

Article

Spatiotemporal Differentiation of Territorial Space Development Intensity and Its Habitat Quality Response in Northeast China

Zhipeng Yang ¹, Shijun Wang ^{1,*}, Meng Guo ¹, Junfeng Tian ² and Yingjie Zhang ¹

¹ School of Geographical Sciences, Northeast Normal University, Changchun 130024, China; yangzp315@nenu.edu.cn (Z.Y.); guom521@nenu.edu.cn (M.G.); zhangyj486@nenu.edu.cn (Y.Z.)

² School of Public Policy and Administration, Chongqing University, Chongqing 400044, China; tianjf@cqu.edu.cn

* Correspondence: wangsj@nenu.edu.cn

Abstract: Studying the spatiotemporal distribution characteristics of territorial space development intensity (TSDI) and its habitat quality (HQ) response is of substantial theoretical and practical significance to optimize regional development patterns and coordinate the relationship between territorial space development and eco-environmental protection. This study establishes a comprehensive assessment model across various aspects, including land, population, economy, and input, to assess the TSDI of each county in Northeast China. We used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to evaluate the HQ of each county and investigated the HQ response to TSDI. The results showed that the TSDI in Northeast China was high in the south and west, low in the north and east, and prominent in urban agglomeration areas, which increased between 2000 and 2015. The spatial pattern of HQ was low in the east and south, high in the west and north, and the HQ was degraded as a whole. Bivariate spatial autocorrelation analysis showed a significant negative spatial correlation between TSDI and HQ, and distinct patterns of local spatial agglomeration were identified. Our findings provide guidelines for territorial space planning and may offer a reference for the ecological civilization construction and the coordinated development of Northeast China.

Keywords: territorial spatial planning; ecological civilization construction; spatiotemporal relationships; response pattern; land-use optimization



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1. Introduction

Coupled with rapidly progressing urbanization and industrialization, the territorial space development intensity (TSDI) of China has increased, and some regions have encountered problems, such as unbalanced territorial space development and serious ecological and environmental pollution [1,2]. Territorial space development and protection of the environment have become a conspicuous contradiction in ecological civilization construction in China. The Chinese government has proposed that optimizing the development pattern of territorial space should be the primary task of China's ecological civilization construction [3,4]. Further, it is necessary to clarify the TSDI and the impacts of development on ecology and the environment, which is the basis and prerequisite for enhancing the configuration of territorial space development.

TSDI is the quantitative expression for the comprehensive utilization degree of a region and reflects the degree of land utilization and human activity concentration in the region, while indicating the level of total regional development [5]. However, regarding the process of territorial space development, human disturbance to ecosystems has affected the quality of biological habitats. This has resulted in a decrease in biodiversity. In particular, the dramatic expansion of construction land has had a significant impact on habitat quality (HQ), which has led to significant challenges in biodiversity conservation [6,7]. HQ is

closely related to biodiversity as well as ecological and environmental conditions [8]. It is also the embodiment of the ecological effect of TSDI. Therefore, under the concept of ecological civilization construction and regional coordinated development, it is urgent to measure TSDI more reasonably to clarify the current situation of territorial space development and its impact on HQ. It is also important to optimize the development direction, control the development intensity, adjust the spatial structure, and gradually form a territorial spatial development pattern with balanced population, resources, and environment alongside unified economic, social, and ecological benefits.

In recent years, territorial space development and its ecological and environmental effects have been a hot topic of research. Many studies have focused on the concept and the specific evaluation methods of TSDI. Some studies believe that TSDI reflects the ratio of construction land area to the total area of the region, and this ratio is used as an index to evaluate TSDI [9–11]. Others believe that the evaluation of regional development intensity should consider the proportion of construction land area and other land-use types along with demographic and economic factors [12–14]. Other authors in the field created an index system to evaluate land development intensity from the aspects of land structure, land benefit, and land investment [15]. In addition, new advances in technology, including remote sensing (RS) and geographic information systems (GIS), have been employed to evaluate TSDI in recent years, and the evaluation accuracy has gradually improved [10,16]. In particular, modern RS technology, such as the Google Earth Engine (GEE) platform, can grasp the spatiotemporal differentiation of TSDI in a timelier manner by analyzing real-time changes of land-use types on the earth's surface [17,18]. Furthermore, some studies have focused on the influencing factors and mechanisms of territorial space development, such as using a spatial panel-ordered response model to study the factors influencing land development intensity differences [19], utilizing GIS and logistic regression to analyze the connection between urban expansion and its associated factors [20,21], and exploring the spatial differentiation mechanisms of construction land development intensity through the ordinary least squares (OLS) and geographically weighted regression (GWR) models [22]. There have also been many discussions surrounding the impact of territorial space development on the ecological environment, which have concentrated on the coupling correlation between TSDI and resource and environmental carrying capacity [23–25] and the bearing of land development intensity on biodiversity [26,27], along with the bearing of land development intensity on ecological service functions [28,29].

In the research on HQ, most scholars have evaluated HQ and the habitat degradation degree based on the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model for regions, cities, and watersheds [30–33]. On the basis of HQ evaluation, various scholars have scrutinized the impact of land-use type changes to HQ [34], the HQ response to urban expansion [35], the impact of urbanization on HQ in rapidly urbanized areas [8,33], and the threat of roads to regional HQ [36,37]. HQ has become a representative index for measuring the quality of the regional ecological environment. The response processes and mechanisms between HQ and various phenomena that reflect human activity have become more important for exploring human–land relations and issues of development and conservation [38].

Overall, current studies focus on evaluating TSDI from the single perspective of land use. However, territorial space is a comprehensive regional space, and a comprehensive evaluation of its development intensity would be relatively insufficient. Moreover, there is abundant research on the impact of land development on resources, environment carrying capacity, and ecological environment. However, there is a lack of in-depth discussion on the impact of territorial space development on HQ. Therefore, this study attempts to evaluate TSDI from a comprehensive perspective and analyze its spatial relationship with HQ.

With regard to the promotion of the Northeast China Revitalization Strategy and the construction of the Harbin–Changchun and Central and Southern Liaoning urban agglomerations, economic and social development and urbanization construction have been gradually promoted, and TSDI has increased and shown significant regional differ-

ences in Northeast China [39,40]. In addition, Northeast China is a key ecological barrier, and the strategic position of maintaining national ecological security is vital [41,42]. The rationality of the HQ response to territorial space development is linked to the sustainable development of the region. Therefore, this study takes Northeast China as its research area and evaluates TSDI and HQ by establishing a comprehensive evaluation system and using the InVEST model. Then, it analyzes the spatial pattern, evolution process, and HQ response characteristics to TSDI in Northeast China. We hope to enrich research on the evaluation of TSDI, offer a reference for studying the HQ response to territorial space development, and provide a scientific basis for ecological civilization construction and regional high-quality development in Northeast China.

2. Background and Theoretical Framework

Territorial space refers to space under the jurisdiction of national sovereignty, and is the location and environment where citizens live [43]. It includes land, sea, and airspace. As a country, China enjoys a massive expanse of land. It is the most sizeable developing country in the world. There are palpable regional disparities in the development and utilization of territorial space in China. This necessitates scientific and rational spatial planning to promote its sustainable development. Therefore, the government of China has instituted numerous plans to achieve regional sustainable development. These include planning for national economic and social development, land use, and urban–rural development. Further, this includes ecological environment protection planning to guide the development and utilization of territorial space [44]. However, the execution of multiple plans results in various problems, such as contradictory planning contents, diverse planning standards, and overlapping control space. This manifests as lost land and space resources, an intensified contradiction of land development, and unbalanced regional development [45,46]. Due to the protracted exposure of traditional planning problems, the Chinese government has established a unified territorial space planning system. The issue of developing and protecting territorial space has received attention from all sectors of society. In 2011, China promulgated the National Main Function Zoning, which divided its territory into “optimized, key, restricted, and prohibited-development zones” based on the available carrying capacity of resources and the environment, current development intensity, and future development potential of different regions [3]. The zoning also determined specific development strategies for different types of zones [3,47]. TSDI is the basic index for “analyzing the development status of a region” [47]. Recently, the Chinese government planned to integrate national economic and social development planning, land-use planning, urban–rural development planning, and ecological environment protection planning. Such a unified territorial space planning will form a “spatial blueprint for sustainable development” [43]. Thus, TSDI has become an important component of the new land space planning system.

TSDI refers to the comprehensive utilization degree of territorial space in a region, which is usually expressed as the ratio of urban and rural construction land area to the overall area [9,47]. However, territorial space is a regional complex system formed by interacting resources, the environment, population, and the social economy. Its development intensity should be able to reflect the specific human–land relationship and supply–demand status of a region. The development intensity index ignores the population carried by territorial space and the economic benefits when it only focuses on the proportion of construction land [5]. The calculation of TSDI should thus consider the degree of regional space development and utilization, and its bearing intensity on the regional population, economy, and land-use scale [12]. Theoretically, population density can reflect the degree of population gathering [5], and the greater the population that gathers, the higher the intensity of territorial space development. Attributes of development are noticed in construction and cultivated land [48]. Those spaces with an above average amount of construction and cultivated land are considered seriously developed. The GDP and non-agricultural industries indicate the degree of regional economic development and the amount of industries

with deep development that are positively correlated with the development of territorial space [49], while territorial space development requires the investment of assets as support, and the investment of fixed assets and fiscal expenditure can promote development. Therefore, the evaluation of TSDI should fully consider the relevant factors of population, land, economy, and investment within the scope of territorial space, and study the current situation of territorial space development from a comprehensive perspective.

The growth process of TSDI concerns the processes of construction land expansion, population agglomeration, increased economic aggregate, and promotion of development investment [5,14]. In these processes, development activities bring about fluctuations to the spatial function and structure of the territorial space, which have impacts or interferences on the ecology and environment, resulting in the degradation of HQ and the hindering of regional sustainable development [26,28]. On the one hand, the development of territorial space promotes the conversion of woodland and grassland into cultivated land and cultivated land into construction land, respectively; thus, a sizeable quota of agricultural land and natural ecological land becomes occupied. On the other hand, territorial space development adds new infrastructure, such as traffic roads, which provides convenience for deep development and breaks the original landscape pattern [36,50]. The evaluation of HQ must consider the following four factors: (1) the relative impact of each threat, (2) the relative sensitivity of each habitat to each threat, (3) the distance between habitats and threat sources, and (4) the degree of legal protection of land [51,52]. Therefore, the conversion of land types or the construction of infrastructure will increase the number of habitat threat sources, aggravate the degree of landscape fragmentation, and ultimately destroy HQ. HQ is degraded when TSDI increases, and it is bound to improve when TSDI decreases, that is, HQ responds to TSDI over time (Figure 1). Understanding the HQ response to TSDI is of great significance for constructing a coordinated relationship between development and protection.

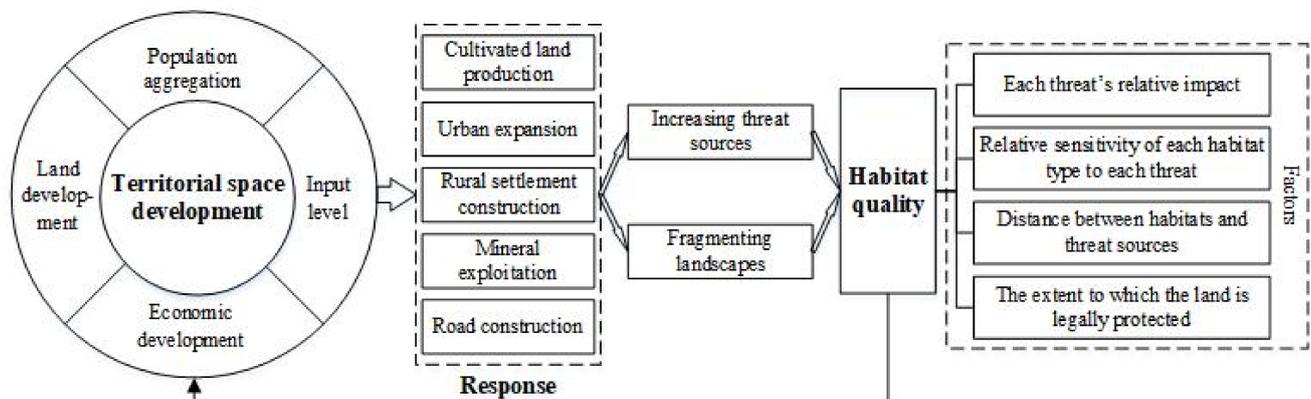


Figure 1. Mechanism of the HQ response to TSDI.

3. Materials and Methods

3.1. Area of Study

The area of study included 179 counties in Northeast China, and the scope of county space in different years was unified according to the administrative divisions of 2015. There are various types of landforms in Northeast China, including the Greater Khingan Range and the Lesser Khingan Range in the north, the Changbai Mountains in the east, the Western Liaoning Hills in the southwest, and the Songnen Plain, the Liao River Plain and the Sanjiang Plain in the center (Figure 2). Moreover, Northeast China has a complete range of land-use types, including cultivated land, forest land, grassland, and construction land. In 2015, production in Northeast China accounted for 19.27% of the country's total grain. The forest coverage rate reached 47.80%, with cultivated land and forests being the primary land-use types in the region. With advancing urbanization and the implementation of

policies for ecological conservation, for example, restoring farmland to forest and grassland, conversions involving land-use types are relatively frequent.

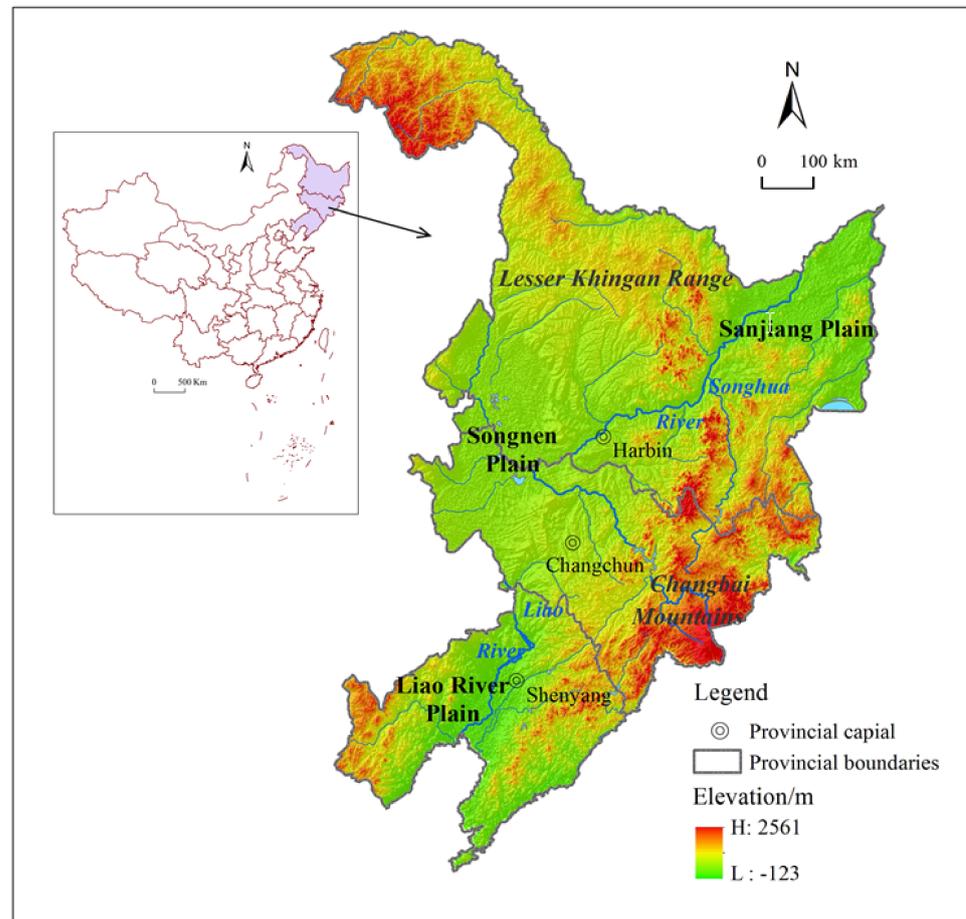


Figure 2. Overview of the study area.

In terms of social and economic development, the extent of urbanization in Northeast China increased from 46.86% in 2000 to 58.58% in 2015. The population growth rate fluctuated in its decline from 3.20‰ in 2005 to −3.60‰ in 2015. The GDP per capita grew significantly from RMB 5023 in 2000 to RMB 23,123 in 2015. However, the GDP growth rate increased and then decreased from 8.49% in 2000 to 14.37% in 2006, and then continued to decline to 4.47% in 2015 [53].

3.2. Data Sources and Processing

Demographic and economic data were mainly collected from the China County Statistical Yearbook (2001, 2006, 2011, 2016) and the China City Statistical Yearbook (2001, 2006, 2011, 2016), and were partly collected from the Liaoning Statistical Yearbook, Jilin Statistical Yearbook, Heilongjiang Statistical Yearbook, and County Statistical Bulletin for corresponding years. To make the economic data of different years comparable and eliminate the impact of price changes, all economic data were deflated by the GDP deflator, with 2000 as the base. Land-use data with 100 m spatial resolution were obtained from the Resources and Environmental Science and Data Center, which is part of the Chinese Academy of Sciences (<http://www.resdc.cn>, at 26 May 2016). According to the classification method for land use of the Standard of Land Use Status Classification (GB/T 21010–2007), land use was divided into six types of first-level categories: cultivated land, forest land, grassland, construction land, water areas, and unused land. The vector data for railways, expressways, national highways, and provincial highways in 2015 were provided by the National Geographic Information Resource Directory Service System (<http://www.webmap.cn>, at

12 September 2020), while other years were revised based on these data by referring to the China Traffic Atlas for corresponding years. These road dates were transformed into raster data matched to land-use data through the ArcGIS 10.4 conversion tool to form one of the input parameters of the InVEST model.

3.3. Methods

3.3.1. TSDI Evaluation

Referring to the current research on territorial space development [5,15,54,55], this study set up an evaluation index system to assess TSDI comprehensively by selecting seven indices from four aspects: population aggregation, land development, economic development, and input level (Table 1). These indices were selected based on the principles of data accessibility and comparability, and the actual situation of territorial space development in Northeast China.

Table 1. Evaluation index system of TSDI.

Target Layer	Standard Layer	Index Layer	Calculation of the Index	Weight
TSDI	Population aggregation	Population density (person/km ²)	Total population/total area	0.1594
	Land development	Construction land ratio (%)	Construction land area/total area	0.1753
		Cultivated land ratio (%)	Cultivated land area/total area	0.1432
	Economic development	GDP per area (10 thousand yuan/km ²)	Total GDP/total area	0.1334
		Industry non-agricultural rate (%)	Total output value of secondary and tertiary industries/total GDP	0.1345
	Input level	Investment in fixed assets per area (10 thousand yuan/km ²)	Total investment in fixed assets/construction land area	0.1383
		Government financial expenditure per area (10 thousand yuan/km ²)	Total government financial expenditure/total area	0.1159

The units and dimensions of each index of the TSDI were different. To make each index comparable, the indices were standardized using the extremum method so that they had values ranging between 0 and 1 [56,57]. The weights of the evaluation indices were calculated using the Delphi method [58] and entropy method [59], respectively, and then combined using the weighted average weight method. The Delphi method determined the weight of the indicators by consulting experts in planning and ecological fields [58]. The entropy method was used to determine the weight by calculating the entropy value to judge the dispersion degree of the index [59]. After standardizing the indices and determining their weights, the linear weighting method was used to measure the TSDI in each region [60]. The formula to calculate TSDI is as follows:

$$TSDI = \sum_{i=1}^n X_{ij}W_i \quad (1)$$

where *TSDI* is the comprehensive evaluation value of territorial space development intensity; X_{ij} is the standardized index; and W_i is the weight determined by the Delphi method and the entropy method.

TSDI differences in different years were analyzed by a one-way ANOVA, followed by Tukey's post-hoc test. These statistical analysis methods were performed in the program R (version 3.5.1) with the "multcomp" package.

3.3.2. HQ Assessment

The development of territorial space can cause an increase in the number and intensity of habitat threat sources, which in turn leads to the degradation of regional HQ [61–63]. The HQ was evaluated using the HQ module of the InVEST model. The HQ values range from 0 to 1, where 1 indicates a habitat of the highest quality and 0 indicates a habitat of the lowest quality. The evaluation model calculates the habitat degradation degree and HQ

based on set parameters, such as the threat source, the sensitivity of the threat source, and the distance between the habitat and threat source, reflecting the degradation status and service capacity of the regional ecosystem [8,64]. The first step was to calculate the degree of habitat degradation, as follows:

$$D_{xj} = \sum_{r=1}^R \sum_{y=1}^{Y_r} r_y \left(\frac{\omega_r}{\sum_{r=1}^R \omega_r} \right) i_{rxy} \beta_x S_{jr} \tag{2}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{rmax}} \right) \text{ (if linear)} \tag{3}$$

$$i_{rxy} = \exp\left(\frac{-2.99d_{xy}}{d_{rmax}}\right) \text{ (if exponential)} \tag{4}$$

where D_{xj} represents the habitat degradation degree in grid cell x with habitat type j ; R denotes the number of threat sources; Y_r is the grid number on a raster map of r ; r_y is the intensity of grid cell y ; ω_r indicates the weight of threat source r ; i_{rxy} denotes the distance between the habitat and the threat source; β_x means the anti-interference level of the grid cell x ; S_{jr} represents the relative sensitivity of habitat type j to the threat source r ; d_{xy} is the distance between grid cells x and y ; and d_{rmax} is the maximum impact distance of the threat source r .

Then, the formula for HQ is as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^z} \right) \right] \tag{5}$$

where Q_{xj} is the HQ of grid cell x in habitat type j ; H_j is the habitat suitability of grid cell x for habitat type j and its range is [0,1]; K is a half-saturation constant; and z is a scaling parameter, generally 2.5.

Referring to the parameters recommended by the InVEST model [65] and set in the study of HQ [66,67], this study defined forest land, grassland, and water areas as habitats since they constitute the main habitats of organisms. This meant that cultivated land, rural settlements, industrial and mining land, urban land, and main traffic roads (e.g., railways, expressways, national highways, and provincial highways) were threat sources. The threat radius of cultivated land, urban land, rural settlements, industrial and mining land, and main traffic roads were set as 5, 12, 10, 10, and 10 km, respectively, and the weights were 0.4, 1.0, 0.8, 0.7, and 0.8, respectively. The distance attenuation of cultivated, urban, industrial and mining land and rural settlements on the habitat was exponential; the main traffic roads were linear [67]. In addition, the habitat suitability of each habitat type and their sensitivity to threat sources was determined by referring to the recommended values of the model and the related literature [8,65,68] (Table 2).

Table 2. Habitat suitability of each habitat type and their sensitivity to threats.

Habitat Types	Habitat Suitability	Sensitivity of Habitat Types to Each Threat				
		Cultivated Land	Urban Land	Rural Settlements	Industrial and Mining Land	Main Traffic Roads
Paddy field	0.4	0.3	0.5	0.4	0.1	0.1
Dryland	0.6	0.3	0.5	0.4	0.1	0.1
Forestland	1.0	0.8	0.9	0.8	0.6	0.6
Bush forestland	1.0	0.4	0.6	0.5	0.2	0.2
Open forestland	1.0	0.9	1.0	0.9	0.7	0.7
Other forestland	1.0	0.9	1.0	0.9	0.7	0.7
High-cover grassland	0.8	0.4	0.6	0.5	0.2	0.3
Medium-cover grassland	0.7	0.5	0.7	0.5	0.3	0.5
Low-cover grassland	0.6	0.5	0.6	0.5	0.4	0.5

Table 2. Cont.

Habitat Types	Habitat Suitability	Sensitivity of Habitat Types to Each Threat				
		Cultivated Land	Urban Land	Rural Settlements	Industrial and Mining Land	Main Traffic Roads
River canal	0.7	0.7	0.9	0.8	0.5	0.5
Lake	0.8	0.7	0.9	0.8	0.5	0.5
Reservoir pit	0.7	0.7	0.9	0.8	0.6	0.5
Mudflat	0.6	0.7	0.9	0.8	0.6	0.6
Flood land	0.6	0.7	0.8	0.7	0.6	0.6
Saline and alkaline land	0.4	0.5	0.6	0.5	0.5	0.7
Marsh	0.5	0.5	0.4	0.2	0.3	0.7

3.3.3. Local Hot Spot Analysis

Getis-Ord G_i^* can be performed to analyze the degree of correlation between the attributes of a unit and the same attributes of neighboring units in the study area [69–71]. This study used Getis-Ord G_i^* to explore the hot and cold spots of the TSDI in Northeast China. The formula is as follows [72]:

$$G_i^* = \frac{\sum_{j=1}^n w_{i,j}x_j - \left(\frac{1}{n} \sum_{j=1}^n x_j\right) \sum_{j=1}^n w_{i,j}}{\sqrt{\frac{1}{n} \sum_{j=1}^n x_j^2 - \left(\frac{1}{n} \sum_{j=1}^n x_j\right)^2} \times \sqrt{\frac{1}{n-1} \left[n \sum_{j=1}^n w_{i,j}^2 - \left(\sum_{j=1}^n w_{i,j}\right)^2 \right]}} \quad (6)$$

where x_j is the attribute value of feature j ; $w_{i,j}$ denotes the spatial weight between features i and j ; and n represents the total number of features.

The z-score and p -value are the output results of Getis-Ord G_i^* , and they are measures of statistical significance. Higher positive z-scores represent hot spots where the clustering of high values is more intense. Cold spots with smaller negative z-scores represent cold spots where the clustering of low values is more intense [73]. The z-score is associated with the p -value. A z-score $< (-1.65)$ or $> (+1.65)$ means that there is a statistically significant cold spot or hot spot at a significance level of p -value < 0.10 (90% confidence level). A z-score $< (-1.96)$ or $> (+1.96)$ indicates that there is a statistically significant cold spot or hot spot at a significance level of p -value < 0.05 (95% confidence level). A z-score $< (-2.58)$ or $> (+2.58)$ denotes that there is a statistically significant cold spot or hot spot at a significance level of p -value < 0.01 (99% confidence level) [74,75].

3.3.4. Bivariate Spatial Autocorrelation Analysis

Bivariate spatial autocorrelation can reveal the correlation between the attribute values of geographic units and other attribute values in adjacent spaces [76,77]. This study explored the spatial correlation between the TSDI and HQ, using bivariate spatial autocorrelation models. Bivariate spatial autocorrelation can be divided into global spatial autocorrelation and local spatial autocorrelation [78]. Bivariate global spatial autocorrelation was described by global Moran’s I, which measured the overall spatial correlation across all spatial units for the total study area [79]. Bivariate local spatial autocorrelation was measured by local Moran’s I, and the aggregation and differentiation characteristics of local spatial elements were analyzed by depicting the local indicators of spatial association (LISA) map [80]. Four aggregation types were formed, including high TSDI counties with high HQ (High–High), high TSDI counties with low HQ (High–Low), low TSDI counties with high HQ (Low–High) and low TSDI counties with low HQ (Low–Low). The formulas are as follows [81,82]:

Global Moran's I:

$$I_{th} = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} \left(\frac{x_t^i - \bar{x}_t}{\sigma_t} \right) \left(\frac{x_h^j - \bar{x}_h}{\sigma_h} \right)}{(n-1) \sum_{i=1}^n \sum_{j=1}^n w_{ij}} \tag{7}$$

Local Moran's I:

$$I_{th}^i = \frac{x_t^i - \bar{x}_t}{\sigma_t} \sum_{j=1}^n w_{ij} \frac{x_h^j - \bar{x}_h}{\sigma_h} \tag{8}$$

where w_{ij} indicates the spatial weight matrix; x_t^i represents the value of attribute t of unit i ; x_h^j denotes the value of attribute h of unit j ; \bar{x}_t and \bar{x}_h are the average values of attributes t and h , respectively; σ_t and σ_h indicate the variances of attributes t and h , respectively; and n is the total number of geographic units.

4. Results

4.1. TSDI

The TSDI of each county in Northeast China was calculated according to the evaluation index system of the TSDI. The value of TSDI was split into different grades, using Jenks in ArcGIS to display its spatial distribution characteristics (Figure 3). In terms of spatial patterns, TSDI in Northeast China is high in the south, low in the north, high in the west, low in the east, and prominent in urban agglomeration areas. Northeast China has various types of landforms. In the central and southern parts, the terrain is relatively flat, there is a concentration of urban and rural areas, and territorial space development is intense. The north and eastern parts contain the Greater Khingan Range, the Lesser Khingan Range, and the Changbai Mountains, with forest land as the main land type. TSDI is low in these areas, and the ecology and environment are well-maintained. By province, TSDI in the Liaoning, Jilin, and Heilongjiang Provinces decrease in turn, which is consistent with the economic development, land use, and population aggregation of each province. In addition, the TSDI of the municipal districts is obviously higher in prefecture-level cities, as they are key areas of territorial space development within prefecture-level cities.

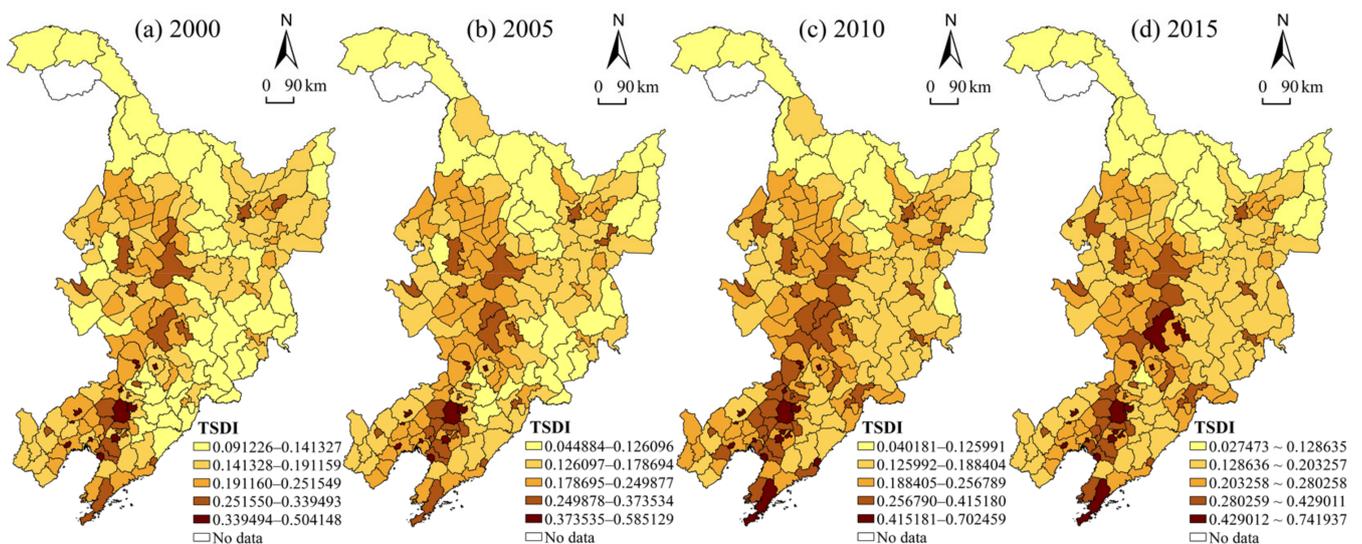


Figure 3. Spatial pattern of TSDI in Northeast China for the years (a) 2000; (b) 2005; (c) 2010; (d) 2015.

On the time scale in Figure 4 (2000–2015), the TSDI in Northeast China indicates that the development intensity increases year by year, with the most significant increase from 2005 to 2010. The overall TSDI of the three provinces in Northeast China was significantly different from 2000 to 2015 ($p < 0.05$); while the difference between 2000–2005

and 2010–2015 was not significant, the difference between 2005 and 2010 was significant. From 2000 to 2005, the development in the region was relatively slow, and the overall development of territorial space was at a low level, with a small increase. From 2005 to 2010, the implementation of the Northeast Revitalization Strategy brought about rapid regional development and the industrialization level and agricultural modernization level were significantly improved, which led to the rapid development of territorial space. From 2010 to 2015, the GDP of Northeast China sharply declined from 13.70% to 4.47%, regional development was under great pressure, and the increment of TSDI decreased accordingly [53]. The changing characteristics of TSDI in Liaoning Province and Jilin Province on the time scale were basically consistent with the overall characteristics of Northeast China; that is, they increased year by year with significant differences. However, TSDI in Heilongjiang Province did not differ significantly from 2005 to 2015 and decreased from 2000 to 2005. Since 2000, there have been many resource-based cities and counties in Heilongjiang Province that have undergone transformations, and the development of secondary industries has evidently reduced.

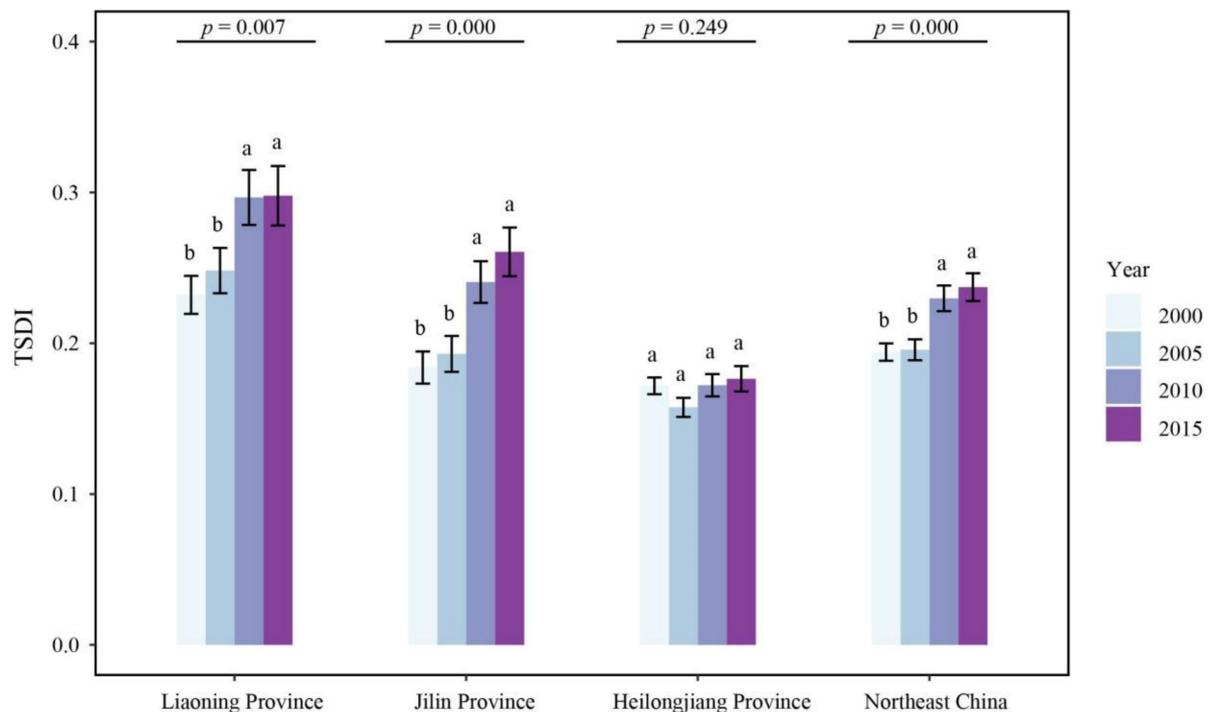


Figure 4. Changes in TSDI in Northeast China. Note: $p < 0.05$ means significant difference. There is no significant difference between the same letters in different years (Tukey's post-hoc test, $p > 0.05$).

The cold and hot spots for the TSDI of Northeast China in 2000, 2005, 2010, and 2015 were calculated using the Getis-Ord G_i^* statistic in ArcGIS. G_i z-score values were divided into different grades to present the spatial heterogeneity of the cold and hot spots for the TSDI (Figure 5). The TSDI hot spots are concentrated in the Central and Southern Liaoning urban agglomeration, which is consistent with the concentration for counties with a high development intensity. The TSDI cold spots are mostly concentrated in the Greater Khingan Range and the Lesser Khingan Range areas. The counties with low development intensity are more concentrated in those areas. The TSDI hot spots are generally stable, but the scope tends to shrink. The TSDI cold spots decrease obviously in the Changbai Mountain areas and increase greatly in the Greater Khingan Range and the Lesser Khingan Range areas. Overall, the hot spots are located in the south of Northeast China and have fewer changes. The cold spots shift from southeast to north of Northeast China.

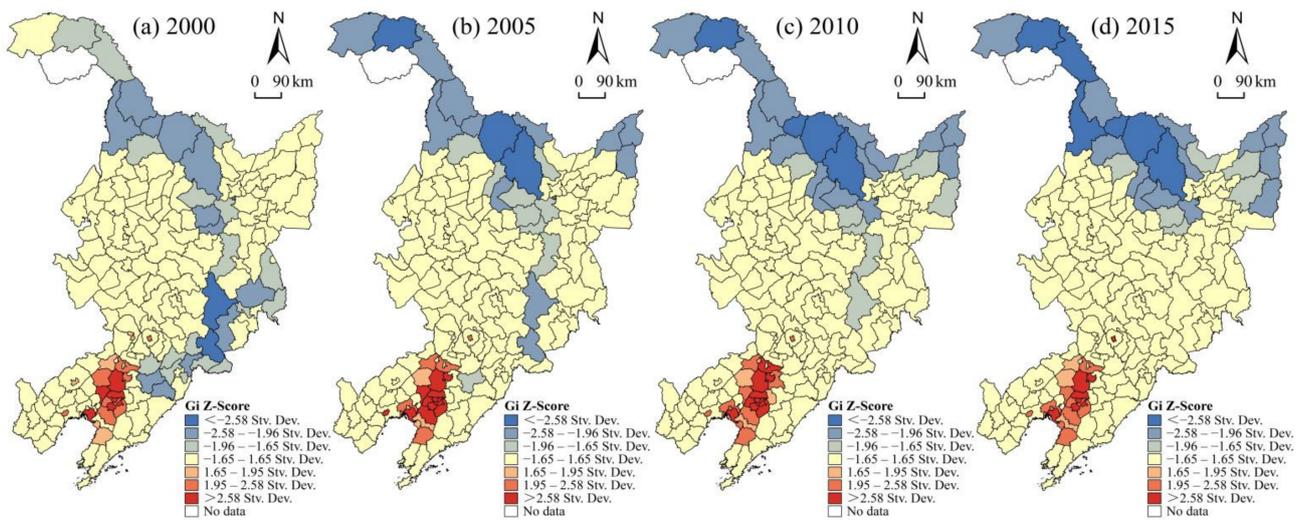


Figure 5. Distribution of cold and hot spots of TSDI in Northeast China for the years (a) 2000; (b) 2005; (c) 2010; (d) 2015.

4.2. HQ

The average values of HQ in each county were counted, using the spatial analyst tool in ArcGIS. HQ values were classified into five categories from low to high by Jenks in ArcGIS to obtain the spatial distribution of HQ in Northeast China in 2000, 2005, 2010, and 2015 (Figure 6). Overall, the spatial pattern of HQ in Northeast China was relatively stable in different years, and counties with the same levels of HQ were concentrated, with evident regional differentiation characteristics. The Central and Southern Liaoning urban agglomerations with the concentrated construction land, a high level of economic development, and a large degree of development constitute the regions with the lowest HQ. The HQ of counties in the Liaohe, Songnen, and Sanjiang Plains, which have vast cultivated land and frequent agricultural activities, is also low. The HQ of ecological protection areas with concentrated forest land and grassland in the Greater Khingan Range, Lesser Khingan Range, and Changbai Mountains is high. Municipal districts of most prefecture-level cities have the lowest point of HQ within the administrative region of the cities. HQ is noticeably different in different landform areas, and human activity is an important factor that affects HQ.

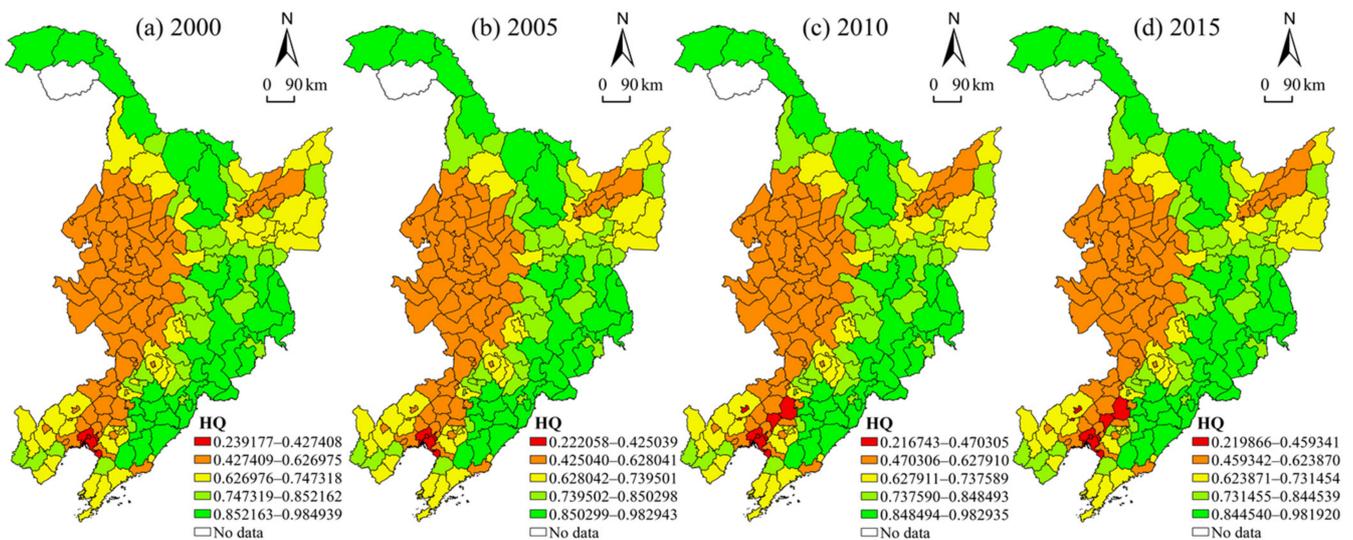


Figure 6. Spatial distribution of HQ in Northeast China for the years (a) 2000; (b) 2005; (c) 2010; (d) 2015.

After analyzing the temporal changes, the mean value of HQ in Northeast China decreased from 0.6996 to 0.6931 between 2000 and 2015, indicating a degradation trend. From 2000 to 2005, the proportion of counties with degraded HQ was comparable to that of counties with improved HQ, and the distribution of these two types of counties was scattered. There were significant regional differences in the changes in HQ (Figure 7). From 2005 to 2010, 77.65% of counties had degraded HQ, which was a significant increase. The Northeast China Revitalization Strategy has brought about rapid social and economic development, intensified human activities, and great challenges to regional HQ, and HQ has faced great challenges accordingly. The newly added counties with degraded HQ were mainly concentrated in the Harbin-Changchun and Central and Southern Liaoning urban agglomerations, which have experienced explosive growth in construction land and posed serious threats to ecological land during this five-year period. From 2010 to 2015, 84.36% of the counties experienced HQ degradation, thus further reducing the overall HQ in Northeast China. In addition, the increased number of counties with degraded HQ was the highest in Heilongjiang Province, which was inevitably related to the development of the Sanjiang Plain, the intensified fragmentation of landscape patterns, and the continuous decline of ecosystem service capacity.

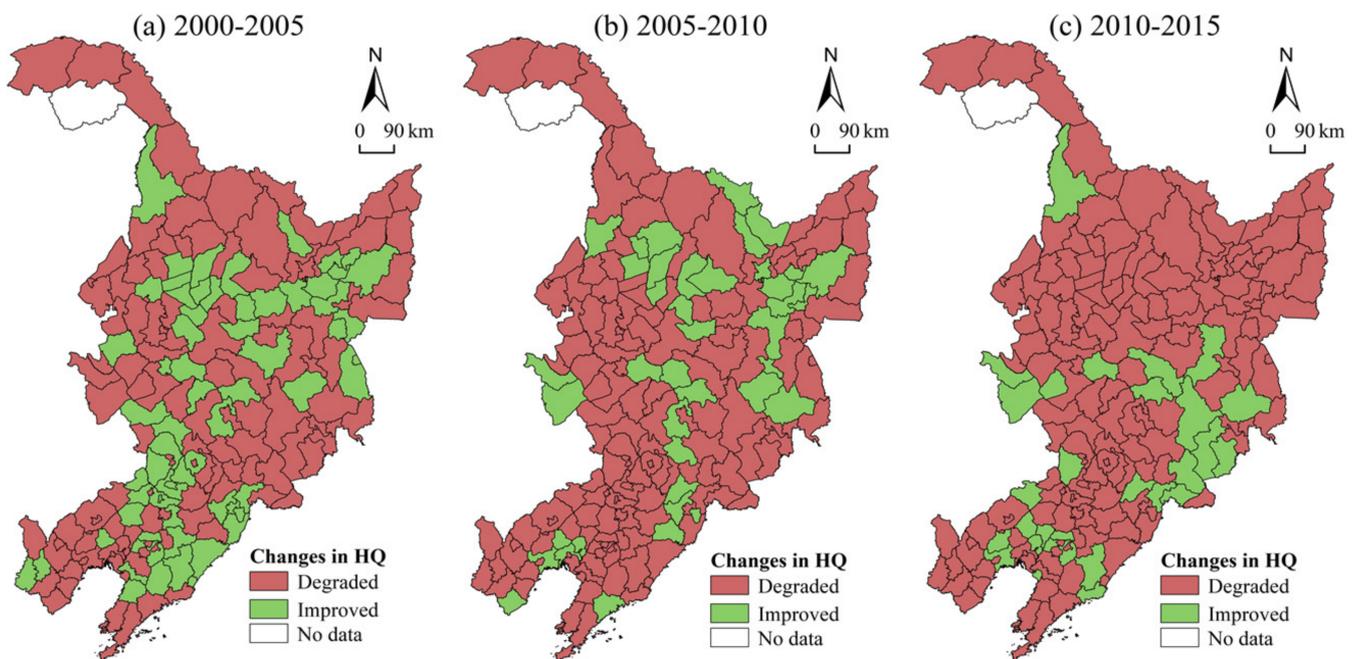


Figure 7. Changes in HQ at the county level in Northeast China during (a) 2000–2005; (b) 2005–2010; (c) 2010–2015.

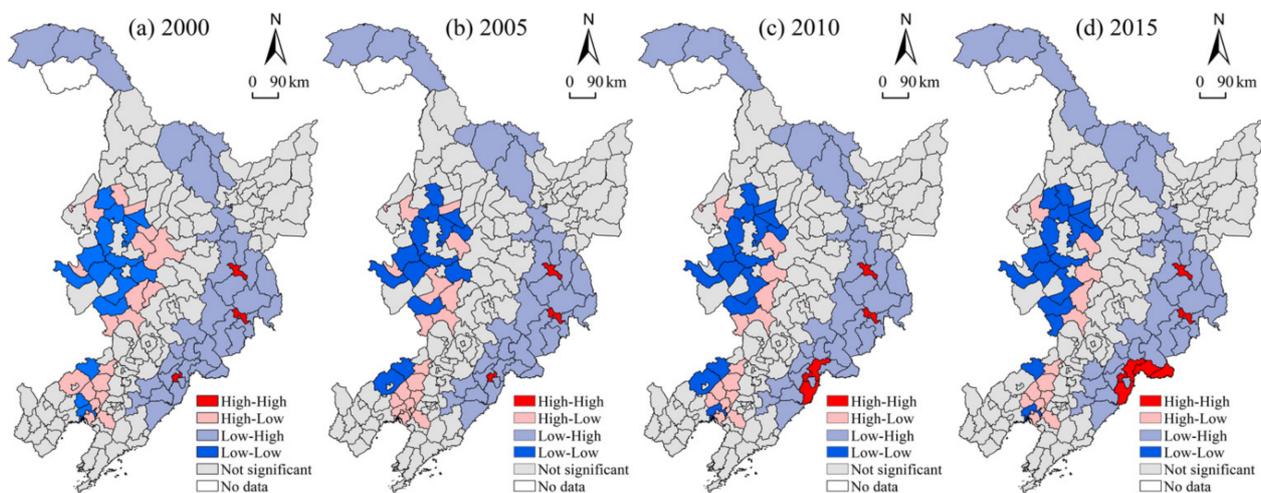
4.3. HQ Responses to TSDI

The global Moran's I index between TSDI and HQ in the counties was calculated using GeoDa, and the results are shown in Table 3. The index passed the significance test at the 1% level. Therefore, TSDI and HQ had a strong negative spatial correlation; that is, the higher the TSDI, the more serious the HQ degradation. The development of territorial space in Northeast China has brought more threats to HQ, increased negative impacts on HQ, and resulted in a decrease in HQ. In addition, the absolute value of Moran's I index decreased continuously from 2000 to 2015, indicating that the correlation between the TSDI and HQ had a slight spatial dispersion trend.

Table 3. Parameter values of bivariate spatial correlation analysis.

Parameters	2000	2005	2010	2015
Moran's I	−0.3301	−0.2946	−0.2420	−0.2289
z-value	−7.9722	−7.1254	−6.0427	−5.7390
p-value	0.0010	0.0010	0.0010	0.0010

A bivariate LISA agglomeration map was drawn to analyze the local spatial correlation. Local spatial correlations between TSDI and HQ were split into the following types: High–High aggregation, High–Low aggregation, Low–High aggregation, Low–Low aggregation, and not significant (Figure 8). Except for the non-significant areas, the counties with Low–High concentrations are dominant. These concentration areas have a low TSDI and high HQ and are distributed mostly along the Greater Khingan Range, the Lesser Khingan Range, and the Changbai Mountains. The number of counties with Low–High concentrations is generally stable from 2000 to 2015, and they comprise important ecological conservation areas in Northeast China, with concentrations of restricted and prohibited-development zones. The proportion of counties with High–Low aggregation and Low–Low aggregation is second only to those with Low–High aggregation, and the number of counties with these two aggregation types is equal. Counties with High–Low aggregation have high TSDI and low HQ and are primarily spread across the center of the Songnen Plain and the Liaohe Plain. In 2000, 2005, 2010, and 2015, there were 20, 18, 15 and 13 counties with High–Low aggregation respectively, showing a decreasing trend. In this area, there is a concentration of cities and agricultural areas, industrial and agricultural activities are frequent, and there is a negative correlation between territorial space development and habitat. Low–Low aggregation counties have low TSDI and low HQ and are mostly concentrated in the west of Jilin Province and the southwest of Heilongjiang Province. From 2000 to 2015, the distribution patterns of these counties changed only slightly. These counties have serious land salinization, poor ecology and environment, and a more serious incongruity between regional development and ecological protection. There are relatively few counties with High–High aggregation, mainly appearing sporadically in the Changbai Mountain areas but the scope is expanding. It is not difficult to notice that there are fewer counties that balance territorial space development and ecological environmental protection, but with the enhancement of people's awareness of environmental protection and the promotion of the National Main Function Zoning, there is a growing trend of counties that balance territorial space development and ecological environmental protection.

**Figure 8.** Spatial corresponding patterns of bivariate spatial autocorrelation between TSDI and HQ for the years (a) 2000; (b) 2005; (c) 2010; (d) 2015.

Overall, there existed a substantial negative spatial correlation between TSDI and HQ in Northeast China from 2000 to 2015, and the HQ response to TSDI is obvious. The areas with the strongest HQ response to territorial space development in Northeast China are mostly spread across the western plains and eastern rugged mountain areas. The Songnen Plain and the Liaohe Plain areas in the west are dominated by High–Low aggregation and Low–Low aggregation, while the Greater Khingan Range, the Lesser Khingan Range, and the Changbai Mountain areas in the east are dominated by Low–High aggregation. Low–High aggregation is the main relationship type between TSDI and HQ in Northeast China, and the scope of this aggregation area is basically stable, reflecting the important position of ecology and environmental protection in the development of counties in Northeast China.

5. Discussion

In recent years, China has experienced rapid urbanization and rural development, and cities and villages have been developed to varying degrees. The Chinese government is vigorously pursuing several policies to deal with contradictions in development and to promote harmonious coexistence between humans and nature. The purpose of this study was to reasonably measure TSDI and HQ and analyze the spatiotemporal relationships between them to coordinate the connection between regional growth and protection.

5.1. Territorial Space Development Is Closely Combined with Ecology, with Implications for the Spatiotemporal Heterogeneity of the HQ Response

This study holds that the development of territorial space involves many aspects, such as land, population, economy, and investment. Thus, it should not consider using only proportional construction land in the region. In contrast to other previous studies, we attempted to establish an analytical framework for TSDI by setting up a comprehensive evaluation index system, using four dimensions (land, population, economy, and investment) to evaluate the TSDI of each county in Northeast China. Through the assessment of this comprehensive evaluation index system, we found that TSDI in Northeast China increased year by year, and that there are obvious spatial differences. Moreover, TSDI increased most significantly between 2005 and 2010, which has also been confirmed by many previous studies [22,83–85]. The pattern of territorial space development is directly related to resource endowment, economic development, and national strategy [47]. Northeast China has a massive expanse of land, and there is great variance in the resource endowments and ranges of economic development among the different counties, which also causes regional differences in spatial land development patterns. The Chinese government began implementing the Northeast Revitalization Strategy at the end of 2003 to vigorously support the development of Northeast China. The key period of the Northeast's revitalization and development was between 2005 and 2010, and territorial space developed rapidly [53]. After this period, development faced great pressure, as it was restricted by factors such as insufficient innovation, and the TSDI increased slowly.

The urbanization and accelerated development of territory in China has brought about a series of resource and environmental problems. Consistent with many existing studies, our study also concluded that the development of territorial space has caused the degradation of regional ecology and environment [28]. However, in contrast to previous studies, our study focused on the spatial response of HQ to territorial space development. Currently, there is no consistent method for assessing HQ. Therefore, by considering the impact of human activity on habitats in the process of territorial space development, we employed the use of the InVEST model to measure regional HQ in this study [33]. The InVEST model is employed worldwide to assess regional HQ and is proved to be reliable [7,34,86]. This would certainly increase the scientific validity of our study.

In addition, bivariate spatial autocorrelation was used to reveal the negative spatial correlation between TSDI and HQ and the spatial difference of the HQ response to TSDI, which provides a new perspective for studying the relationship between landscape patterns and ecosystem services in the process of territorial space development. Bivariate spatial autocorrelation has been widely used to explore the correlation between two sys-

tems. Scholars from different countries and regions used this method to analyze different problems, such as the relationship between air pollution and allergic diseases [87], spatial relationship between economic growth and renewable energy consumption [88]. The TSDI and HQ are interactive variables. It is reasonable to use bivariate spatial autocorrelation to analyze the spatial relationship between them, and it is also applicable worldwide. Exploring the HQ response to territorial space development could help society better understand the impact of human activity on biodiversity and ecological service levels [8].

5.2. Policy Implications for Territorial Space Development in Northeast China

Northeast China has relatively rich cultivated land and ecological resources. Under the development strategy for food and ecological security, the relationship between development and protection in this area is important, and there is a large space for optimizing the relationship between humans and land [89]. By analyzing the spatiotemporal variation of TSDI and the HQ response to TSDI in Northeast China, we can clarify the impact of unreasonable land use on HQ and advance the understanding of optimizing territorial space development and improve the ecological environment quality. We provide the proposals below to help land management and regional development.

First, the difference between TSDI and its relationship with HQ can guide land management in Northeast China. In the context of the irreversible trend of population urbanization, the government should formulate specific land-control policies to strictly control the scale of construction land, improve the level of land intensive and economical use, and rationally plan infrastructure construction. The strict protection policies for ecological land should also be implemented to minimize the number of habitat threats and prevent further fragmentation of the ecological landscape. Second, the four types of clustering patterns (i.e., High–High, High–Low, Low–High, Low–Low) between TSDI and HQ can be combined with the development requirements of priority, key, restricted, and prohibited-development zones in the National Main Function Zoning to scientifically guide the development of a county. Areas with high TSDI and high HQ should promote the process of industrialization and urbanization. Areas with high TSDI and low HQ should alter their ideas regarding development, and any regional development activities in these areas should be subject to strict review. There are ecologically advantageous areas where TSDI is low and HQ is high. Development and construction activities in areas that are not related to conservation should be eliminated. Ecological restoration projects should be prioritized in areas with low TSDI and low HQ [90]. Additionally, attention should be afforded to the development and protection of key regions. For example, the TSDI of counties in the Changbai Mountain area has increased significantly, and the development intensity has gradually changed from cold spots to sub-cold spots in Northeast China. When developing tourism and the forest economy, it is imperative to reinforce the investment in ecological and environmental protection in these counties to obtain development benefits and avoid sacrificing habitats. The counties to the west of Jilin Province and southwest of Heilongjiang Province are ecologically fragile areas with problems of low development and low HQ. These counties should actively implement projects that connect rivers and lakes to enhance landscape connectivity [91], promote ecological management and restoration, and improve regional ecology and the environment.

5.3. Limitations and Prospects for Further Study

This study is not without some limitations. First, we focused on the objectivity of the evaluation index system when assessing TSDI, but some subjectivity is inevitable. Second, considering the availability of data and the analysis at equal annual intervals, we used data for 2000, 2002, 2010, and 2015. Future studies should supplement the recent data and lengthen the time span to better discover changes in territorial space development and the related ecological effects. Finally, the connotations of TSDI and HQ are profound, so it is a relatively grand systematic project to attempt to study the relationship and coordinated development between them. Territorial space is a complex and integrated area, and

achieving overall coordination between its socioeconomic development and environmental protection is a gradual process. In this study, the HQ response to TSDI constitutes a relatively preliminary study of the relationship between them. Our selection of habitat threat sources also only considered the most direct impacts of territorial development. Thus, the HQ response under multiple ecological functions and the comprehensive ecological effects of territorial space development should be considered directions for improvement and in-depth study in the future.

6. Conclusions

This study established a comprehensive evaluation system for TSDI and evaluated and analyzed its spatiotemporal variation characteristics of counties in Northeast China. The HQ of counties was evaluated using the InVEST model, and the HQ response pattern to TSDI was further discussed.

The main conclusions are as follows: (1) TSDI in Northeast China was higher in the south, lower in the north, higher in the west, and lower in the east, and prominent in urban agglomeration areas, which grew continuously during the study period. The growth was most obvious at the initial stage of implementation of the Northeast Revitalization Strategy. (2) The HQ of counties in Northeast China was lower in the east, higher in the west, lower in the south, and higher in the north. During the study period, the proportion of counties with degraded HQ increased, and the challenges of regional ecological and environmental protection increased. (3) There was a significant negative spatial correlation between TSDI and HQ in Northeast China. The Low–High aggregation type was the main relationship between the two and was mainly distributed in mountainous areas with better ecological protection. However, there were some counties with the Low–Low aggregation type in ecologically fragile areas, and the uncoordinated problems between space development and ecological protection in these regions were severe, which should be afforded more attention in the future.

Our study not only considered the influence of the construction land on TSDI, as in previous studies, but also increased the indicators of population, economy, and investment to evaluate the current situation of TSDI in Northeast China more scientifically and comprehensively. In addition, we focused on the spatial response relationship between HQ and TSDI to integrate territorial space development with ecology. Our study can improve the evaluation of TSDI and provide methodological references and new perspectives for studying the relationship between development activities and ecological levels. The findings of this study are important for understanding the synergistic effects between human activity and ecological systems and can provide practical guidance for territorial space planning. We suggest that the TSDI should be controlled reasonably so as to promote the coordinated and sustainable development of TSDI and HQ. In addition, the government should arrange differentiated development strategies and land management measures based on the regional differentiation of TSDI and HQ when formulating territorial space planning.

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