Study on Driving Mechanism of Geological Environment Carrying Capacity

-- Taking Dongning-Suifenhe Region as an Example

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Abstract. The carrying capacity of the geological environment to human activities is limited, and the maximum limit of this carrying capacity is the geological environment carrying capacity. It is necessary to scientifically understand the concept of geological environment carrying capacity from two dimensions: the geological environmental conditions (the carrier) and human activities (the load). To date, research on geological environment carrying capacity has focused on the establishment of evaluation methods and indicator systems, and the research seldom deals with the driving mechanism of geological environment carrying capacity. This paper evaluates the background carrying capacity and the carrying state of the geological environment in the Dongning-Suifenhe region by using the hierarchical comprehensive index method. On this basis, the geological weighted regression model is used to study the driving mechanism of geological environment carrying capacity. The background carrying capacity of the geological environment, primary sector, and population are identified as the three driving factors. All of them have positive driving effects on the geological environment carrying state.

Keywords: Geological environment, Evaluation of geological environment carrying capacity, Driving mechanism, Dongning-Suifenhe region.

1. Introduction

The geological environment is an independent and open environmental system, an important part of the natural environment, the most basic habitat and space of activities for human beings, and the fundamental carrier of materials needed for production and life [1]. The geological environment's carrying capacity for human activities is limited, and this maximum limit is the geological environment carrying capacity [2, 3].

It is necessary to scientifically understand the concept of geological environment carrying capacity from two dimensions: the geological environmental conditions (the carrier) [4, 5] and human activities (the load) [6, 7]. The first is the supporting and limiting role of the geological environment. For the same scale and intensity of human activities, different geological environment conditions provide different supporting and limiting roles [8, 9]. The second is about the activity and transformation ability of the load. Under the same geological environment conditions, different ways and intensities of human activities will have different impacts on the geological environment. The concept of geological environment carrying capacity essentially interprets the dialectical relationship between the geological environment and human activities and can serve as a criterion for measuring the coordination between the two [10, 11].

Geological carrying capacity is the result of the comprehensive effects of numerous factors, and the study of its driving mechanisms can reveal the extent and manner of the effects of various factors on carrying capacity. However, literature in this area is currently relatively inadequate and urgently needs to be supplemented [12, 13].

Research on the driving mechanisms of carrying capacity based on units of geological environmental conditions will not only identify the inherent mechanisms underlying the evaluation results of carrying capacity but also enrich the literature on geological environment carrying capacity, so it has practical and theoretical significance.

2. Overview of the Study Area

The Dongning-Suifenhe region is located in Mudanjiang City, in the eastern part of Heilongjiang Province. It borders Muling City on the north, borders Wangqing and Hunchun in Jilin Province on the south, Ning'an on the west, and Russia on the east, being an important part of the China-Russia-Mongolia Economic Corridor. The geographic coordinates are 130°9′ - 130°18′E, 43°25′ - 44°48′N, with a study area of 7,561.36 km^2 (Figure 1). China trades with 11 countries via the Dongning and Suifenhe ports, mainly including Russia, North Korea, South Korea, and Japan.

The study area is located on the eastern slope of the Taiping Ridge of the Laoyeling Mountain, a branch of the Changbai Mountain Range, at the junction of Laoyeling Mountain and Wanda Mountain foothills, with a topography characterized by middle- and low-mountainous shallow cutting terrains. The topography of the area is generally high in the northwest, southwest, and south, with low mountainous terrains and low in the middle and east with hilly and river valley plain terrains, resembling a horseshoe shape with low mountains embracing the middle. The highest point is Tonggouling in the central part of the study area, with an altitude of 1,102 meters, while the lowest point is at the exit of the Dongning port, with an altitude of 86.5 meters.

The climate in the study area is a mix of mid-temperate continental monsoon and oceanic climate, with an average temperature higher than that in neighboring areas, a mild climate, and a long winter and short summer. The average annual precipitation is 510.30 mm, and the average annual evaporation is 863.26 mm. The study area has a well-developed water system with four major rivers: the Dasuifen River, Xiaosuifen River, Suifen River, and Huhubao River.

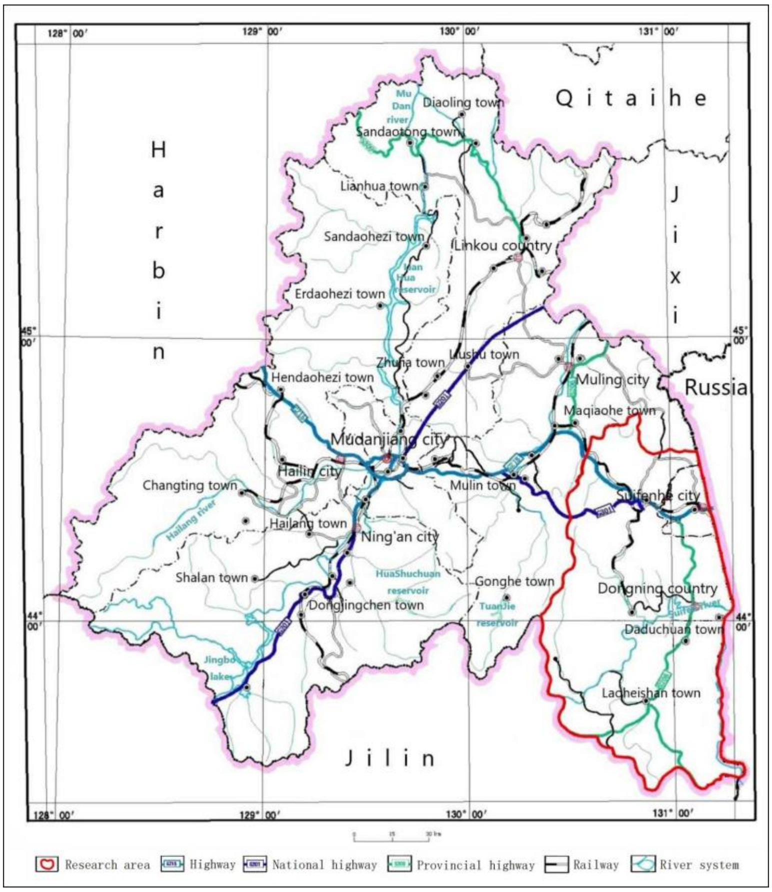

Figure 1. Geographical location of the study area

3. Evaluation of Geological Environment Carrying Capacity

The geological environmental elements at the criteria layer and indicator layer have been comprehensively evaluated by using the hierarchical comprehensive index method based on the indicator system of geological environment evaluation established with an analytic hierarchy framework. The comprehensive evaluation adopts the comprehensive index method [14] with the following evaluation model:

$$M_i = \sum_{j=1}^{n} Z_j \times W_j = \sum_{j=1}^{n} (\sum P_{ji} \times W_i) \quad (1)$$

Where: M_i - Comprehensive evaluation index of geological environment carrying capacity;
Z_j- The evaluation index value of the *j*-th criteria layer;
W_j - The weight of the *j*-th criteria layers, i=1, 2, …, n;
P_{ji} - The score of the *i*-th indicator of the indicator layer corresponding to the *j*-th criteria layer;
W_i - The weight of the *i*-th indicator, i=1, 2, …, n.

There are five background levels of geological environment carrying capacity: low, relatively low, moderate, relatively high, and high, and there are three geological environmental carrying states: surplus, balanced, and overloaded.

3.1. Background Evaluation of Geological Environment Carrying Capacity

3.1.1. Determine weights of background evaluation indicators

According to the weights of various evaluation indicators determined by using the Analytic Hierarchy Process (AHP), the four indicators with a relatively high impact on the background levels of geological environment carrying capacity in the study area are tectonic stability, land resources, ground slope, and groundwater resources. The weights of indicators are shown in Table 1.

Table 1. Weights of indicators for comprehensive background evaluation

Goal layer	Criteria layer	Weight (W_j)	Indicator layer	Weight (W_{ji})	Comprehensive weight (W_i)
Background level of geological environment carrying capacity (A)	Basic condition (C_1)	0.423	Topography (P_1)	0.109	0.046
			Ground slope (P_2)	0.309	0.131
			Tectonic stability (P_3)	0.582	0.246
	Hydrogeological conditions (C_2)	0.227	Groundwater resources (P_4)	0.540	0.123
			Groundwater depth (P_5)	0.163	0.037
			Groundwater quality (P_6)	0.297	0.067
	Environmental geological conditions (C_3)	0.123	Geological hazard susceptibility (P_7)	0.833	0.102
			Primary inferior water body (P_8)	0.167	0.021
	Resource conditions (C_4)	0.227	Mineral resources (P_9)	0.333	0.076
			Land resources (P_{10})	0.667	0.151

3.1.2. Results of background evaluation of geological environment carrying capacity

The comprehensive background evaluation of the geological environment carrying capacity is conducted on a GIS platform using the comprehensive evaluation model to calculate the comprehensive background evaluation index. The background levels of carrying capacity are then classified based on the criteria (Table 2).

Table 2. Classification of comprehensive background evaluation of carrying capacity

Classification of carrying capacity	Low	Relatively low	Moderate	Relatively high	High
Comprehensive background evaluation index	[0.1, 0.25)	[0.25, 0.4)	[0.4, 0.6)	[0.6, 0.8)	[0.8, 1]

The background carrying capacity of the geological environment in the study area is mainly divided into five levels. In terms of distribution, the areas with low and relatively low carrying capacity are concentrated, mainly distributed in the core of the rhomboid belt-shaped area with moderate carrying capacity, along the main faults in the study area, accounting for 7.45% of the study area. The areas with moderate carrying capacity include the Jinchanggou-Wanlugou and the area south of Maying Village in the east, the area west of Shuangqiaozi Forest Farm in the north, and the nearly rhomboid-shaped area of Jinchang-Huangnihe-Wanbaowan Forest Farm-Benloutou-Daohe, accounting for 29.43% of the study area, with a moderate development potential (Figure 2).

The areas with relatively high carrying capacity are the most widely distributed, mainly covering large areas in the north, middle, and southeast, accounting for 45.93% of the study area, with a relatively good development potential.

The areas with high carrying capacity are distributed in the east, northeast, and south of the study area, accounting for 17.19% of the study area. These areas can accommodate relatively intense human activities in terms of development and transformation of the geological environment, with a good development potential.

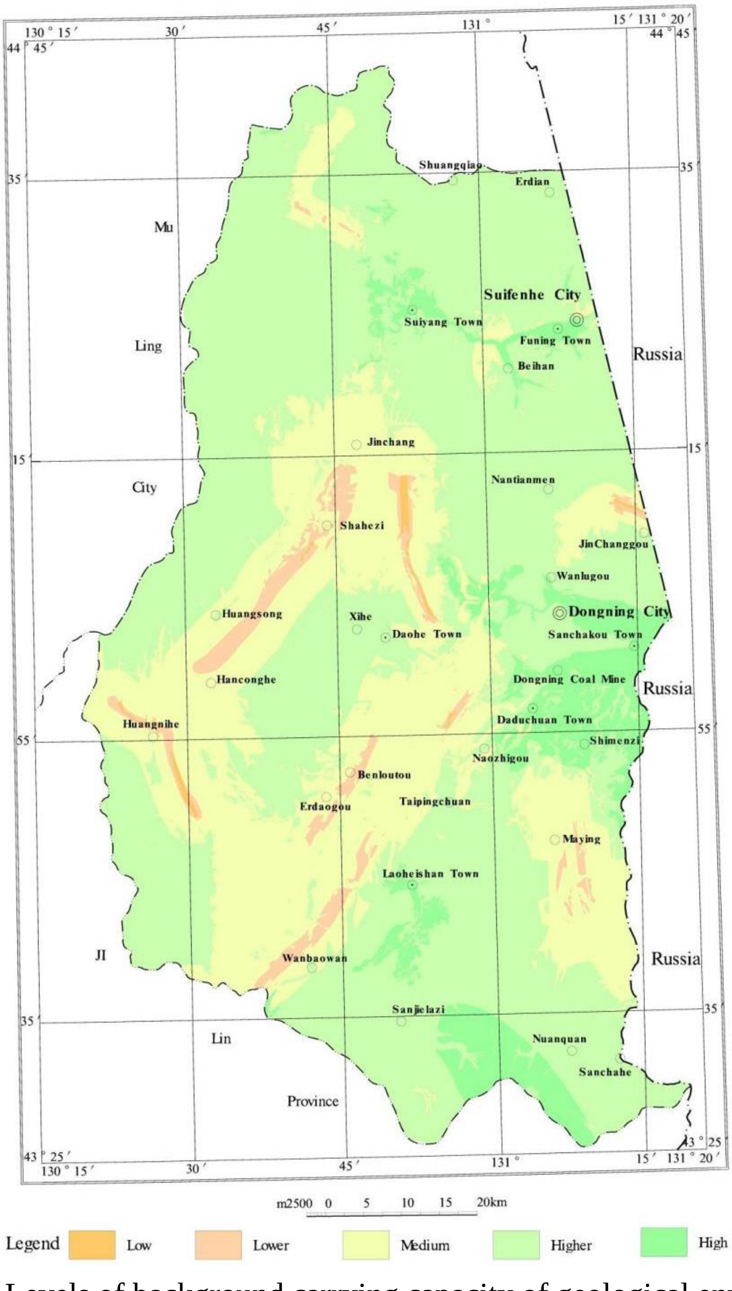

Figure 2. Levels of background carrying capacity of geological environment

3.2. Evaluation of Geological Environment Carrying State

3.2.1. Determine weights of state evaluation indicators

According to the calculations by using the Analytic Hierarchy Process (AHP), the three indicators of the indicator layer elements of the geological environmental carrying state evaluation with the largest comprehensive weight impact on the goal layer are the current state of land use, geological hazard risk, and current state of groundwater development. The weights of indicators are shown in Table 3.

Table 3. Weights of indicators for comprehensive state evaluation

Goal layer	Criteria layer	Weight (W_j)	Indicator layer	Weight (W_{ji})	Comprehensive weight (W_i)
Level of geological environment carrying state (B)	Current state of environmental geology (D_1)	0.5	Geological disaster risk (U_1)	0.500	0.250
			Current state of groundwater pollution (U_2)	0.250	0.125
			Current state of soil pollution (U_3)	0.250	0.125
	Current state of resource development (D_2)	0.5	Current state of mineral development (U_4)	0.163	0.082
			Current state of land use (U_5)	0.540	0.270
			Current state of groundwater development (U_6)	0.297	0.148

3.2.2. Evaluation results of geological environment carrying state

The comprehensive state evaluation of geological environment carrying capacity is conducted on a GIS platform using the comprehensive evaluation model to calculate the comprehensive state evaluation index. The classification criteria are shown in Table 4.

Table 4. Classification of comprehensive state evaluation of carrying capacity

Classification of carrying state	Surplus	Balanced	Overloaded
Comprehensive state evaluation index	[0.3, 0.5)	[0.5, 0.7)	[0.7, 1]

The carrying capacity state of the geological environment in the study area is mainly divided into three levels. In terms of distribution, the areas in a surplus state are the most widely distributed, accounting for 87.19% of the study area. These areas have relatively few geological environmental issues, a low degree of resource development and utilization, and a low impact caused by human activities. Overall, they are in a surplus state (Figure 3).

The balanced areas are distributed in the east and center of the study area, mainly with relatively concentrated populations, accounting for 11.03% of the study area. These areas have a certain development potential, but caution should be taken to prevent an overloaded state.

The overloaded areas are concentrated in areas such as Suifenhe-Funing Town, Jinchang, Dongning Town, and Dongning Coal Mine-Shimenzi Village, accounting for 1.78% of the study area. In these areas, land use is mostly in an overloaded state, and corresponding measures should be formulated to alleviate the overloaded state.

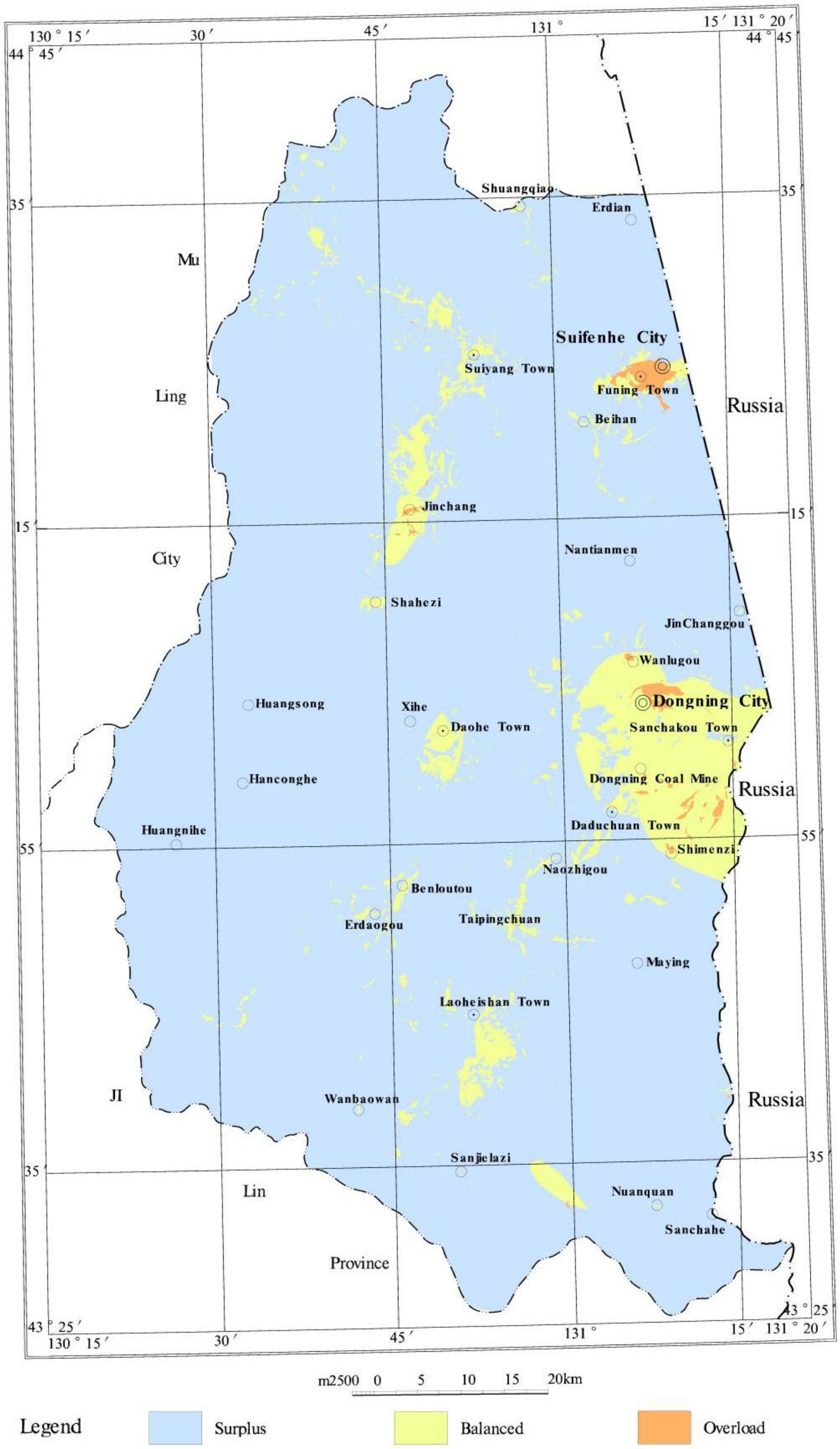

Figure 3. Classification of geological environment carrying state

4. Study on Driving Mechanism of Evolution of Geological Environment Carrying Capacity

4.1. Study on Driving Model of Evolution of Carrying Capacity State

The Geographically Weighted Regression (GWR) model is a localized spatial extension based on classical multiple linear regression [15, 16]. The magnitude of the regression coefficients can be used to characterize the different degrees of influence of the driving factors on the carrying state. When organically integrated with GIS, it can highlight the differences in the effects of these factors on the carrying state in different spaces, facilitating the investigation of the driving mechanisms of different driving factors on the evolution of carrying state [17].

On this basis, the driving model of the driving factors for the evolution of the carrying state is constructed as follows:

$$M_i = \beta_0(u_i, v_i) + \sum_k \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \tag{2}$$

Where: M_i - The comprehensive index of the geological environment carrying state of the i-th unit;
$\beta_0(u_i,v_i)$ - Regression constant term of the i-th unit;
$\beta_k(u_i,v_i)$ - The regression coefficient of the k-th driving factor at the i-th unit;
x_{ik} - The socioeconomic value of the k-th driving factor at the i-th unit;
k - Number of driving factors;
ε_i - Residual.

4.2. Identification of Driving Factors of Carrying State Evolution

4.2.1. Selection of influencing factors

A wide range of factors could affect the evolution of geological environment carrying state and can be classified into two categories: natural factors and human activity factors [18]. Among the natural factors, geological geomorphology, hydrogeology, environmental geology, and resources undergo little changes during short terms, but they have a significant impact on the evolution of geological environmental carrying state [19]. In this paper, the background carrying capacity of geological environment is selected as the comprehensive natural influence factor of the evolution of carrying state.

Different types of human activities may exert different impacts on the evolution of geological environmental carrying state. For example, in the economic development of the primary sector, increasing yield per would inevitably lead to increased application of chemical fertilizers and pesticides, posing greater threats of soil and water pollution. Increasing cultivated land will result in a decrease in other available land. In the secondary sector, such as manufacturing and construction, the production processes discharge pollutants that may affect the surrounding soil and water environment and consume water resources, and mining production may lead to resource depletion, trigger geological disasters, etc., resulting in the escalation of the geological environmental carrying state level [20]. The economic output of the tertiary sector has the lowest consumption of resources and environment, but it does not mean that it has no impact on the geological environmental carrying state. This direct impact is relatively lighter in relation to the primary and secondary sectors [21]. Population is one of the important influencing factors on the evolution of geological environmental carrying state, exerting a significant comprehensive impact.

This paper selects the background carrying capacity of the geological environment, the primary sector, the secondary sector, the tertiary sector, and the population as the influencing factors for the evolution of geological environmental carrying state.

4.2.2. Quantification of influencing factors

(1) Quantification of natural factor indicators

In this paper, the background carrying capacity of geological environment is selected as the natural influencing factor of the evolution of carrying state, and the quantification of the background carrying capacity of geological environment is based on the background evaluation index.

(2) Quantification of human activity indicators

Take the quantification of primary sector statistics as an example, based on the statistical yearbooks of Dongning and Suifenhe. The primary sector data is geographically discretized according to the distribution of cultivated land, considering that farming is the main segment of the primary sector in the study area, with fishery and animal husbandry accounting for a relatively low proportion.

The value of the primary sector assigned to each cultivated land unit is calculated by regression analysis. The regression model is as follows:

$$P_i = \sum_{j=1}^{n} a_j x_j \tag{3}$$

Where: P_i - The value of the primary sector in township i, in RMB 10,000;

a_j - The unit area value of the primary sector of the j-th cultivated land block in township i, in RMB 10,000/km^2;

x_j - The area of the j-th cultivated land block in township i, in km^2;

n - The number of cultivated land units in township i.

The process of geographic discretization of other socioeconomic data is similar to that of the primary sector, with the difference being that the data is allocated to the corresponding units of different land use types.

4.2.3. Identification of Driving Factors

In this study, the dependent variable is the geological environmental carrying state, and the primarily selected independent variables are the background carrying capacity, population, and the primary, secondary, and tertiary sectors, totaling 5 indicators. Before modeling, the independent variables and the dependent variable need to meet statistical test requirements.

(1) Bivariate correlation between independent variables and dependent variable

The independent variables and the dependent variable have spatial attributes. The classic and commonly used Moran's I is adopted to analyze the spatial correlation, and the formula is as follows:

$$I_{kl}^{i} = \frac{X_k^i - \overline{X_k}}{\sigma_k} \sum_{j=1}^{n} W_{ij} \frac{X_l^i - \overline{X_l}}{\sigma_l} \tag{4}$$

Where: I_{kl}^{i} - Moran's I of variable k and variable l of spatial unit i;

W_{ij} - Weight of spatial distance between calculation point jand data point i;

X_k^i, X_l^i - Values of variable k and variable l, respectively, of spatial unit i;

$\overline{X_k}$, $\overline{X_l}$ - Average values of variable k and variable l, respectively;

σ_k, σ_l - Variances of variable k and variable l, respectively.

The calculation results of the correlation between the influencing factors and the carrying state show that the Moran's I values are all greater than zero, indicating that the influencing factors have a positive driving effect on the carrying state and all pass the significance test. Therefore, these influencing factors have statistical significance in the geographically weighted regression model (Table 5).

Table 5. Bivariate spatial correlation analysis of independent and dependent variables

Correlation indicator / Indicators-state	Moran's I	P value	Significance
Background - carrying state	0.22	0.001	***
Primary sector - carrying state	0.53	0.001	***
Secondary sector - carrying state	0.32	0.001	***
Tertiary sector - carrying state	0.27	0.001	***
Population - carrying state	0.38	0.001	***

(Note: *** significance 0.1%)

(2) Multicollinearity between independent variables

In a regression model, a high correlation between two or more independent variables is called multicollinearity. The formula for judging multicollinearity among influencing factors is as follows:

$$VIF = \frac{1}{1-R^2} \tag{5}$$

Where: *VIF* - Variance inflation factor;

R^2 - Correlation coefficient.

When the VIF of two or more variables is greater than 10, it indicates severe multicollinearity, and one or more variables should be excluded to leave only one relatively independent variable.

The calculation results of the correlation among the influencing factors show that the VIF values of the secondary sector, tertiary sector, and population are all greater than 10, indicating multicollinearity among these three influencing factors (Table 6). Considering that the study area has a relatively high urbanization rate, with the population mainly distributed in urban areas and that urban areas and major towns and townships are the main sources of the secondary and tertiary sectors, the population is a comprehensive indicator that can indirectly reflect the influence of the secondary and tertiary sectors due to the multicollinearity among these three factors [22]. Therefore, the background carrying capacity, primary sector, and population are finally identified as the driving factors.

Table 6. Multicollinearity judgment among influencing factors

Indicator	Background carrying capacity	Primary sector	Secondary sector	Tertiary sector	Population
VIF	1.634	4.498	13.463	18.355	11.327

4.3. Driving Effects of Driving Factors on Evolution of Load-Carrying States

From the diagnostic results of geographical weighted regression fitting, the goodness-of-fit R2 and adjusted goodness-of-fit R_{adj}^2 all are higher than 0.8, indicating that the independent variables of the established model can explain more than 80% of the information of the dependent variable. The statistical value of the significance test F is large, and the P-value is extremely small, indicating that the geographical weighted regression model established is highly significant as a whole (Table 7).

Table 7. Diagnosis of goodness-of-fit of geological weighted regression model

Indicator	R^2	R_{adj}^2	F	P-value
Value	0.853	0.846	733.15	<0.001

4.3.1. The driving effect of background carrying capacity on the evolution of carrying state

The low-effect areas are the most widely distributed, the moderate-effect areas are distributed in the main urban areas and towns and sporadic strip areas, and the high-effect areas are distributed in the old urban areas of Dongning and Suifenhe (Figure 4).

Through a comparative analysis of the background carrying capacity and carrying state in the areas with moderate and relatively high driving effects, it can be seen that these areas have relatively high levels of background carrying capacity and relatively active human activities. When the background carrying capacity level of geological environment is relatively high, it represents the supporting capacity of the geological environment. As the development and transformation of the geological environment and resources intensifies, the carrying state also rises accordingly. Conversely, when the background carrying capacity level of geological environment is relatively low, it represents limited capacity. Therefore, the background carrying capacity has a positive driving effect on the evolution of geological environmental carrying state.

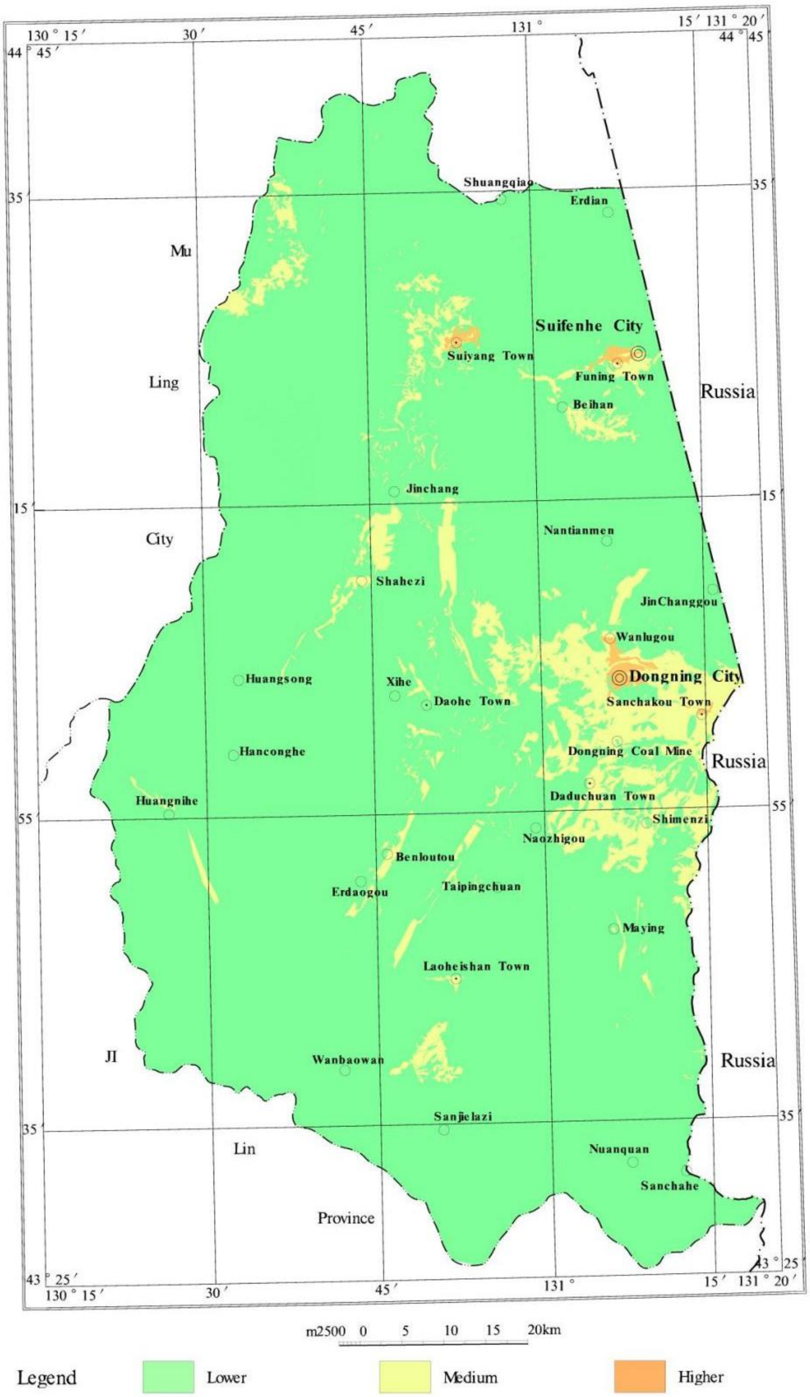

Figure 4. Degree of driving effect of background carrying capacity on carrying state

4.3.2. The driving effect of the primary sector on the evolution of the carrying state

Over a 20-year period, the cultivated land area increased by 17.33%, and the added value of the primary sector increased nearly eightfold. Excluding the impact of commodity price factors, grain yield per unit area increased by 22.46%, and economic crop yield per unit area increased by 28.11%. From the perspective of the spatial distribution of the effect of the primary sector on the carrying state, the areas with a relatively low effect are the most widely distributed, with land use types mainly being forests and grasslands. The areas with a moderate effect are distributed around major towns and townships and in mountains, transition zones between mountains and valleys, and transition zones between mountains and hills. The areas with a relatively high effect are mainly distributed in the areas around Dongning, Sanchakou, and Daduchuan, as well as in towns such as Suiyang Town (Figure 5).

The continuous increase in the added value of the primary sector mainly stems from the improvement in the output value per unit area. The added value is primarily contributed by areas stringing up Dongning, Sanchakou Daduchuan, and Suiyang Town. As a result, a large amount of chemical fertilizers and pesticides are used, increasing the possibility of organic, nitrogen, and heavy metal pollution in soil and groundwater. It will also increase the intensity of groundwater resource development. The rise in the added value of the primary sector has exacerbated the geological environmental carrying state. Therefore, the primary sector has a positive driving effect on the evolution of geological environmental carrying state.

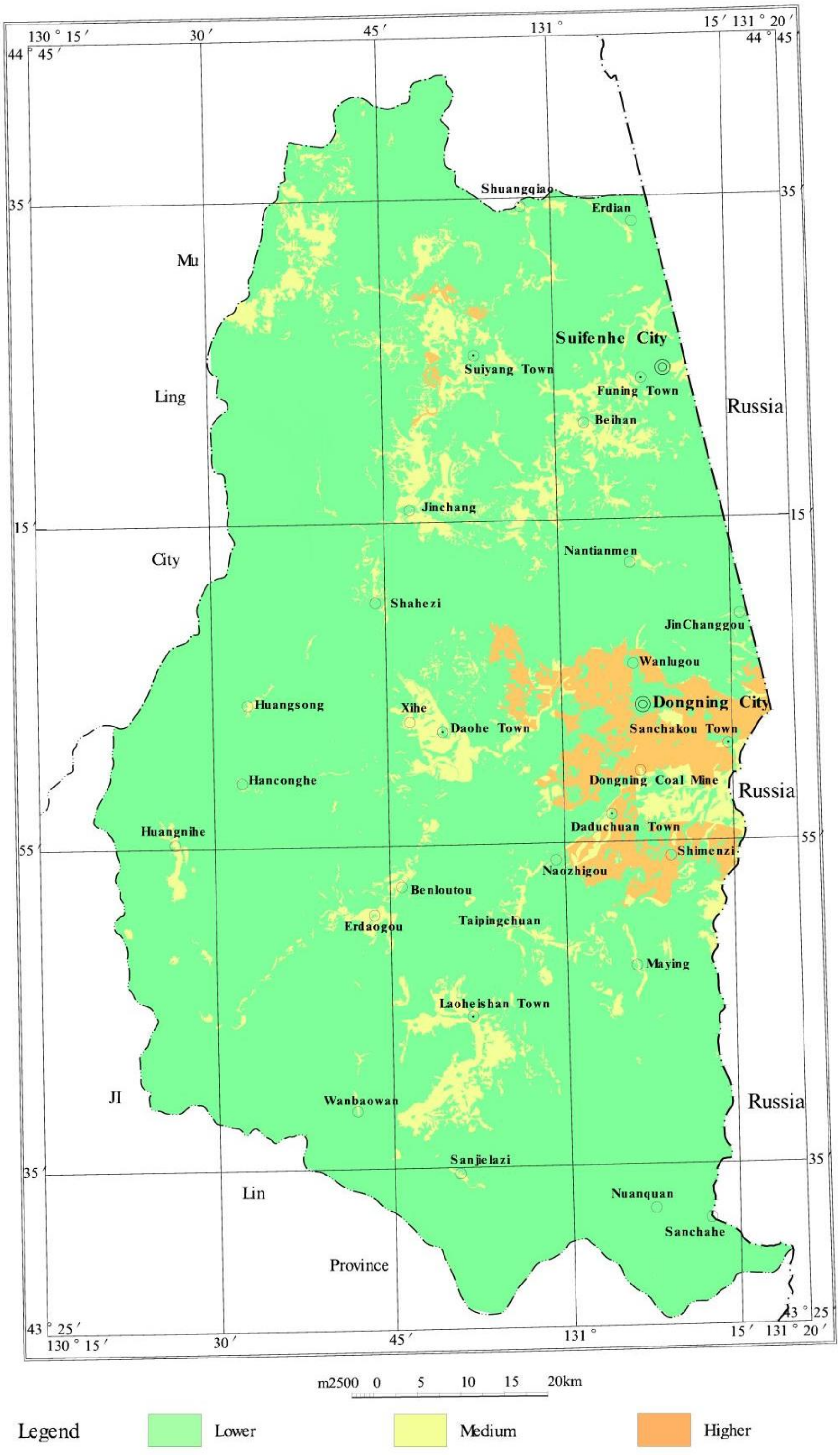

Figure 5. The driving effect of the primary sector on the carrying state

4.3.3. Driving effect of population on evolution of carrying state

The areas with low effect are the most widely distributed, the areas with moderate effect are distributed in major towns and villages, and the areas with high effect degree are mainly main urban areas of Dongning and Suifenhe, as well as Suiyang Sanchakou, Daduchuan, and Laoheishan Towns(Figure 6).

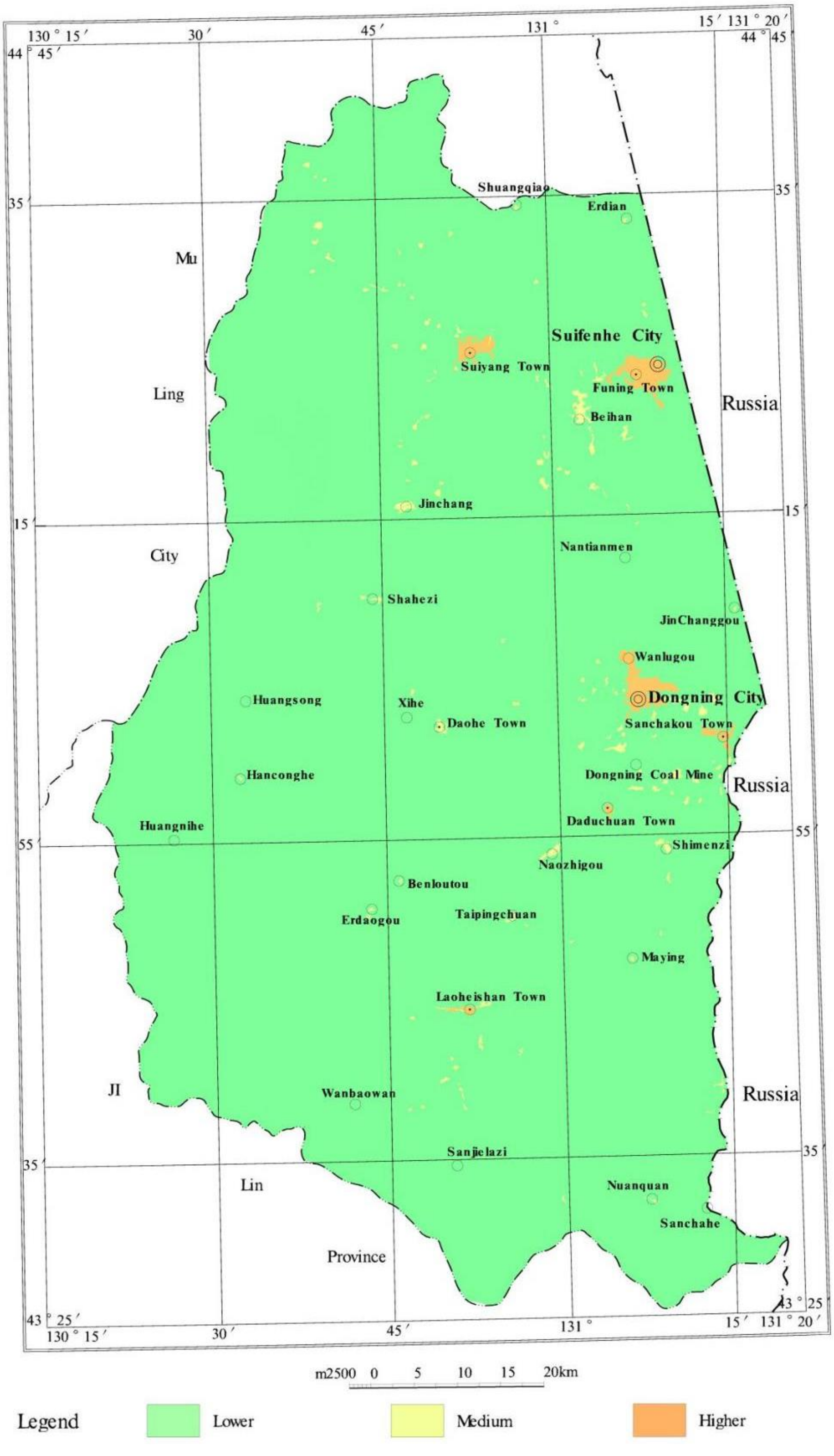

Figure 6. Driving effect of population on carrying state

Population is a comprehensive indicator that can indirectly reflect the influence of the secondary and tertiary sectors. Over a 20-year period, the population increased by 34,500, with a growth rate of 14.08%. The added value of the secondary sector increased by 11.5 times, and the added value of the tertiary sector increased by nearly 35 times. With economic growth and population increase, various construction activities in the main urban areas have increased year by year, and the scale of land resource utilization has gradually expanded, showing a trend of gradual outward expansion from the center. The amount of available land resources has been continuously decreasing. The concentration of population and the increase in industrial enterprises have not only increased the exploitation of groundwater resources, leading to escalation of the carrying state level in the urban areas but have even caused an overloaded state in some areas. Although the concentration of population, the intensity of construction activities, and the scale of industrial enterprises in major towns are weaker than in the main urban areas, they have also exacerbated the geological environmental carrying state over the past 20 years. Therefore, the population has a positive driving effect on the evolution of geological environment carrying state.

5. Summary

The background carrying capacity, primary sector, and population all have a positive driving effect on the evolution of geological environmental carrying state. The areas with a relatively high driving effect of the background carrying capacity on the geological environmental carrying state are mainly the urban areas of Dongning and Suifenhe, as well as Sanchakou and Suiyang Towns. The areas with a relatively high driving effect of the primary sector are distributed in Dongning, Sanchakou, and Daduchuan, as well as their surrounding areas and the surrounding areas of Suiyang Town. The areas with a relatively high driving effect from the population are mainly the urban areas of Dongning and Suifenhe, as well as Suiyang, Sanchakou, Daduchuan, and Laoheishan Town.

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