional wetland monitoring methods are difficult, and it is costly to acquire continuous data on a large scale and over a long period, while remote-sensing satellite data, with its advantages of timeliness, wide coverage, and relatively low cost, provide a major source of data for monitoring the dynamics of isolated marsh wetlands [7]. For example, Robert C. Frohn et al. used Landsat-7 series image data to identify isolated marsh wetlands in the St. Johns River Water Management Area, Alachua County, USA [27]. E. Teferi et al. used remote sensing to quantify the dynamics of wetlands in the choke range of the Upper Blue Nile Basin, Ethiopia [28]. Therefore, the use of remotely sensed imagery data has certain advantages over traditional methods for monitoring long-term dynamic changes in isolated marsh wetland ecosystems. Quantifying the importance of patches in maintaining and improving functional connectivity can provide an important basis for the landscape conservation and restoration of isolated marsh wetlands [29]. The Geodetector is a powerful and straightforward method to quantify the impacts of drivers and their interactions [30], without having to strictly follow the assumptions of traditional statistical methods and the complex parameterization process involved [31], which allows for the effective quantification of multiple drivers of regionally isolated marshy wetlands. Therefore, the combination of remotely sensed image data and geographic information technology (GIT) can better study the evolution of long-term spatial and temporal patterns and drivers of isolated marsh wetlands.

This study is significantly different from the existing studies limited to the dynamic changes in marsh wetlands and their functional roles [23–25] as well as the spatial changes in landscape patterns of isolated marsh wetlands in a certain period [13], which will effectively fill the gap of the lack of research on the dynamic changes in isolated marsh wetlands and the quantitative analysis of their driving factors, and assist in the protection and restoration of regional ecosystems as well as the exertion of their ecological effects. The purposes of this study are as follows: (1) Identify the spatial and temporal dynamics of the three types of marsh wetlands in the Sanjiang Plain and the variability of evolutionary trends from 1975 to 2020. (2) Calculate the integral index of connectivity for the three marsh wetland types and assess the wetland patch importance value. (3) Analyze the drivers of isolated marsh wetlands in the Sanjiang Plain and evaluate the drivers and their interactions.

Through the above study, the value of isolated marsh wetlands, non-isolated marsh wetlands, and natural marsh wetlands in the Sanjiang Plain can be effectively assessed, and wetlands of historical significance can be identified to provide a meaningful basis for restoring and protecting wetlands and maintaining the stability of natural ecosystems. The driving factors of isolated marsh wetlands were analyzed to evaluate the driving forces and interactions of various types of factors, which will help in the restoration and protection of regional marsh wetlands.

2. Materials and Methods

2.1. Study Area

The Sanjiang Plain is located in the northeastern part of Heilongjiang Province, China, in the low-lying alluvial plains of the Heilong River, Songhua River, and Ussuri River [32], with geographic coordinates of 43°50′ N–48°27′ N, 129°11′ E–135°05′ E, and a total area of 108,830 km^2, which is one of the most widely distributed and concentrated marsh wetlands in China's plains [32], and also one of China's isolated marsh wetlands that demonstrate a distribution more typical of the region (Figure 1). It mainly includes 21 counties and cities belonging to Jiamusi City, Hegang City, Shuangyashan City, Qitaihe City and Jixi City, as well as Muleng County in Mudanjiang City and Yilan County in Harbin City. The gross domestic product (GDP) of the region's 23 counties and cities in 2020 will be about 270 billion yuan, with a population of about 6.9 million people (Heilongjiang Provincial Statistical Yearbook, 2021).

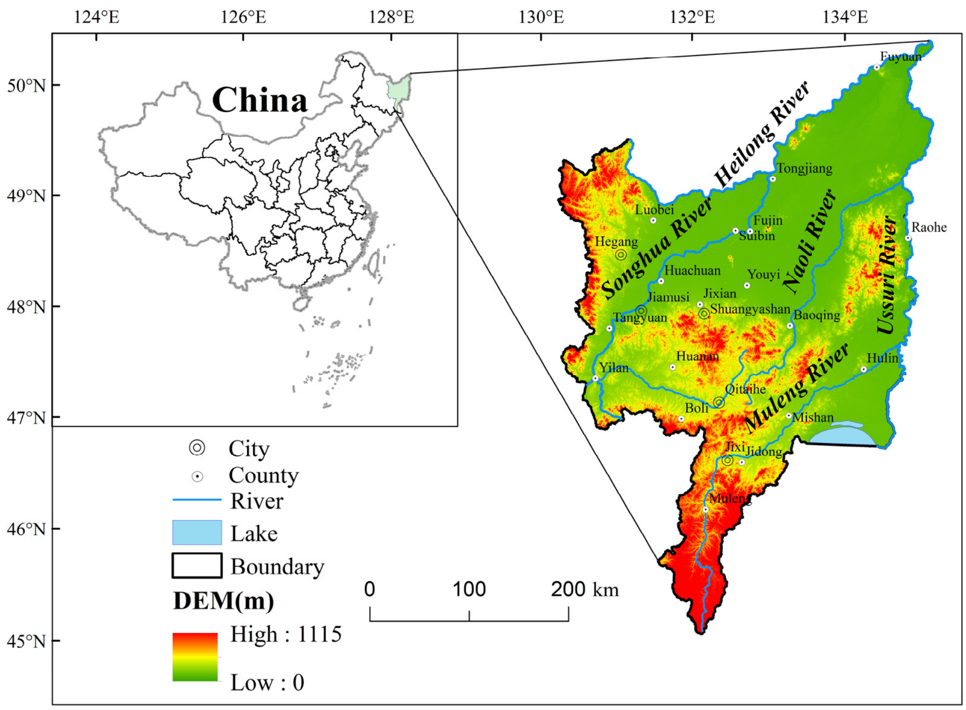

Figure 1. The location of the Sanjiang Plain in China.

The Sanjiang Plain is high in the southwest and low in the northeast, the terrain is dominated by plains, and the altitude is below 1100 m. The wetland vegetation types are mainly dominated by tussock marshes, followed by reed marshes [33]. The climate is a temperate humid, semi-humid continental monsoon climate, with a mean temperature below −18 °C in January and 21–22 °C in July, and an annual precipitation of 500–650 mm [34]. Soil types are dominated by white slurry, meadow, marsh soils, and black soils [35].

2.2. Data Sources

Referring to the 'Rules for Classification and Determination of Land Types for the Third National Land Survey Work' revised by the Ministry of Land and Resources, and taking into account the actual situation of the study area, we define marsh wetland as land with long-term water accumulation and a dominant community of hygrophilous plants, and use this to distinguish marsh wetland from non-marsh wetland. The main data include the distribution maps of marsh wetlands in the Sanjiang Plain area in 1975, 1986, 2000, 2010, and 2020, as well as natural (average annual temperature, annual precipitation, elevation, slope, aspect, landform type, soil type, etc.), socio-economic (distance from settlements, population density, GDP), and other relevant data in the study area.

The data from marsh wetlands, rivers, lakes, and settlements selected for this study were evenly distributed over time. The MSS imagery was used in 1975 with a resolution of 80 m; 1986, 2000, and 2010 data were from Landsat TM remotely sensed data, and 2020 data were from Landsat OLI remotely sensed data with a resolution of 30 m for the period of June–September. We extracted the marsh wetland data through the field survey in August 2020 by combining visual interpretation with the Random Forest Algorithm. After several tests, it was found that the best classification accuracy was achieved when the Random Forest classification tree was taken as 900. Therefore, in the interval of 0–1500 classification trees, we finally set the number of classifications to 900 for subsequent interpretation and classification work. The overall accuracies of 83.4%, 84.8%, 86.3%, 88.1%, and 90.4% were obtained for 1975, 1986, 2000, 2010, and 2020, respectively. Temperature and precipitation data were obtained through the China Meteorological Data Network (http://data.cma.cn/, accessed on 5 November 2023); DEM data were obtained through the University of Maryland Geoscience Research Center (http://data.cma.cn/, accessed on 5 November 2023); geomorphological and soil data were obtained from the Resource and Environmental Science Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 5 November 2023); population and GDP data were obtained by looking up the statistical yearbooks required for the period of the study.

2.3. Methods

In this study, the spatial and temporal dynamics of natural marsh wetlands, non-isolated marsh wetlands, and isolated marsh wetlands from 1975 to 2020 were identified using the Sanjiang Plain as an example, combined with Landsat series image data [36]. Analyzing the spatial distribution characteristics of the three types of wetlands over different study periods with the help of the standard deviation ellipse and center of mass module [37], the patch importance value of wetlands in the study area was assessed by the dynamic changes in the integral index of connectivity of the wetlands in the Sanjiang Plain. Finally, the "GD" package of R 4.4.0 software was used for optimal discretization [38], and the drivers of the dynamics of the isolated marsh wetlands in the Sanjiang Plain were quantitatively analyzed by Geodetector software. The research framework diagram for this study is shown in Figure 2.

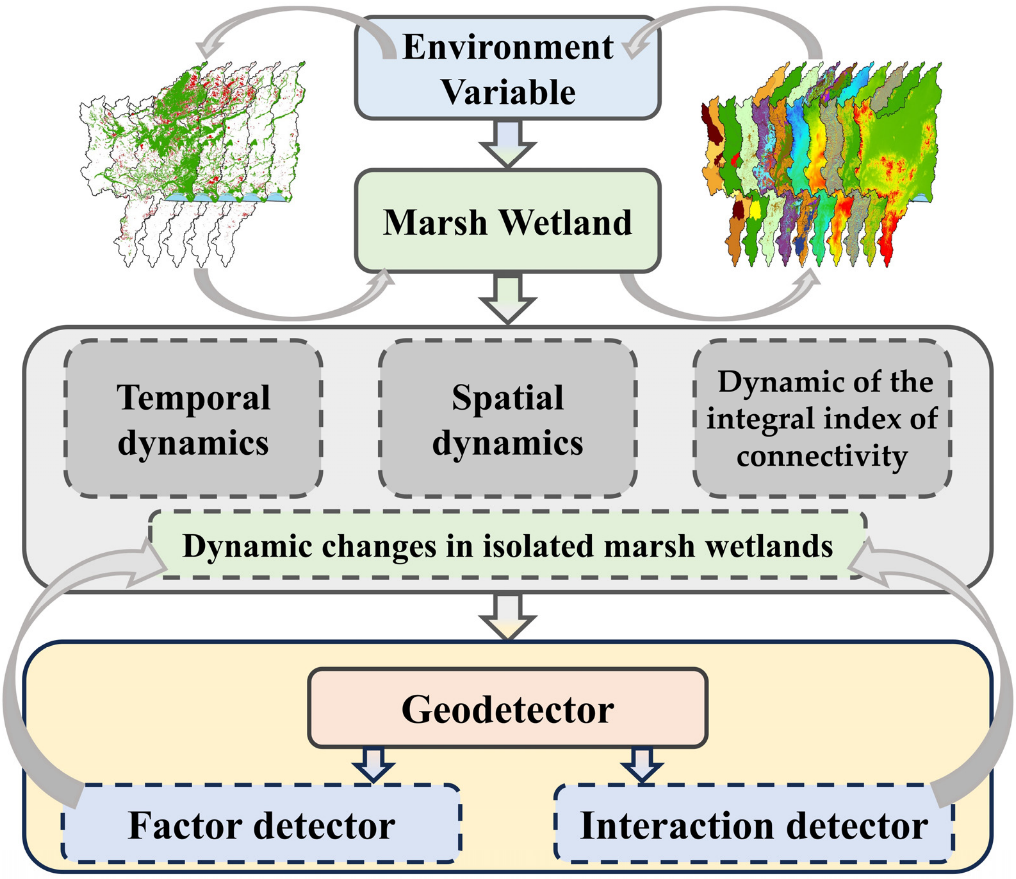

Figure 2. Research framework diagram in this study.

2.3.1. Dynamic Change

The dynamic degree describes the degree of change in a wetland relative to itself. It highlights the temporal characteristics of wetland change, which is an important model for wetland dynamics research [7]. It can accurately measure the rate of change in marsh wetlands in the study area. Therefore, we used the dynamic degree model to calculate the dynamic degree of isolated marsh wetlands, non-isolated marsh wetlands, and natural marsh wetlands, and used it to represent temporal dynamics. The formula is as follows:

$$n = \frac{S_b - S_a}{S_a t} \times 100\% \tag{1}$$

where S_a and S_b are the wetland areas (km^2) at the beginning and end of the study period. t is the time between the two periods of monitoring data. n is the absolute value of n. The larger the absolute value of n, the greater the degree of change in the area.

2.3.2. The Standard Deviation Ellipse

The standard deviation ellipse is a commonly used spatial statistical method that can accurately reveal the characteristics of the spatial pattern of geographic things and quantitatively describe the centrality of the spatial distribution of geographic elements, spatial patterns, and other characteristics through the center of mass, perimeter, area, and other basic parameters [37].

The center of mass of an ellipse indicates the relative position of the spatial distribution of geographical things, which can reflect the centrality of the distribution of geographical things [35,39]. The long and short axes of the ellipse reflect the direction and extent of wetland changes, respectively; the azimuth angle can reveal the trend direction of wetland distribution, and the larger the perimeter–area ratio of the ellipse, the more dispersed the wetland [40]. We apply it to represent the dynamic trend of the spatial pattern of marsh wetlands, which can accurately reflect the spatial evolution tendency of marsh wetlands. The formula is as follows:

$$X = \sum_{i=1}^{n} (a_i X_i) / \sum_{i=1}^{n} a_i \tag{2}$$

$$Y = \sum_{i=1}^{n} (a_i Y_i) / \sum_{i=1}^{n} a_i \tag{3}$$

where X and Y denote the center of gravity coordinates of the wetland; X_i and Y_i denote the center of gravity coordinates of the ith wetland patch; n and a_i indicate the number of wetland patches and the area of the ith wetland patch, respectively.

$$\tan\theta = \frac{\sum_{i=1}^{n} \overline{X}_i^2 - \sum_{i=1}^{n} \overline{Y}_i^2 + \sqrt{\left(\sum_{i=1}^{n} \overline{X}_i^2 - \sum_{i=1}^{n} \overline{Y}_i^2\right) + 4\left(\sum_{i=1}^{n} \overline{XY}\right)^2}}{2\sum_{i=1}^{n} \overline{XY}} \tag{4}$$

$$\sigma_X = \sqrt{2\sum_{i=1}^{n} \left(\overline{X}_i \cos\theta - \overline{X}_i \sin\theta\right)^2} \tag{5}$$

$$\sigma_Y = \sqrt{2\sum_{i=1}^{n} \left(\overline{Y}_i \cos\theta - \overline{Y}_i \sin\theta\right)^2} \tag{6}$$

where σ_X and σ_Y are the X and Y axes of the ellipse; $\overline{X}_i$ and $\overline{Y}_i$ are the difference between X_i and Y_i and the center of gravity; and θ is the azimuth.

2.3.3. The Integral Index of Connectivity

The integral index of connectivity (IIC) reflects the degree of connectivity of the wetland landscape [29]. The Patch Importance Index (dIIC) identifies the importance of wetland patches and is a quantified metric. It can effectively quantify the importance of patches in maintaining and improving functional connectivity [41]. Therefore, we apply it to the dynamics of isolated and non-isolated marsh wetlands, which can provide an important basis for the landscape conservation and restoration of isolated marsh wetlands. The formula is as follows:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \cdot a_j}{1 + nl_{ij}}}{A_L^2} \tag{7}$$

$$dIIC = \frac{IIC - IIC_{Remove}}{IIC} \times 100\% \tag{8}$$

where n is the total number of patches; a_i, a_j are the areas of patch i and patch j; nl_{ij} is the number of connections between patch i and patch j; A_L is the total area of the landscape; $0 \leq IIC \leq 1$—the larger the IIC value, the better its connectivity [41]; IIC_{Remove} is the connectivity index of the remaining patches after removing individual patches; $dIIC$ refers to the use of the change in IIC after the removal of a patch to measure the importance of the patch in maintaining landscape connectivity. The patch importance values were categorized as high ($dIIC \geq 11.5$), medium ($1.7 \leq dIIC < 11.5$), and low ($dIIC < 1.7$), and were used to assess the patch importance values of isolated marsh wetlands and non-isolated marsh wetlands.

The ecological distance threshold needs to be entered in the calculation of the Sanjiang Plain wetlands patch connectivity index. The setting of the distance threshold size first needs to consider the species dispersal range; the average search range of birds is 30–32,000 m [42], and the average dispersal range of some small and medium-sized mammals and amphibious reptiles is 50–1000 m [43]. When the distance threshold exceeds 5000 m, the connectivity index changes very little, so five thresholds of 250 m, 500 m, 1000 m, 3000 m, and 5000 m were set for the landscape connectivity study.

2.3.4. Geodetector

The Geodetector is a spatial analysis model for detecting spatial heterogeneity and revealing the driving forces behind it [30,44]. The model is mainly composed of the following four parts: factor detector, risk detector, ecological detector, and an interaction detector [45], and its main advantage is that it has no prerequisites and constraints and is universal, thus effectively overcoming the limitations of the traditional statistical analysis methods in dealing with categorical variables [46]. The model has a well-defined form and a clear physical meaning and has been applied to several research areas in the natural sciences, social sciences, environmental sciences, and human health [47,48]. In this study, the factor detector and interaction detector are selected to detect the driving force and interaction of the driving factors affecting the isolated marsh wetland.

(1) Factor detector: Analyzes the driving factors affecting the isolated marsh wetlands in the Sanjiang Plain and derives the relative importance of each driving factor [49]. Drivers are measured by q-values, where the larger the q-value, the higher the contribution of the factor to wetland change and vice versa [30]. The formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{9}$$

where $h = 1, \ldots; L$ is the stratification of variable Y or factor X; N_h and N are the number of cells in layer h and the whole region; and σ_h^2 and σ^2 are the variance of Y values for stratum h and the whole region. The value range of q is [0, 1]. A larger value of q indicates that the independent variable X has a stronger explanatory power for attribute Y and vice versa [44,50].

(2) Interaction detector: Detects the effect of different influences interacting on the area of an isolated marsh wetland. The model can identify whether the combined effect between environmental variables enhances or reduces the explanatory power of the dependent variable Y. A comprehensive overview of the types of interactions is shown in Table 1.

Table 1. Interaction types of driving factors in the Geodetector model.

Relations of q-Value	Type of Interaction
q(X1∩X2) < Min (q(X1), q(X2))	Non-linear weakened
Min (q(X1), q(X2)) < q(X1∩X2) < Max (q(X1), q(X2))	Single-factor non-linear weakened
q(X1∩X2) > Max (q(X1), q(X2))	Bivariable enhanced
q(X1∩X2) = q(X1) + q(X2)	Independent
q(X1∩X2) > q(X1) + q(X2)	Non-linear enhanced

3. Results

We compared the remote-sensing images obtained from 1975 to 2020 with previous studies conducted on the wetlands in the Sanjiang Plain [22,38,51]. We found that using the Landsat series of image data can meet the requirements for studying the evolution of spatial–temporal patterns of isolated marsh wetlands. It is an effective data source for studying the evolution of spatial–temporal patterns of isolated marsh wetlands. We compared the extracted data on marsh wetlands in the Sanjiang Plain with the data on rivers and lakes and combined them with the study of Liu et al. [13]. It was found that 10 m is a reasonable buffer distance [52]. After that, we superimposed the buffer rivers and lakes with the obtained marsh wetlands. A marsh wetland is an isolated marsh wetland if it does not intersect a buffer river lake and is not connected to any river wetland. Those that had an overlapping portion with the buffer river lake were non-isolated marsh wetlands (Figure 3) [52]. The natural marsh wetlands in this study are composed of isolated and non-isolated marsh wetlands. Therefore, in Figure 3, we only show the isolated marsh wetland with the non-isolated marsh wetland.

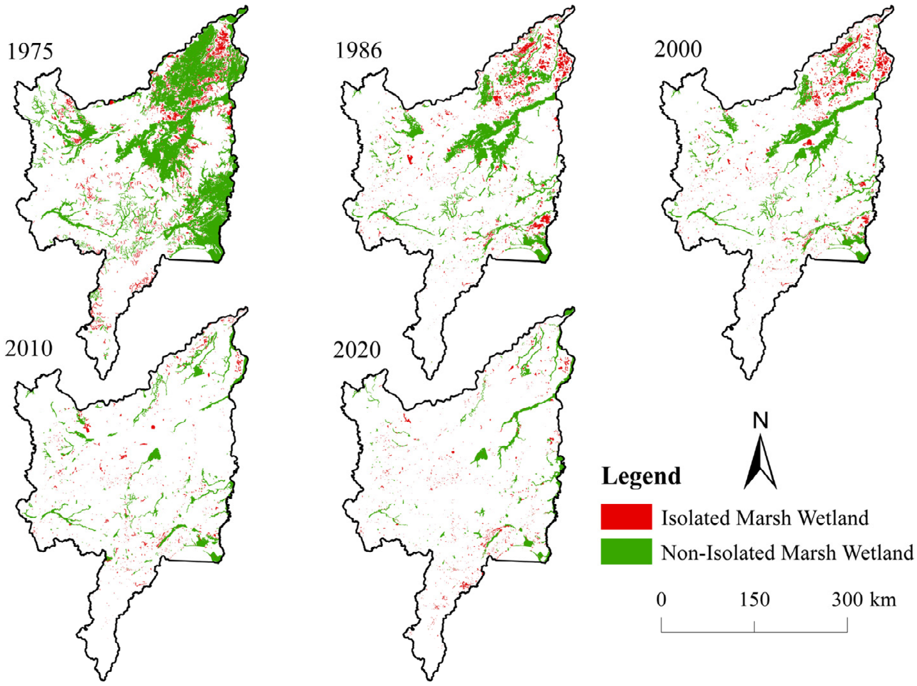

Figure 3. The distribution of isolated and non-isolated marsh wetlands in the Sanjiang Plain, 1975 to 2020.

3.1. The Spatial and Temporal Dynamics of Isolated Marsh Wetlands

3.1.1. Temporal Dynamics

The number of isolated marsh wetlands decreases and then increases from 1975 to 2020, with a decrease in the number of isolated marsh wetlands from 1975 to 1986, a slight increase in the number in 2000 relative to 1986, a decline in the number from 2000 to 2010, and an increase in the number from 2010 to 2020 that does not exceed the number of isolated marsh wetlands in 2000. Over the overall study period, the number of isolated marsh wetlands has decreased. The number of isolated marsh wetlands as a percentage of all natural marsh wetlands also declined from 91.46% to 77.26% during this period. The number of non-isolated marsh wetlands increased, then decreased, then increased again from 1975 to 2020, with an increase from 1975 to 1986, a slight decrease in 2010 relative to 1986, and then an increase again from 2010 to 2020. Over the overall study period, the number of non-isolated marsh wetlands is increasing. It also increased from 8.54% to 22.74% of the total number of natural marsh wetlands. Trends in the number of natural marsh wetlands and isolated wetlands were generally consistent. However, there are large differences between these two and the changes in the number of non-isolated marsh wetlands (Figure 4). This indicates that changes in the number of isolated marsh wetlands play a decisive role in changes in the number of natural marsh wetlands, and that changes in the number of isolated and non-isolated marsh wetlands are negatively correlated to a certain extent.

The area of isolated marsh wetlands from 1975 to 2020 showed a trend of increasing and then decreasing, with an increase in area from 1975 to 1986 to reach the maximum during the study period and a continued decrease from 1986 to 2020 to reach the minimum in 2020, with a continued reduction in non-isolated and natural marsh wetlands from 1975 to 2020. Overall, the area of isolated marsh wetlands, non-isolated marsh wetlands, and natural marsh wetlands all decreased between 1975 and 2020 (Figure 5). During this period, the area of non-isolated marsh wetlands decreased from 92.51% to 85.53% of all natural marsh wetlands, while isolated marsh wetlands increased from 7.49% to 14.47%. The number of isolated marsh wetlands in 1975 compared to 1986 was high, but the area was small, and the number after 2000 decreased and the area was also reduced;

the number of non-isolated marsh wetlands firstly increased and then decreased and then increased again, and the number in 2020 increased compared to 1975, but the area was obviously reduced, indicating that the fragmentation of non-isolated marsh wetlands of the Sanjiang Plain was intensified. The number of non-isolated marsh wetlands in 1975 was small relative to other periods, but the area was the largest; non-isolated marsh wetland fragmentation was relatively light, and non-isolated marsh wetland patches were relatively intact. Between 1975 and 1986, the trends in the area of isolated and non-isolated marsh wetlands differed, with non-isolated marsh wetlands decreasing in area and isolated marsh wetlands increasing in area. From 1986 to 2020, the change in area is similar for both, with both showing a decreasing trend.

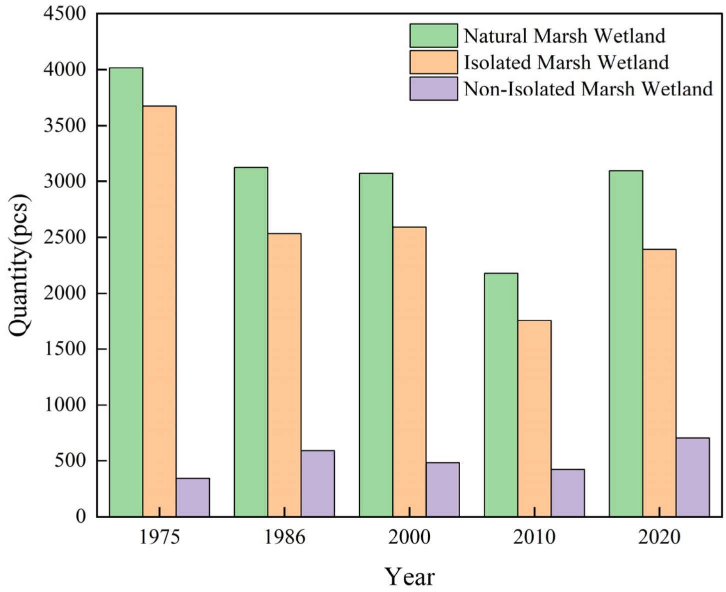

Figure 4. The changes in the number of three types of wetlands in the Sanjiang Plain from 1975 to 2020.

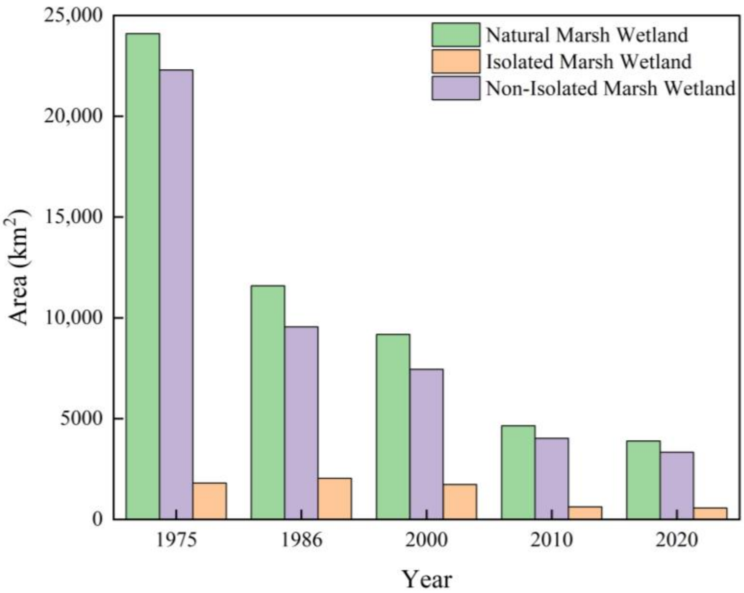

Figure 5. The changes in the areas of three types of wetlands in the Sanjiang Plain from 1975 to 2020.

In addition, we compared the conversion relationship between non-isolated marsh wetlands and isolated marsh wetlands (Table 2). The area of interconversion between the two decreased over the four time periods and was greatest from 1975 to 1986. The largest area of non-isolated marsh wetlands was lost during this period. Consequently, the area of lost non-isolated marsh wetlands converted to isolated marsh wetlands was also relatively large. Although the area of isolated marsh wetland increased, it was largely converted from non-isolated marsh wetland. If we do not take into account the portion converted from non-isolated marsh wetlands, the area lost can be considered up to 1201.28 km^2, which represents 66.36% of the area of isolated marsh wetlands. Thereafter, the area where the two are converted to each other decreases. Between 2010 and 2020, the area of isolated marsh wetlands converted to non-isolated marsh wetlands increased to 20.75 km^2 and the area of non-isolated marsh wetlands converted to isolated marsh wetlands reached a minimum of 175.21 km^2.

Table 2. Conversion between isolated and non-isolated marsh wetlands different periods.

Different Periods	1975–1986	1986–2000	2000–2010	2010–2020
Isolated marsh wetlands to non-isolated marsh wetlands	89.81 km^2	18.13 km^2	16.54 km^2	20.75 km^2
Non-isolated marsh wetlands to isolated marsh wetlands	1526.44 km^2	366.30 km^2	179.27 km^2	175.21 km^2

The results of wetland dynamics (Figure 6) show that, except for isolated marsh wetland dynamics, which was positive in 1975–1986, the dynamics of all three types of wetlands were less than 0, indicating that the area of all three types of wetlands declined in the remaining stages. The most significant decrease in wetland dynamics was observed between 2000 and 2010, and the least change was observed between 2010 and 2020. Over the entire study period, the dynamics of non-isolated marsh wetlands and natural marsh wetlands changed at a rate of −0.019 per year, and the dynamics of isolated marsh wetlands changed at a rate of −0.015 per year. The dynamics of isolated marsh wetlands were more significant than the former two, but generally, the dynamics of all three categories were more variable.

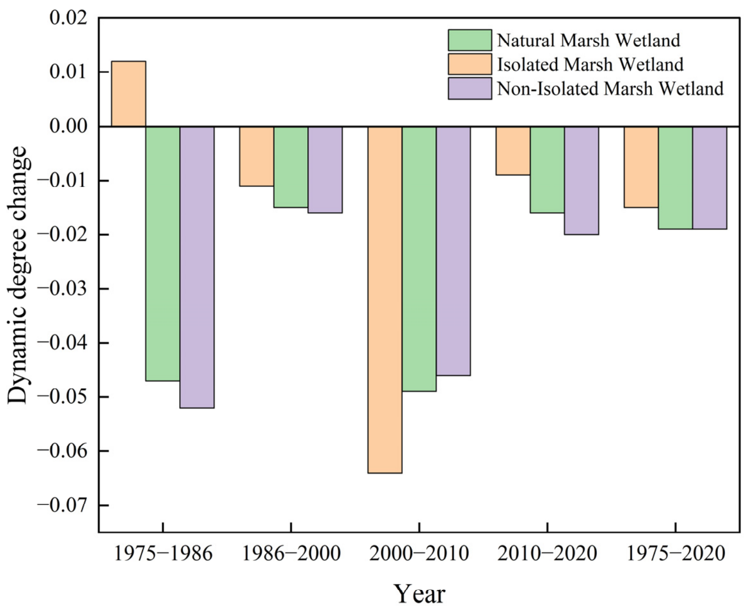

Figure 6. Dynamic changes in three types of wetlands from 1975 to 2020.

3.1.2. Spatial Dynamics

The center of mass of the standard deviation ellipse of isolated and natural marsh wetlands in the Sanjiang Plain in 1975 was biased toward the northeast (Figure 7). Compared with its area distribution map in 1975 (Figure 3), it can also be seen that the wetlands in the Sanjiang Plain are mainly located in the northeastern region, which is a large area and the distribution of the wetlands is more clustered. The standard deviation ellipse for non-isolated marsh wetlands is located roughly in the center, and the standard deviation ellipse for all three moves from the northeastern region to the southwest by 2020, suggesting that the share of wetland area in the northeast part of the Sanjiang Plain is generally decreasing, while that in the southwestern part is increasing. The standard deviation ellipse angle decreases from 1975 to 2020 for isolated and natural marsh wetlands, and the standard deviation ellipse angle generally increases for non-isolated marsh wetlands. This suggests that the distribution of isolated and natural marsh wetlands typically increases the percentage of wetland areas in a north and south direction. In contrast, non-isolated marsh wetlands increase the percentage of wetland area in an east and west direction.

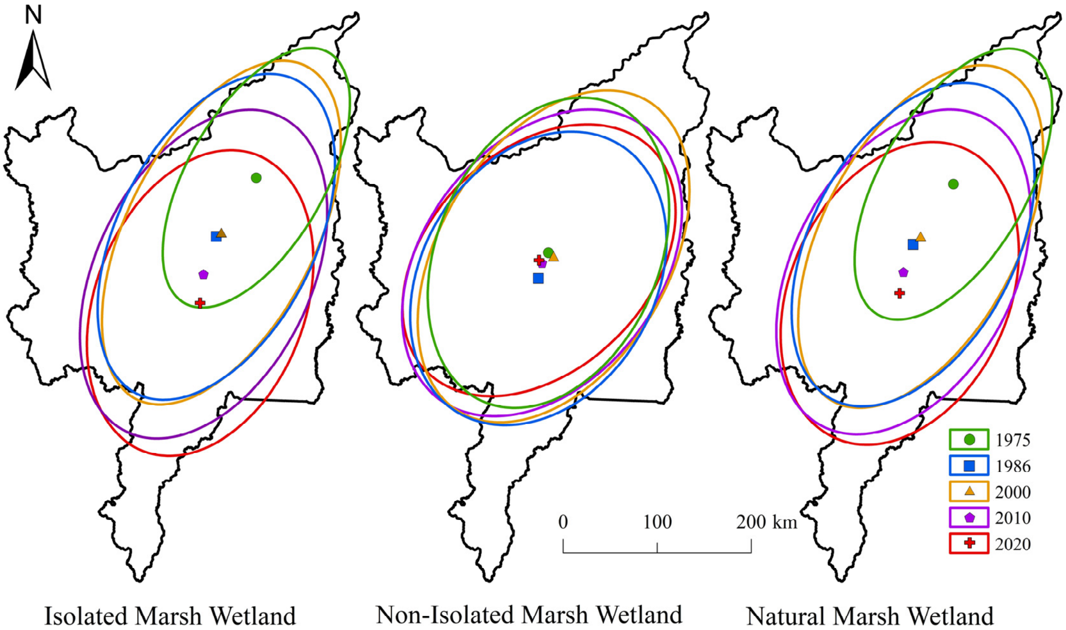

Figure 7. The standard deviation ellipse and centroid variation in three types of wetlands in the Sanjiang Plain from 1975 to 2020.

The angle, perimeter, and area of the elliptical direction of the isolated marsh wetland all increased and then decreased, with the angle and perimeter reaching a maximum of 27.29° and 961.63 km, respectively, in 2000, and the area reaching a maximum of 66,578.54 km^2 in 2010; the angle of the elliptical direction of the non-isolated marsh wetland continued to increase, the angle continued to expand to 45.80° in 2020, its perimeter and area both increased and then decreased, and the perimeter and area reached the maximum in 2010, which were 997.76 km and 73,175.05 km^2, respectively. The angle fluctuation of the ellipse direction of the natural marsh wetland decreased, the perimeter and area both increased and then decreased, and the maximum values of the perimeter and area were reached in 2000 and 2010, which were 970.28 km and 68,071.46 km^2, respectively (Table 3).

Table 3. Elliptical statistics of standard deviation for three types of wetlands from 1975 to 2020.

Year	Wetland Type	Direction (°)	Perimeter (km)	Area (km^2)	Perimeter-to-Area Ratio
1975	Isolated Marsh Wetland	30.26	733.40	35,099.55	0.0209
	Non-Isolated Marsh Wetland	24.15	917.29	63,488.04	0.0144
	Natural Marsh Wetland	30.44	769.38	39,138.29	0.0197
1986	Isolated Marsh Wetland	27.21	932.31	61,257.21	0.0152
	Non-Isolated Marsh Wetland	31.50	913.11	64,228.24	0.0142
	Natural Marsh Wetland	27.86	937.50	63,035.69	0.0149

Table 3. *Cont.*

Year	Wetland Type	Direction (°)	Perimeter (km)	Area (km^2)	Perimeter-to-Area Ratio
2000	Isolated Marsh Wetland	27.29	961.63	62,140.65	0.0155
	Non-Isolated Marsh Wetland	31.78	997.76	73,175.05	0.0136
	Natural Marsh Wetland	27.96	970.28	64,384.12	0.0151
2010	Isolated Marsh Swamp Wetland	26.53	955.90	66,578.54	0.0144
	Non-Isolated Marsh Wetland	37.89	969.88	71,205.12	0.0136
	Natural Marsh Wetland	28.29	961.67	68,071.46	0.0141
2020	Isolated Marsh Wetland	21.18	886.58	58,807.98	0.0151
	Non-Isolated Marsh Wetland	45.80	900.31	61,353.49	0.0147
	Natural Marsh Wetland	24.72	899.24	61,183.51	0.0147

The perimeter–area ratio of the standard deviation ellipse of the isolated marsh wetland and the natural marsh wetland showed fluctuating changes, with the perimeter–area ratio of the two ellipses being the largest in 1975 and the perimeter–area ratio of the ellipse of the isolated marsh wetland decreasing in 2020 compared to that in 1975, with large areas of contiguous wetlands being destroyed and wetlands being fragmented. In addition, the elliptical perimeter area ratios of isolated marsh wetlands were more significant than those of non-isolated marsh wetlands to natural marsh wetlands in each period, suggesting dispersal in the former and aggregation in the latter.

3.1.3. Dynamic of the Integral Index of Connectivity

The changes in the integral index of connectivity of wetlands in different periods at distance thresholds of 250 m and 500 m were small; the changes in the integral index of connectivity of wetlands in different periods at distance thresholds of 3000 m and 5000 m were significant, and the changes in the integral index of connectivity of wetlands in different periods at distance thresholds of 1000 m were in the middle. Therefore, the integral index of connectivity of wetlands in all periods at distance thresholds of 1000 m was selected for the analyses (Figure 8).

The performance of the integral index of connectivity of the isolated marsh wetlands in the Sanjiang Plain is 1986 > 2000 > 2010 > 1975 > 2020; and the performance of the natural marsh wetlands and non-isolated marsh wetlands is 1975 >1986 > 2000 > 2020 > 2010. At the distance threshold of 1000 m, the integral index of connectivity of isolated marsh wetlands increased from 0.0099 to 0.0170 from 1975 to 1986. Then, there was a decreasing trend in connectivity from 1986 to 2020, from 0.0170 to 0.0089. This indicates an increased fragmentation of isolated marsh wetlands, and relevant measures should be taken to protect isolated marsh wetlands. The integral index of connectivity of non-isolated marsh wetlands and natural marsh wetlands decreased and then increased from 1975 to 2020, with a minimum of 0.0351 and 0.0279, respectively, in 2010; it increased to 0.0615 and 0.0644, respectively, by 2020, and the difference in the integral index of connectivity between the different years increased with the increase in the distance threshold.

In 1975, the high-grade isolated marsh wetland patches were mainly distributed in the northeastern part of the Sanjiang Plain region, and by 2020, the high-grade isolated marsh wetland patches were significantly reduced and primarily distributed in the western part of the Sanjiang Plain (Figure 9). The isolated marsh wetland patches of medium grade in 1975 were located mainly in the northeastern, western, and southeastern parts of the Sanjiang Plain. By 2020, the isolated marsh wetland patches of the medium grade will have disappeared. Protective measures should be focused on the isolated marsh wetland patches that degraded to a low grade in 2020 in the northeast, due to their high historical patch importance values. The area of the isolated marsh wetland patches with both high and medium importance values decreased during the period of 1975–2020; the area of low-grade isolated marsh wetland patches showed fluctuating changes throughout the period, with a decreasing trend in the total area of patches, more frequent changes in isolated marsh wetlands, and wetland fragmentation.

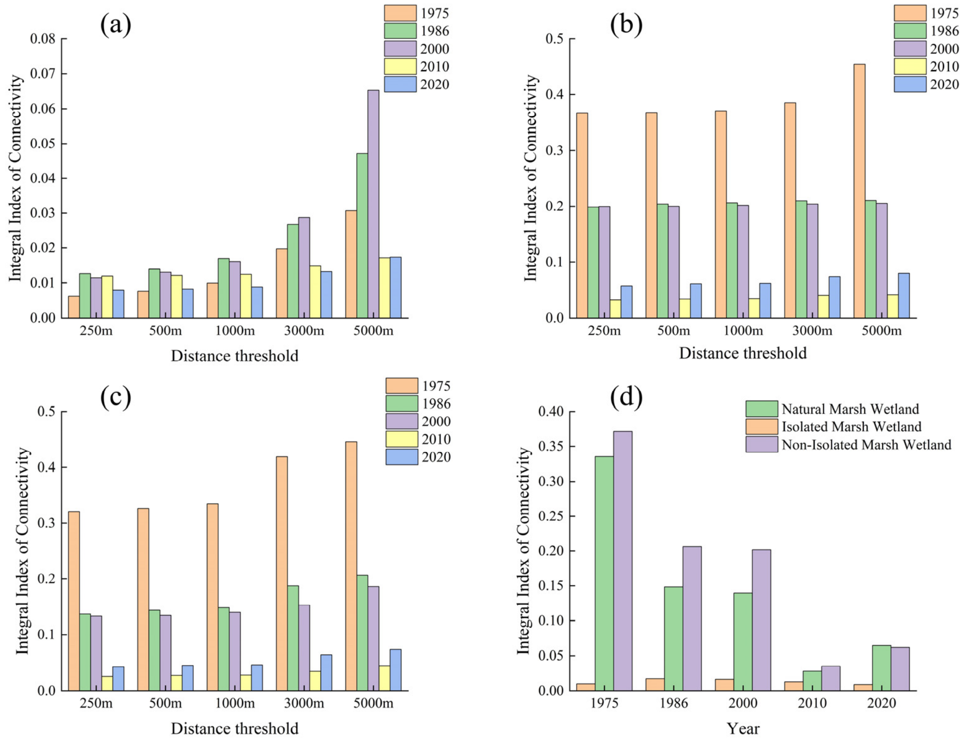

Figure 8. The changes in IIC of three types of wetlands under different distance thresholds and 1000 m distance thresholds from 1975 to 2020. (**a**) indicates isolated marsh wetlands; (**b**) indicates non-isolated marsh wetlands; (**c**) indicates natural marsh wetlands; (**d**) indicates the changes in IIC of three types of wetlands at a distance threshold of 1000 m.

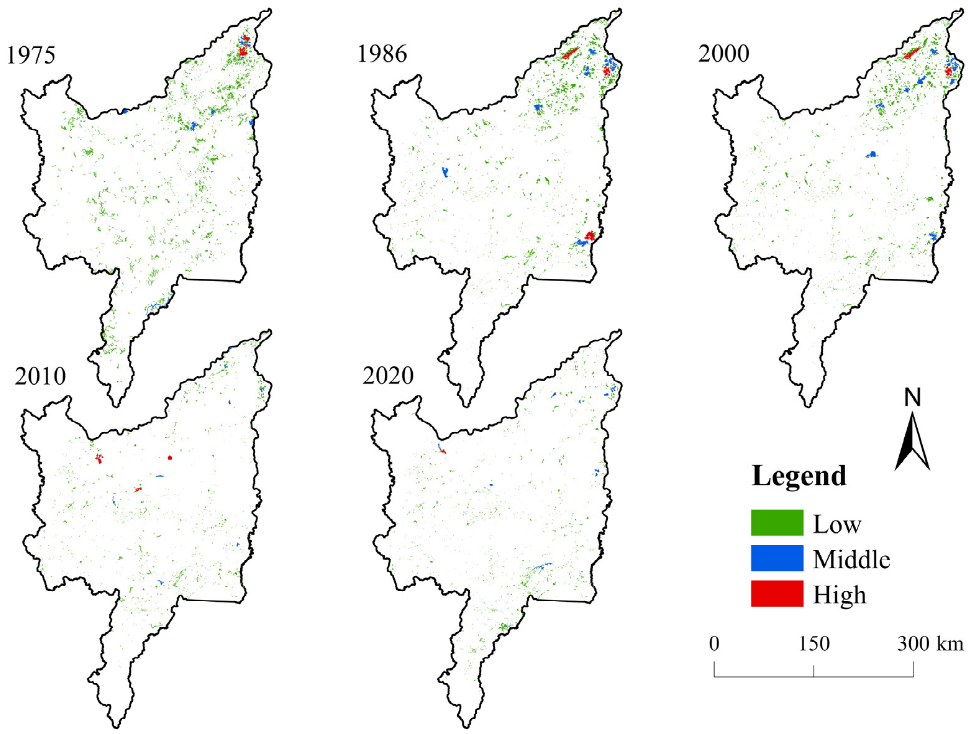

Figure 9. Important values of isolated marsh wetland patches from 1975 to 2020.

In 1975, the high-grade non-isolated marsh wetland patches were concentrated in the northeast and southeast (Figure 10), which were overwhelmingly dominant in size. Most of the northeast and southeast patches, from 1975 to 2000, were successively converted from high to medium and then to low-grade. From 2000 to 2020, there was a significant decrease in high- and low-grade patches and a fluctuating change in medium-grade patches. The non-isolated marsh wetlands are more severely damaged, and their patch importance values change more frequently, increasing wetland fragmentation. Large areas of the high-grade wetland patches were lost in the non-isolated marsh wetlands between 1975 and 2020, so conservation and restoration should be prioritized for existing high-grade patches in 2020, followed by medium- and low-grade wetland patches.

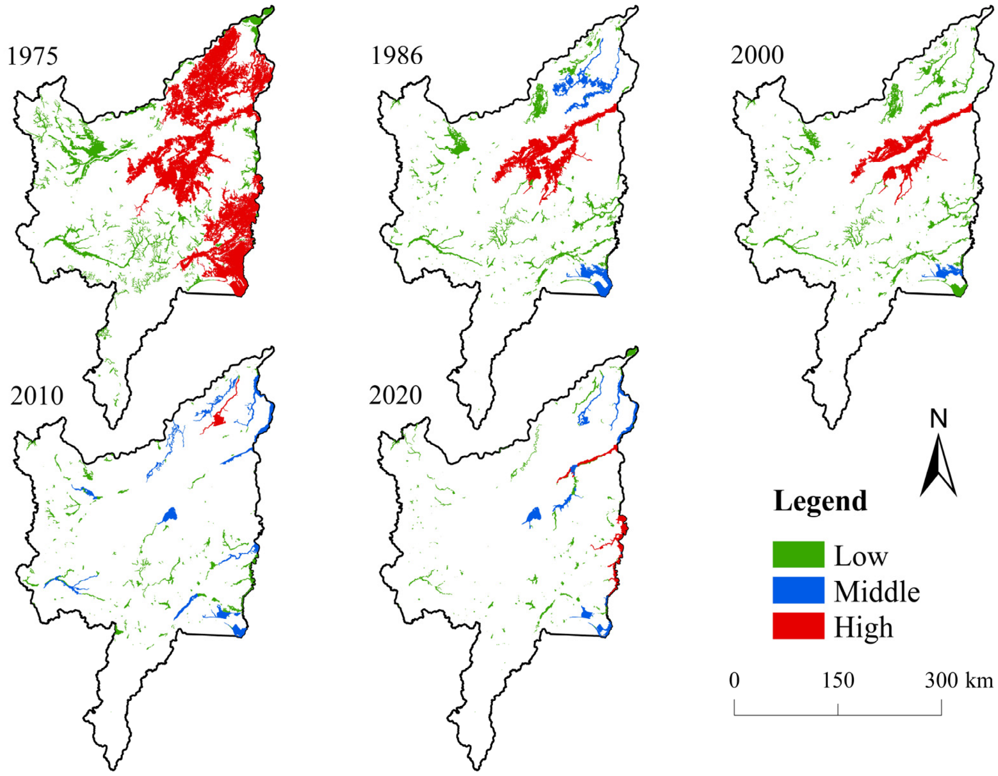

Figure 10. Important values of non-isolated marsh wetland patches from 1975 to 2020.

3.2. Drivers of Change in the Dynamics of the Isolated Marsh Wetlands

Based on previous studies [23,53–55], 10 environmental variables, namely, elevation, slope, slope direction, mean annual temperature, annual precipitation, geomorphology, soil, distance from settlements, population density, and GDP, were selected to analyze their relationship with the area of isolated wetlands. Since the Geodetector algorithm operates on discrete data, an optimization method is used to transform the 10 variables into discrete variables [30]. The optimal discretization of the environment variables is based on the "GD" language package in the R 4.4.0 software [38]. The results of the 2020 optimal discretization are illustrated in spatial form in Figure 11.

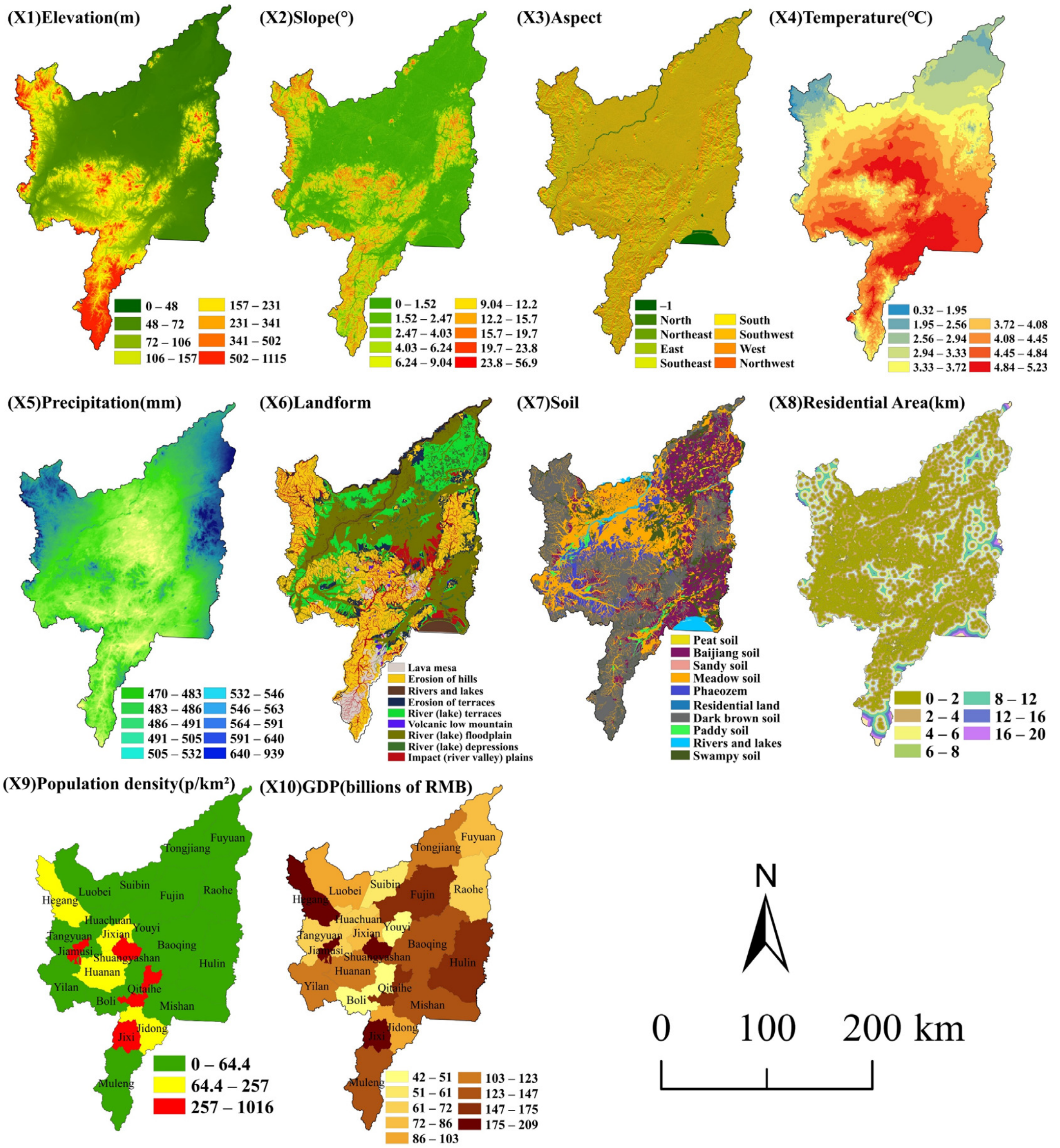

Figure 11. Ten environmental factors in the Sanjiang Plain in 2020: (X1) elevation, (X2) slope, (X3)aspect, (X4) temperature, (X5) precipitation, (X6) landform, (X7) soil, (X8) residential area, (X9) population density, and (X10) GDP.

3.2.1. Changes in q-Values of Drivers of Isolated Marsh Wetlands

The relative importance of natural factors and settlement distance in the distribution of isolated marsh wetlands was assessed from the selected data for 1975 and 1986, as well as the relative importance of natural and socio-economic factors in the distribution of isolated marsh wetlands for the years 2000, 2010, and 2020.

A factor detector analysis of each environmental variable of the isolated marsh wetlands area from 1975 to 2020 was carried out to obtain the explanatory power of different driving factors on the area of isolated marsh wetland (Figure 12), and each driving factor passed the test of significance ($p < 0.05$) for isolated marsh wetlands. The elevation had the largest q-value among the drivers of isolated marsh wetlands in 1975, 1986, and 2000, with an explanatory power of 0.113, 0.265, and 0.246, respectively. The aspect became the most influential driver of the isolated marsh wetlands in 2010 and 2020, with an explanatory power of 0.125 and 0.087, respectively.

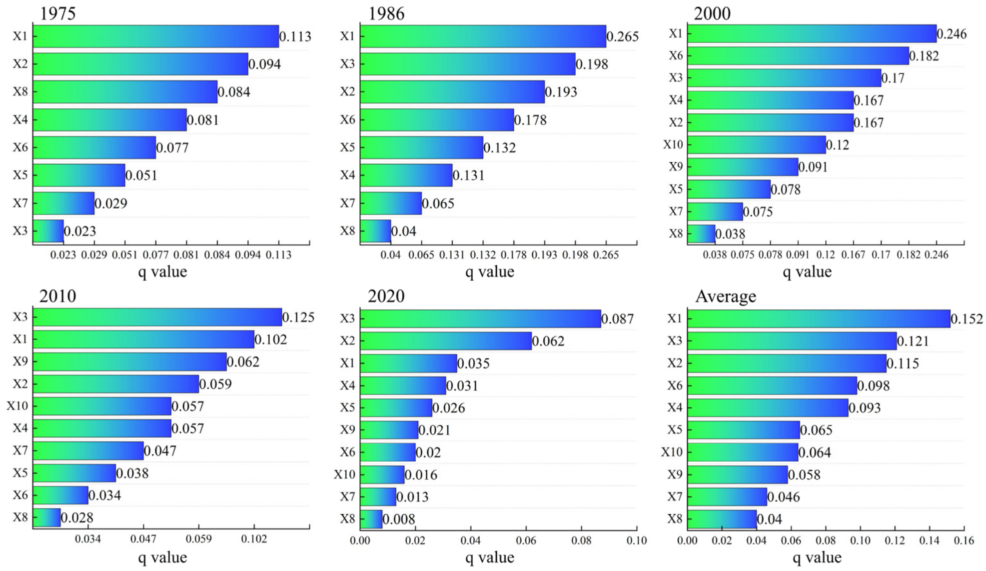

Figure 12. The changes in the driving forces of isolated marsh wetlands from 1975 to 2020. The average indicates the average driving force of isolated marsh wetlands over the years.

The q-value of each impact factor for isolated marsh wetlands changed to varying degrees over the study periods, with the q-value of elevation in 1986 being the greatest across the study periods at 0.265. This suggests that its distribution was most influenced by elevation in 1986. The q-value of elevation on isolated marsh wetlands gradually decreased from 1986 to 2020, reaching the lowest in the study period of 2020 at 0.035. The q-value of slope on isolated wetlands was most remarkable in 1986 at 0.193, and its driving force generally declined after that, with its driving force in 2010 being the lowest for the entire study period at 0.059. The q-value of the slope increased slightly on isolated marsh wetlands in 2020 but remained downward throughout the study period. The aspect had the most negligible effect on isolated marsh wetlands in 1975. Still, by 1986, the aspect q-value became the second most important driver after elevation. Then, its driving force, although also trending downward, was the largest in 2020 compared to other environmental factors. The q-value of mean annual temperature on the distribution of isolated marsh wetlands increased and then decreased, with its q-value reaching a maximum of 0.170 in 2000 and then a minimum in 2020. The annual precipitation was highest in 1986, with a q-value of 0.132, and decreased after that, falling to a minimum in 2020. The q-value for landforms and soils reached a maximum in 2000 at 0.182 and 0.075, respectively, and decreased to a minimum in 2020 at 0.020 and 0.013, respectively. The trends of the three socio-economic factors, distance from settlements, population density, and GDP, all show a decreasing trend. In addition, regarding drivers averaged from 1975 to 2020, elevation was the dominant factor influencing the distribution of isolated wetlands, followed by aspect, slope, landform, temperature, precipitation, GDP, population density, precipitation, and distance from settlements, respectively.

3.2.2. The Drivers' Interactions of the Isolated Marsh Wetlands

With the help of Interaction_detector in Geodetector, we explored the effects of the interaction between two important factors on the changes in isolated marsh wetlands (Figure 13). The results showed that in the analysis of the interaction, the interaction between all the factors had two main important effects on the change in isolated marsh wetland in the Sanjiang Plain, which were non-linear-enhanced and bivariate-enhanced. The interaction of two factors obviously had greater q-value compared with a single factor, and the interactions among the driving factors were different in different years. In 1975, 1986, 2000, and 2010, the interaction between elevation and aspect was the largest among the drivers, followed by the interaction between the slope and aspect, elevation and slope, and so on. The q-value (X1∩X3) for elevation and aspect are 0.193 (bivariate-enhanced), 0.367 (bivariate-enhanced), 0.356 (bivariate-enhanced), and 0.237 (non-linear-enhanced), respectively. This indicates that the interaction of elevation and aspect plays an important role in influencing the changes in isolated marsh wetlands in the Sanjiang Plain during these four study periods. However, it is important to note that all of the interactions related to distance from settlement were larger in 1975. This again suggests that distance from settlement had a large effect on the distribution of isolated marsh wetlands during this period. In 2020, slope and aspect became the interaction with the largest driving force, and the value of the q-statistic (X2∩X3) was 0.190 (non-linear enhancement). This indicates that the interaction of slope and aspect played a major role in influencing changes in isolated marsh wetlands in 2020, followed by the interaction of elevation and aspect. Over these five years, the interaction of isolated marsh wetland drivers increased and then decreased, being largest in 1986, followed by 2000, 2010, 1975, and 2020, in that order.

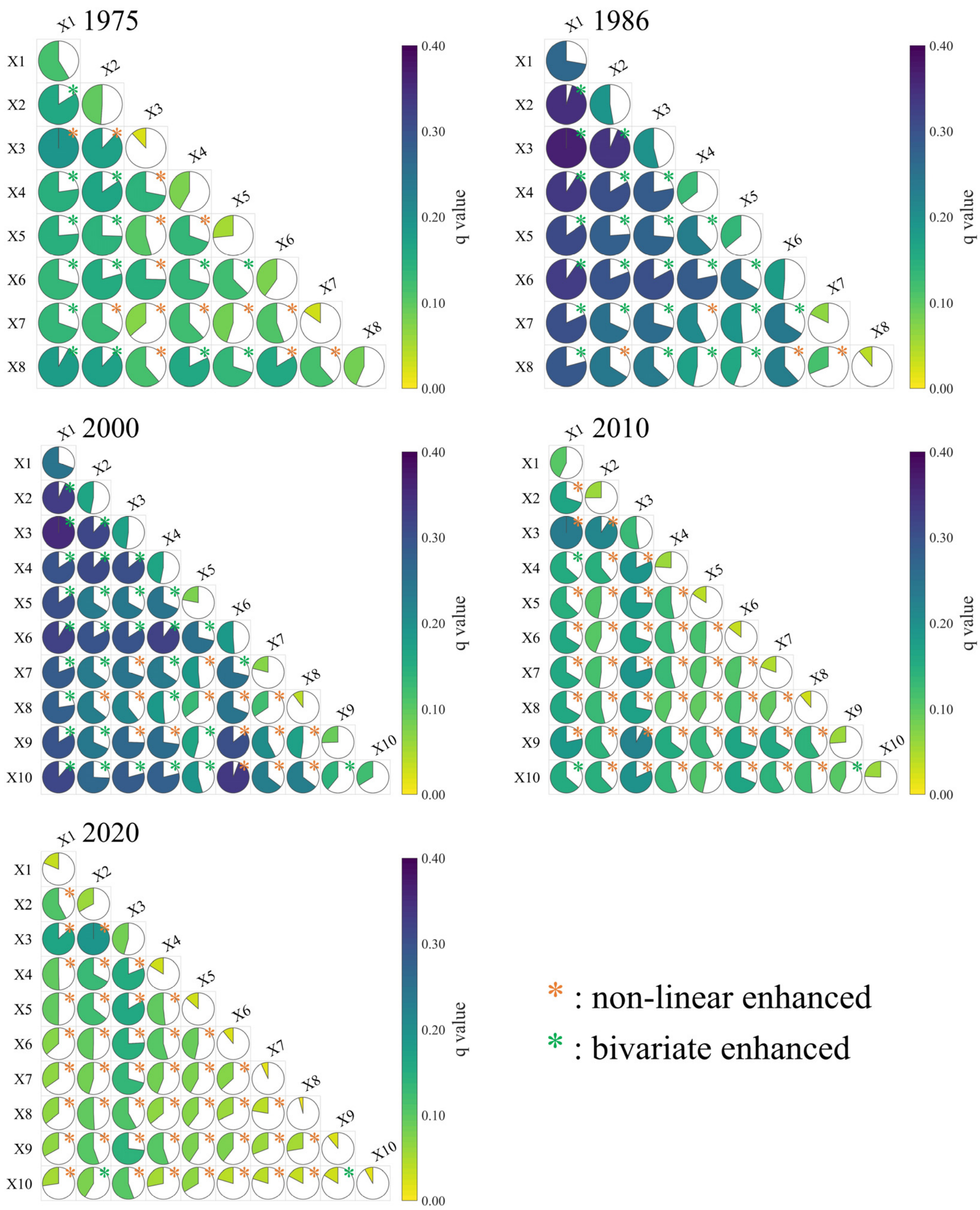

Figure 13. The interaction of driving factors in isolated marsh wetlands in 1975–2020.

4. Discussion

Geographically isolated wetlands do not imply functional segregation [56], and isolated marsh wetlands have essential implications for biology and hydrological and water quality connectivity [57]. Many studies on wetlands in time and space have been conducted. Still, most of them have been conducted on natural marsh wetlands [58,59], and there are fewer quantitative studies on the spatial and temporal variability and drivers of isolated marsh wetlands. Wetlands in the Sanjiang Plain are severely degraded [60], and many isolated marsh wetlands have emerged. Taking the Sanjiang Plain in Northeast China as the study area, this paper explores the spatial and temporal changes in isolated marsh wetlands in the Sanjiang Plain in Northeast China from 1975 to 2020 and their main influencing factors, which assist in the restoration and protection of regionally isolated marsh wetlands.

4.1. Analysis of the Dynamics of Marsh Wetlands

In terms of temporal dynamics, the number of non-isolated marsh wetlands has increased, while the number of isolated marsh wetlands has decreased. The number of non-isolated marsh wetlands increased from 8.54% to 22.74% of all natural marsh wetlands, while the number of isolated marsh wetlands decreased from 91.46% to 77.26%. All three types of wetlands have decreased in size. The area of non-isolated marsh wetlands decreased from 92.51% to 85.53% of all natural marsh wetlands, while isolated marsh wetlands increased from 7.49% to 14.47%. The overall change in the temporal dynamics of the three types of wetlands calculated from this is less than 0, with the isolated marsh wetland having the greatest change in temporal dynamics of the three. There is a difference in the change in number and area between isolated and non-isolated marsh wetlands. From 1975 to 2000, the number as well as the area change in the two are negatively correlated to some extent. This is consistent with the study of Liu et al. [13]. The reason for this is that the non-isolated marsh wetlands are large in area and are distributed in concentrated patches [22], so the number is small. However, the wetlands were fragmented by many factors [6], and some of them were transformed into isolated marsh wetlands. As a result, its area decreased and the number showed an increasing trend. During 1975–1986, the area of isolated marsh wetlands increased. However, during the period 1986–2020, it showed a decreasing trend because it lost more area to disturbance than it gained. Due to their more dispersed distribution and small size and number, they are more sensitive to external changes. Therefore, both its number and area decreased on the whole [25,61]. In terms of the relationship between the conversion of isolated and non-isolated marsh wetlands, although the area of isolated marsh wetlands increased in 1986, this was not due to ecological improvements. This was mainly due to the conversion of non-isolated marsh wetlands [13]. This is also an important indication of the fragmentation of marsh wetlands. This is due to the fact that national policies during this period have played a very important role in influencing the changes in the marsh wetlands of the Sanjiang Plain. The "Going to the Countryside and Settling in the Communes" policy in the early 1970s promoted local agricultural development as well as large-scale land reclamation [62]. This has largely contributed to the degradation of the marsh wetland, so the area conversion of both was greatest during this period (Table 3). The "returning farmland to wetland" policy in the late 1990s and the establishment of reserves during 1986–2020 somewhat reduced the decline of marsh area changes [63]. The rate of degradation of marsh wetlands slowed after 1986, and the area of non-isolated marsh wetland interconversion of isolated marsh wetlands gradually decreased. In particular, the area of isolated marsh wetlands converted to non-isolated marsh wetlands increases and the area of non-isolated marsh wetlands converted to isolated marsh wetlands reaches a minimum in 2010–2020.

Regarding spatial dynamics, the center of mass of the standard deviation ellipse shifted from northeast to southwest, with the center of mass of the isolated marsh wetlands moving more than that of the non-isolated marsh wetlands. Between 1975 and 2020, wetland loss was most severe in the northeast, with the standard deviation ellipse centers of mass all moving from northeast to southwest. The center of mass of non-isolated marsh wetlands has shifted to the southwest, but the trend is not significant. This does not mean that the non-isolated marsh wetlands are less disturbed, but it is because the non-isolated marsh wetlands decreased in all regions, with more loss in the northeast and relatively more aggregated wetlands in the southwest relative to the southwest region. This is also in line with the studies of Qu [5], Yan [24], and Song [60] et al. on the evolution of marshy wetlands in the Sanjiang Plain. Therefore, the center of mass moves slightly to the southwest, and the movement is small. A large number of isolated marsh wetlands are concentrated in the northeast, and anthropogenic development and utilization have led to the serious loss of a large number of isolated marsh wetlands, most of which have been transformed into farmland [24,64]. Therefore, the center of mass of the isolated marsh wetlands moves towards the southwest. The natural marsh wetland ellipse and center of mass are similar to the isolated marsh wetland. This is because the natural marsh wetland in this study is composed of isolated marsh wetlands and non-isolated marsh wetlands, and the change in its ellipse and center of mass is influenced by the change in ellipse and center of mass of both. Overall, the non-isolated marsh wetland does not have much change in ellipse and center of mass, so the change in ellipse and center of mass of the natural marsh wetland is mainly affected by the isolated marsh wetland and is similar to it. In addition, because the distribution area of isolated marsh wetlands is small, but the number is large, its distribution in the Sanjiang Plain is more dispersed than that of non-isolated marsh wetlands [13]. Therefore, the ratio of its elliptical perimeter area in each period is larger than that of non-isolated marsh wetland and natural marsh wetland. This also indicates that the non-isolated marsh wetlands are aggregated, while the distribution of isolated marsh wetlands in the Sanjiang Plain is dispersed and fragmented. This is consistent with the findings of Liu et al. [13].

The IIC of isolated marsh wetlands in the Sanjiang Plain increased and decreased from 1976 to 2020. The IIC reached the maximum in 1986, while the integral index of connectivity of non-isolated marsh wetlands and natural marsh wetlands decreased and then increased. The IIC of both was the smallest in 2010. This is because the isolated marsh wetlands had the most significant area and the best connectivity in 1986 and the smallest area in 2020, lowering its connectivity index. While not the smallest in size, non-isolated marsh wetlands and natural marsh wetlands had fewer wetlands and the lowest connectivity index with each other in 2010. Although the area is the smallest in 2020, due to the increased protection of wetlands by the government and relevant authorities in recent years [65], the wetlands have been damaged to a lesser extent, resulting in an increased degree of connectivity with each other. The study found that the IIC for the isolated marsh wetlands was low in 1975, but this did not mean they had poor landscape connectivity [41]. This is due to the high number and size of isolated marshy wetland patches in the study area in 1975, so their connectivity was at its best during this period [29]. When there is only one continuous large habitat patch in the landscape, there is no inter-patch movement of organisms, and the value calculated for landscape connectivity will be equal to zero [41]. The changes in the IIC of wetlands in the Sanjiang Plain are consistent with changes in the number of wetland patches in the study area. Still, there is a difference between the changes in the IIC of isolated wetlands and the trend of changes in the number of patches in individual years, such as 2010 and 2020, which is because the changes in wetland connectivity are not only affected by the number of patches but also by the area of the patches [41]. For example, during this period, the number of isolated marsh wetlands increased, but their area decreased. As a result, the connectivity of isolated marsh wetlands declined during the 2010–2020 period. The importance rating of a patch reflects, to some extent, the degree of connectivity of that patch, so the higher the importance rating of a patch, the better its connectivity [66]. The loss of isolated marsh wetlands was most severe in the northeast from 1975 to 2020. As a result, the IIC of isolated marsh wetlands in the northeastern decreased, with fewer patches of high and medium importance values, and by 2020, high-grade patches were only found in the northwestern part of the study area. This is because isolated marsh wetlands in the northwest are relatively undisturbed by the factors, and patches are better preserved [51]. This also indicates that the isolated marsh wetlands here perform better as 'stepping stones' for the conservation of endemic species and ecological functions such as carbon sinks [67]. The number of high-grade non-isolated marsh wetland patches has decreased, while the number of medium-grade patches has slightly increased compared with 1975, and the high-grade patches, by 2020, will mainly be distributed along the Ussuri River and the Fuli River in the eastern part of the study area. This is due to the presence of national nature reserves such as the Naoli River and Dongfanghong [68]. In addition, rivers can also ensure the hydrological connectivity of non-isolated marsh wetlands and increase the connectivity grade of wetlands here [69].

4.2. Analysis of the Drivers of Isolated Marsh Wetlands

The elevation was the main factor influencing the distribution of isolated marsh wetlands in 1975–2000, followed by aspect, slope, and distance from settlements. The reason for this is that the overall altitude of the Sanjiang Plain is low, and wetlands are mainly distributed in these low-altitude areas [51]. Therefore, the human exploitation of isolated marsh wetlands has likewise been concentrated in areas with low elevation, small slopes, and close to settlements, leading to the destruction of wetlands in these areas [40], a reduction in area and increase in number, and the fragmentation of wetlands into farmland and other land types [30]. The most important factor influencing the distribution of isolated marsh wetlands shifts to aspect in 2010–2020, followed by different factors such as elevation and slope. This is due to a decrease in isolated marsh wetlands at low elevations due to the human exploitation of areas at lower elevations and closer to settlements after 2000 [64], resulting in a gradual decrease in the driving force of elevation versus distance from settlements. However, since the data on aspect and slope selected for this study were extracted from the elevation data, the elevation is still the most dominant influence factor, which is inextricably linked to the overall low elevation of the Sanjiang Plain. The drivers of population density and GDP in 2020 are lower than in 2000, but their relative rankings are elevated. Although the overall population density of the Sanjiang Plain decreased and GDP increased during this period [25]. However, this would be equally affected by a reduction in the area of isolated marsh wetlands, making them less driven. Since population density and GDP are roughly negatively correlated with the distribution of isolated marsh wetlands [70], their drivers were elevated in the ranking of the factors. It should be noted, however, that GDP represents the income level of the region, but this only reflects the increase in the relative productivity of the region, and does not fully reflect the impact of production activities on natural ecosystems [71]. In addition, due to the reduction in the area and the number of isolated marsh wetlands, the driving force of each driver also declined, with the most pronounced driver being the distance from settlements, whose driving force declined from 0.084 in 1975 to 0.008 in 2020. This is because in 1975, the human exploitation of wetlands was minor [22], and the isolated marsh wetlands closer to settlements were more widely distributed, whereas with human activities [51], the loss of all isolated marsh wetlands closer to settlements was more severe [5,60], and thus their driving force showed a decreasing trend. This is consistent with the findings of McCauley, L.A. et al. [72]. Although elevation is the main influence factor affecting the distribution of isolated marsh wetlands, Liu et al. [13], in 2016, also showed that the lower the elevation and the smaller the slope, the smaller the distribution of isolated marsh wetlands. This further indicates that factors such as elevation have a greater influence on isolated marsh wetlands. At the same time, the specific correlation between isolated marsh wetlands and each influencing factor is also something we should study more deeply.

By detecting the interactions among the drivers of the isolated marsh wetlands, the interaction between elevation and aspect was the largest among the drivers in 1975, 1986, 2000, and 2010, with q-values ($X1 \cap X3$) of 0.193 (bivariate-enhanced), 0.367 (bivariate-enhanced), 0.356 (bivariate-enhanced), and 0.237 (non-linear-enhanced), respectively, and in 2020, the most considerable interaction between drivers shifted to slope and aspect, followed by the elevation and aspect, with q-values of 0.190 (non-linear-enhanced), 0.237

(non-linear-enhanced), and 0.237 (non-linear-enhanced), and the most significant interaction shift between the drivers in 2020 was between slope and aspect, followed by elevation and aspect, with q-values of 0.190 (non-linear-enhanced) and 0.165 (non-linear-enhanced), respectively. Although the driver with the most significant interaction has changed in recent years, isolated marsh wetlands in the Sanjiang Plain are still mainly affected by interactions such as elevation because the slope and aspect data are extracted from elevation [51]. The increase in the interaction of the drivers from 1975 to 1986 is due to the fact that although the increase in the area of isolated marsh wetlands was large during this period, it was concentrated at lower elevations [13,24]. Therefore, the interactions related to elevation were all larger compared to the other drivers. In addition, similar to the pattern of change in the single driver for isolated marsh wetlands, the interaction related to distance from settlements was initially large. In 1975, the interaction between distance from settlement and elevation was the second largest, after elevation and aspect. However, due to the loss of isolated marsh wetlands closer to settlements [51,64], the interactions with the drivers associated with them first increased and then decreased, falling to their lowest levels by 2020. Due to the ongoing loss of isolated marsh wetlands associated with each factor [34], the interactions of the drivers also decreased, all reaching a minimum in 2020.

There are some limitations in this study. Although the spatial and temporal dynamics of isolated marsh wetlands in the Sanjiang Plain were investigated over 45 years, the resolution of the selected remote-sensing image data varies due to the land use data being limited by the study period. There is also some influence of anthropogenic drivers in 1975 and 1986 [51,60], but the lack of anthropogenic data from 1975 to 1986 does not allow for a quantitative analysis. Therefore, this study did not consider the drivers and interactions of anthropogenic factors on isolated marsh wetlands during the 1975 and 1986 periods. The 2000 to 2020 population density and GDP data are characterized by county and city and do not consider the spatial heterogeneity of population and GDP, which has some impact on the results. In addition, the study did not consider factors such as distance from protected areas, light brightness, and rivers due to data acquisition and time constraints. They should be included in future work to increase the study's accuracy and scientific validity.

5. Conclusions

Based on the current research status, most of the studies are limited to the dynamic changes in marsh wetlands and their functional roles, as well as the spatial changes in the landscape pattern of isolated marsh wetlands within a certain period, and there is a lack of monitoring the long-term dynamic changes in isolated marsh wetlands. We used remote-sensing image data, combined with geographic information technologies such as dynamic degree, standard deviation ellipses, the integral index of connectivity, and the Geodetector, to monitor the long-term dynamic evolution of spatial and temporal patterns and the connectivity of isolated marsh wetlands, and quantitatively analyzed their drivers and their interactions. The following conclusions were obtained:

(1) The temporal dynamics of the three types of wetlands from 1975 to 2020 are generally less than 0, and the temporal dynamics of isolated marsh wetlands are the largest of the three. The loss of marsh wetlands is concentrated in the northeastern and east-central regions of the Sanjiang Plain. The center of mass of the standard deviation ellipse all moved from northeast to southwest, and the isolated marsh wetland moved the most.

(2) When the distance threshold is 1000 m, the integral index of connectivity (IIC) of non-isolated marsh wetlands and natural marsh wetlands decreases and then increases, while that of isolated marsh wetlands increases and then decreases. Non-isolated marsh wetlands with high-grade connectivity are mainly distributed in the northeastern and east–central regions, while isolated marsh wetlands with high-grade connectivity are mainly distributed in the northeastern region. We should prioritize conservation for existing high-grade patches and restoration for historical high-grade patches that are currently degraded to medium- or low-grade.

(3) Elevation, aspect, and slope are the most important driving factors affecting the distribution of isolated marsh wetlands in the Sanjiang Plain. The interaction between the driving factors has a significantly higher effect on the distribution of isolated marsh wetlands than that of a single driving factor. The most substantial interactions are found between aspect and elevation in 1975, 1986, 2000, and 2010, and aspect and slope in 2020, which are 0.193, 0.367, 0.356, 0.237, and 0.190, respectively.

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