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Spatial correlation analysis and prediction of carbon stock of "Production-living-ecological spaces" in the three northeastern provinces, China

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ABSTRACT

The "Production-Living-Ecological Space" (PLES) is a paramount indicator in the filed of territory space development and optimization in China, under the new era. Exploring the driving factors of the PLES'land expansion is of great significance for improving space utilization, mitigating severe climate changes, and promoting green, healthy and sustainable development. In the background of the "Carbon Emissions Peak and Carbon Neutrality" strategy, analyzing and predicting the carbon stock of PLES is effective to boosting the achievement of 'Dual-Carbon' vision. Based on the above research questions， this study constructs the PLES based on statistics about land use (Year 1990, 2000, 2010 and 2020) in three northeastern provinces, and reveals the spatial correlation of PLES' carbon stock in the research area through ArcGIS spatial analysis and InVEST model. Then, the PLUS model was used to clarify the contribution of each driver to the conversion of space land, and to predict the distribution of the PLES pattern and the carbon stock's spatial correlation in 2030 and 2060 under the Natural-Development Scene and Ecological-Protection-Development Scene. Results show that: (1) The PLES in the three northeastern provinces of China is primarily green ecological space (55.71%) and agricultural production space (38.10%), while industrial production space (3.60%) and urban living space (2.76%) expand significantly, and green ecological space (−0.17%) and blue ecological space (−0.89%) are on a recession trend. Besides, 2000–2010 is the most intense period of all kinds of space land transformation in the study area. (2) Population density, proximity to roads at all levels, annual average temperature and elevation are the prime drivers of PLES' profile within the scope of the study region, but the contribution rate is significant difference. (3) The urban living space decreases and the green and blue ecological space increases significantly in the predicted years under the scene of Natural-Development and Ecological-Protection development; the pattern of PLES is relatively stable in the predicted years under both scenarios. (4) The spatial correlation of carbon stock is closely related to the distribution of PLES, with the high-value significant regions primarily in the distribution region of green ecological space, otherwise, the low-value significant regions mostly concentrated in the region with complex spatial land use types and large spatial development intensity; the overall structure within the scope of the study region shows a layout of high value areas surrounding low value areas. It can show that insisting on the ecological civilization construction is an effective way to achieve sustainable development and practice the "double carbon"

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strategy; in the future spatial land use control, ecological protection measures should still be adopted to ensure the sustainable development and positive operation of the study area.

1. Introduction

Global warming has develop into an essential constraint on the sustainable development of both economy and society. Based on this background, China has put forward a Dual-Carbon strategy, that is, peaking CO_2 emissions before 2030 and achieving carbon neutrality before 2060. Next, how to control CO_2 emissions has become a major issue of mankind. To expedite the attainment of the Dual-Carbon objective, it is necessary to work together from carbon emissions to carbon sinks and carbon stocks. Combined with relevant studies, it can be inferred that the terrestrial ecosystem constitutes the second most sizeable repository of carbon within the system of global carbon stocks. China's terrestrial ecosystem carbon sinks can offset about 7–15% of anthropogenic CO_2 emissions [1]. Therefore, finding out the transformation pattern of land resources and the spatial correlation of carbon stock are crucial steps in advancing the achievement of the Dual-Carbon Goal from its origin [2–6]. In the light of related research of land use carbon stock, the most widely used carbon stock calculation method is to use the Carbon Module of the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) [7,8], at present. And most scholars have been based on different land use types to carried out researches [9,10]. However, only considering land use and land cover is not enough to cope with the continuous change of spatial land, it is due to as a key measure it's planning is intently connected with regional progress [11]. Given these facts, the orderly and healthy development of land resources, land environment and land function is essential for sustained response to land change [12]. Thus, the present investigation is founded upon the premises of "Production-Living-Ecological Space" (PLES) as research unit. The PLES is a new development pattern within the filed of China territorial space development, as well as a crucial indicator of China territorial space development and optimization in a new period [13,14].

From a land-oriented perspective, the region under investigation possesses a variety of land environments, inclusive of land desertification, forest and grassland degradation, and black land degradation. Relevant studies have shown that land use carbon emissions in Northeast China are higher than those in other regions [15]. This is also a vital reason why the land environment in the three northeastern provinces of China has always been concerned [16]. Moreover, the three northeastern provinces of China as the old revolutionary regions and the old industrial bases, have an indispensable strategic position in the construction and development of China. Nevertheless, the research on the three northeastern provinces, the research direction is more inclined to its development weaknesses, such as poor land environment and serious soil erosion [16](Zheng et al., 2021), population loss [17] and single industrial structure [18] and its conclusions are mostly to provide policy recommendations for its high-quality development [19,20]. Insufficient inquiry has been conducted regarding the land resource, land environment and land function in the three provinces, while also ignoring the development advantages of the region. Hence, the exploration of the PLES in the three northeastern provinces and the study of the spatial correlation of carbon stock will not only help to enhance the land environment management, but also boost the coordinated development of China's regions, besides, it is also likely to facilitate a paramount strategic deployment to promote the revitalization of the Northeast.

Study the relevant literature found that there are two main approaches to classify the PLES, one is the qualitative analysis on the dominant functions of land use [21–23], another is the quantitative analysis using weighted assignment [24–26]. However, regardless of the classification method, the PLES are roughly classified into 6 [21] or 8 secondary spaces [24,27,28]; meanwhile, a few scholars classify them into 4 [29] or 7 [30] categories, and both of them propose the concept of potential space, classifying bare land and unused land as potential space, respectively. However, regardless of how many categories it is divided into, PLES is based on land resources, land management and land functions. On the other hand, there are more applications of models for land use prediction and simulation, among which, the Cellular Automata (CA) analysis model is more commonly and classically used [31–34], which was initially applied to the study of spatially complex systems [35,36], and as the model has been continuously refined extended to be used for land use [37–40], but in recent years there has been a lack of sufficient research progress. Thus, among many models, the Path-generating land use simulation model (PLUS) is chosen in this study. Because different from the existing transformation rules, Transition Analysis Strategy (TAS) [41] and Pattern Analysis Strategy (PAS) [42] have low flexibility, lack of period concept and defects in driving mechanism mining, PLUS through the Land Expansion Analysis Strategy (LEAS) [43] to predict, which combines the advantages of the above two strategies. The conversion rule of LEAS has three advantages: Firstly, it can simultaneously obtain all kinds of space land probability maps, also can get the contribution of each driver to the development probability of various spatial land use types. Secondly, it is more suitable for large-scale simulation studies. And thirdly, it can realize the coupling of multiple targeting algorithms [43–45].

This study is different from the simulation of prediction and conversion of land types based on land use data by most scholars, but based on the data of PLES to predict and simulate the constructed six secondary spaces in 2030 and 2060, and to probe the spatial correlation and conversion regulation of carbon stock through ArcGIS and Originl software. The research extends the practical application of the PLUS model, meanwhile, combines and applies the PLES and InVEST models as well as the PLUS model highly. On the one hand, it can deeply explore the spatial correlation of PLES carbon stock in the investigation area from the view of the spatial utilization of land. On the other hand, it can forecast the unfolding trajectory of space land in diverse developmental contexts. To providing theoretical support for the realization of low-carbon and healthy advancement in Chinese important strategic safeguard areas in the new developmental epoch, and providing reference for global land use, land environment and spatial planning governance as well as sustainable green and healthy development.

2. Study area and data sources

2.1. Study area

Investigation area (118°53′∼135°05′E, 38°43′∼53°33′N) are located in the northeast of China, adjacent to North Korea, Russia and the Sea of Japan, it has an essential strategic geographical position in the international arena (Fig. 1), it covers an area of 787,300 square kilometers, takes a count of 8.20% of the country; there are 36 prefecture-level cities total, 21 of which are resource-based cities like mines, forests and others.

The three northeastern provinces are rich in resources and are crucial mineral resources and timber production bases in China, and are the most oil-rich regions in the country, with the largest crude oil supply base and the first steel rolling mills in the country. At the inception of the new China, in the research area, the layout of automobile manufacturing, chemical energy, steel and other major industrial projects established the bedrock for the country's progress. As the birthplace of China's heavy industry, the region has garnered the reputation of the "Eldest Son of the Republic". In terms of agriculture, the black soil of China northeastern area is one of the three biggest black soil area globally, and is a vital commodity food base in China, as well as a "ballast" to ensure national food security. Whether from the industrial dimension or from the agricultural perspective, the three northeastern provinces are typical areas of the Dual-Carbon strategy, therefore, it is imperative to do this research of the transformation of the PLES and their carbon stock in the three northeastern provinces of China.

2.2. Data sources

The land use data were downloaded from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.Resdc.cn) with 30 m × 30 m spatial resolution. The data set was made by visual interpretation of Landsat-TM/ETM and Landsat8 satellite images. The driving factors data were downloaded form the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.Resdc.cn), the National Catalogue Service For Geographic Information and the website of OpenStreetMap (https://www.openstreetmap.org), besides, the POI data of the municipal governments and the railway stations were obtained through the Guihuayun website (http://guihuayun.com/). All data were selected from the year of 1990, 2000, 2010 and 2020. The carbon pool data of land use types in the study area are draw on the relevant research results of domestic and foreign scholars [46–53]. Considering that the carbon density value is affected by soil type, topography, vegetation cover, climate and environment and other factors, this study comprehensively considers the relevant attributes of the investigation area, summarizes and completes the carbon density of it (Supplementary Table 1).

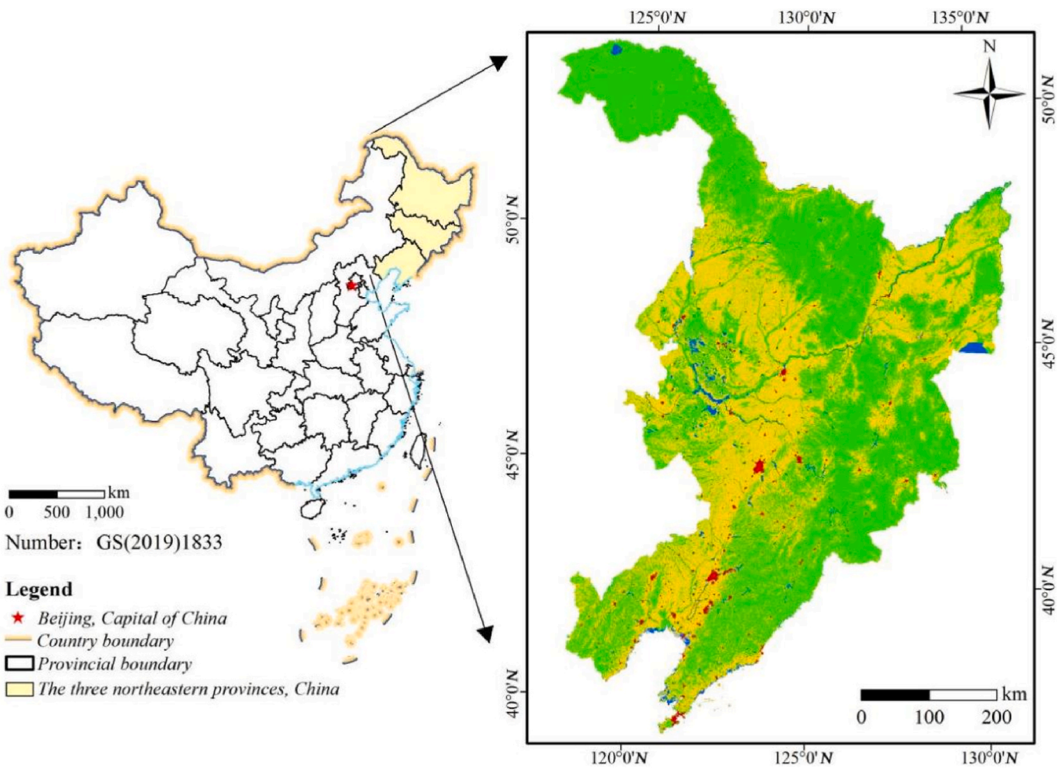


Fig. 1. Map of the study area location and the LUCC of 2020 year.

It should be noted that the administrative center city of the Daxinganling region, Jiagedaqi, is located in the Inner Mongolia Autonomous Region. Considering its special attributes, we finally selected Heihe City government as the reference point for the municipal government of the Daxinganling region in this study, which is the only county-level city in the Daxinganling region.

3. Methodology

3.1. Construction of classification framework of "Production- Living-Ecological Space"

PLES is the land of Production Space, Life Space and Ecology Space, and the initial step of this inquiry commences with the scientific and objective identification of the PLES. As a paramount spatial support for China's territorial space governance, the theoretical connotation of "Production-Life-Ecology" is the basic foundation for PLES' establishment. Specifically, the space of production is dominated by production functions, including the food supply and other living supplies needed by human beings as well as the space for providing primary products; the space of living is dominated by living function, which should meet the needs of human living, transportation, education, medical treatment, entertainment and other living needs, as well as provide non-material services for activities; the space of ecological represent the space with natural attributes, carrying the formation and development of human survival system and natural ecosystem, and providing ecological products or ecological services as the main function [54]. Specifically, the seasonality of the Northeast region makes the field and dryland fallow for half of the year, thus weakening their ecological functions, mainly in the agricultural production function of supplying agricultural products. Urban land is a gathering place for facilities related to the life of urban residents, while rural settlements are a gathering place for facilities related to the life of rural residents, and are thus classified as urban living space and rural living space respectively. The land of the mountains-rivers-forests-farmlands-lakes-grasslands are all completely belong to ecological land, which can be summarized as green ecological space and blue ecological space by their different attributes.

Taking into account the land environment, the main function of land use and the basis of land use division, drawing on Liu Jilai et al. [25], through the assignment method to build the national PLES classification and evaluation system, Chen Meijing et al. [27] and other scholars research results, the PLES in the investigation area are divided as follows (Table 1).

3.2. Theoretical framework analysis

At a microscopic level, the PLES is partitioned in accordance with land use data, so the transformation of it is inevitably influenced by climate, environment and socio-economic aspects. Some scholars have confirmed that elevation, slope, temperature and precipitation are important climatic and environmental factors affecting land change [9,24,55,56]; among the socio-economic factors, population density and regional GDP hold the utmost significance as influential determinants [57–59]. In addition, there is a saying in China: "To be rich, build roads firstly", the idea has been running through the region development, permanently. From the planning point of view, the road has radiation effect, it is not only the link between regions, but also an imperative link between economic and development. Regional development is inseparable from road transportation, the transportation and communication functions of roads also promote the region development. Furthermore, regional development will inevitably change the land use and require spatial adjustment. Therefore, roads also play a significant role in the conversion of PLES, and scholars have proved that the proximity to roads can affect the conversion of land types and the alteration of patterns through empirical studies [43,60,61].

From the perspective of macroscopic, China has emphasized the importance of ecological civilization construction in a series of important meetings and regarded it as a momentous strategic deployment of national construction. In Chinese new developmental epoch, the ecological civilization construction is a key initiative in the overall layout of our nation building and is listed as a serious part of the new journey of socialist modernization with Chinese characteristics. At the same time, the "Two Mountains Theory" as the

Table 1
Classification framework of "Production- Living-Ecological Space" in the three northeastern provinces.

First-level Space	Number	Second-level Space	《National Remote Sensing Monitoring Land Use/Land Cover Classification System》 Secondary Land Type
Production Space	I	Agricultural Production Space	11. Field, 12. Dryland
	II	Industrial Production Space	53. Other Construction Land
Living Space	III	Urban Living Space	51. Town Land
	IV	Rural Living Space	52. Rural Residential Area
Ecology Space	V	Green Ecology Space	21. Forested Land, 22 Shrubbery, 23. Open Forested Land, 24. Other Forested Land 31. High Coverage Grassland, 32. Middle Coverage Grassland, 33. Low Coverage Grassland 61. Sand Land, 62. Saline-alkali Land, 63. Algae Land, 64. Bare Land, 65. Bare Rocky Ground
	VI	Blue Ecology Space	41. Rrivers and Canals, 42. Lake, 43. Reservoir ponds 44. Permanent Glacier Snow Land, 45. Mudflats, 46 Tidal Land 99. Ocean

basic idea and policy for the ecological civilization construction with Chinese characteristics in the new epoch. Further consolidate and deepen the development principle, and then put forward to stick to the principle of the green hills is the development concept of golden hills. With in-depth implementation of ecological civilization and the "Two Mountains Theory", sustainable development is the basic concept of current territorial spatial planning and spatial governance [13,62,63]. Therefore, this study simulated the pattern of PLES under the two modes of Natural-Development Scene and Ecological-Protection-Development Scene, in 2030 and 2060, and then further compared and analyzed.

Subsequent to the aforementioned explanation, the theoretical framework of this study is as follows (Fig. 2).

3.3. Land use dynamic degree

The degree of land use dynamics is able to accurately depict the degree of dynamic change occurring within different land use types. It consists two distinct metrics, namely, single and comprehensive land use dynamic degree. Among them, the former is a description of a certain land use type change in a given region over a certain period [56,64].

The calculation formula is:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

3.4. PLUS model prediction

The PLUS model plays a predictive role in the research. From the algorithm point of view, the PLUS model combines the advantages of TAS and PAS. By extracting the expansion of various types of land use between the two periods of land use change, and sampling from the added part, then adopted the random forest algorithm to mine the factors of expansion and driving of various types of land use one by one, so as to obtain the development probability of different spaces in each period and the contribution rate of each driving factor, as well as to clarify the main driving forces affecting the development of various types of space. The transformation rule is Land Expansion Analysis Strategy (LEAS) [43]. Based on this, based on the CA model (CA based on Multi-type Random Patch Seeds，CARS) to calculate it. Then, after comparing the accuracy based on Markov chain and linear prediction, the final simulation value is brought into the CARS model by using the mean method of the two, next imulating the distribution of future space to improve the prediction ability and explanatory power of the future PLES [65,66].

Random forest algorithm formula is:

$$P_{i,k}^{d}(x) = \frac{\sum_{n=1}^{M} I = [h_n(x) = d]}{M} \tag{2}$$

In formula (2), the variable d is a binary value, taking on a value of either 1 or 0, if $d = 1$, it signifies that there are other secondary spaces transformed into secondary spaces of type k; When $d = 0$, it means that the secondary space is transformed into a secondary space other than k; x is the vector composed of driving factors, Function I is the indicator function of decision tree set; M is the total

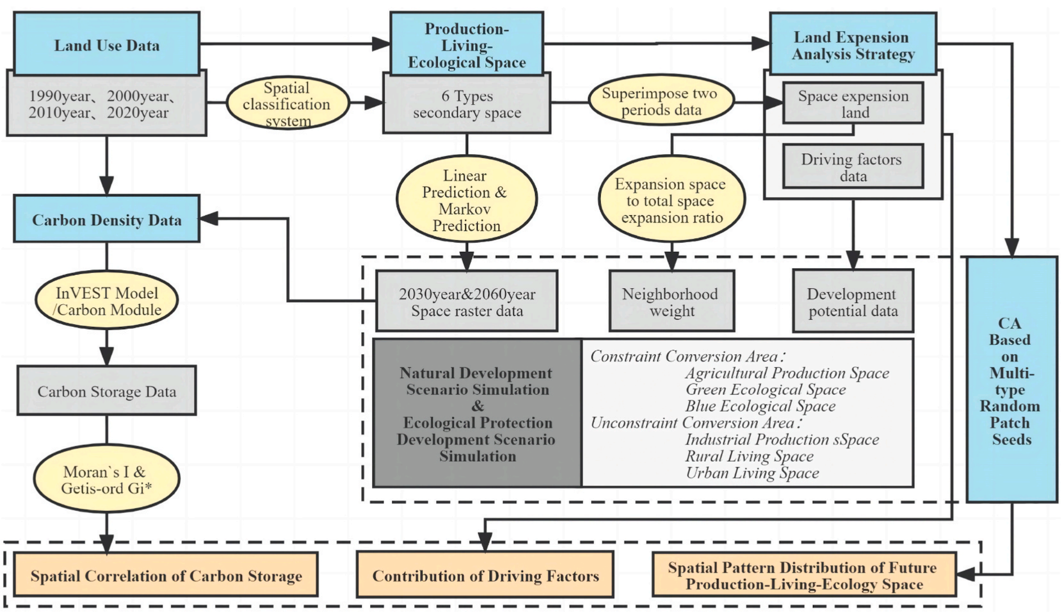


Fig. 2. Theoretical framework diagram.

number of decision trees.

3.5. InVEST carbon stock assessment model

The carbon module of InVEST contains four basic carbon pools are: C_{i_above}, represents aboveground biomass carbon pool, C_{i_below}, represents belowground biomass carbon pool, C_{i_soil}, represents soil organic matter carbon pool, and C_{i_dead}, represents dead organic matter carbon pool [67–69].

InVEST model calculation equation is as follows:

$$C_i = C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead} \tag{3}$$

$$C_{i\_total} = C_i \times S_i \tag{4}$$

$$C_{P\_total} = C_i \times S_P \tag{5}$$

$$C_{L\_total} = C_i \times S_L \tag{6}$$

$$C_{E\_total} = C_i \times S_E \tag{7}$$

In formula (3), C represents the carbon density; S represents the area; P, L and E mean the Production Space, Living Space, and Ecological Space, respectively.

3.6. Spatial correlation analysis based on grid

Exploratory Spatial Data Analysis (ESDA) classified into two categories, namely, Global Spatial Autocorrelation and Local Spatial Aautocorrelation [70,71]. The former can reveal the heterogeneity of factor space, usually represented by Moran's I; and the latter can reflect the cold and hot distribution of variables in local space, usually represented by $\text{Getis} - \text{Ord}\ G_i^*$ [72,73].

The global Moran's I formula is:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})^2} \tag{8}$$

In formula (8), n stand for the number of research units; x_i is the observed value of grid i; x denotes the mean value of all grid cell

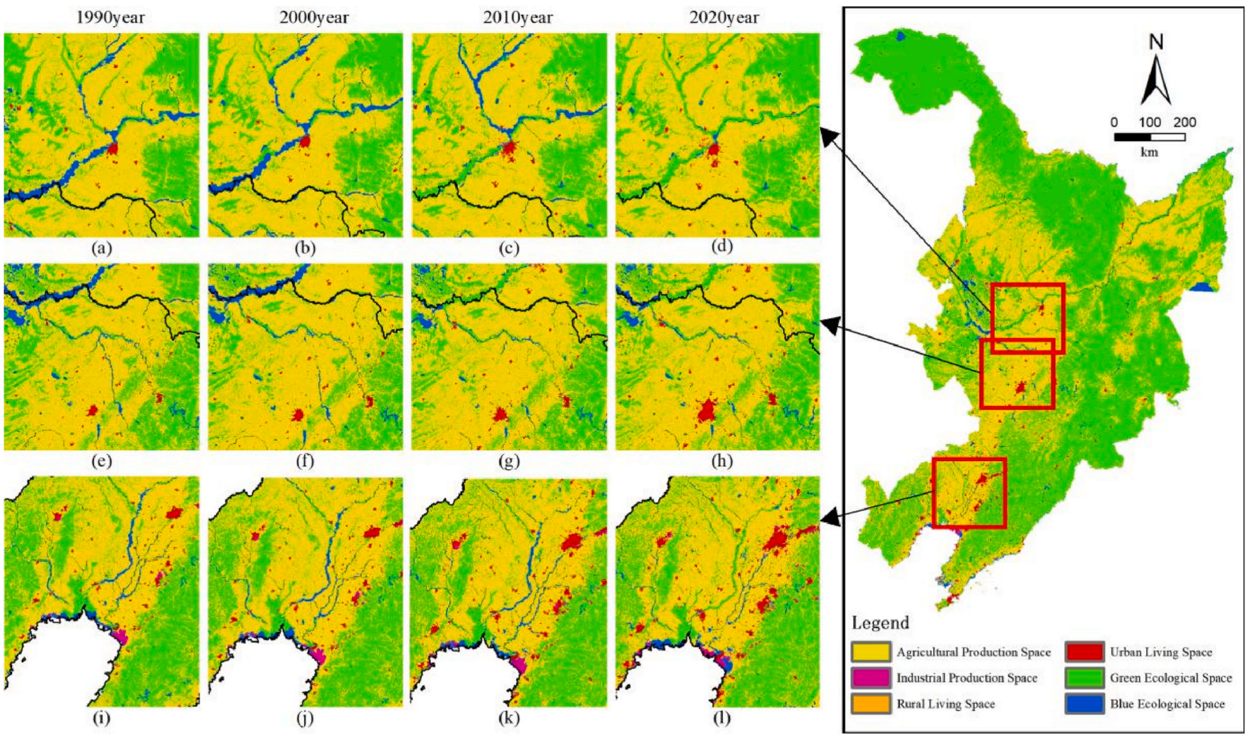


Fig. 3. Distribution pattern of PLES in research area from 1990 to 2020.

observations; w_{ij} indicates the adjacency relationship between grid i and grid j, if grid i is adjacent to grid j, $w_{ij} = 1$; conversely, $w_{ij} = 0$;

The global Getis − Ord G_i^* formula is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \overline{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{9}$$

In formula (9), G_i^* counted the z score, z score greater than 0, and the higher the high value (Hot Spot) cluster of the target object attribute is closer; the lower the z score is less than 0, the low value (Cold Spot) cluster of the target object attributes is closer.

4. Results and analysis

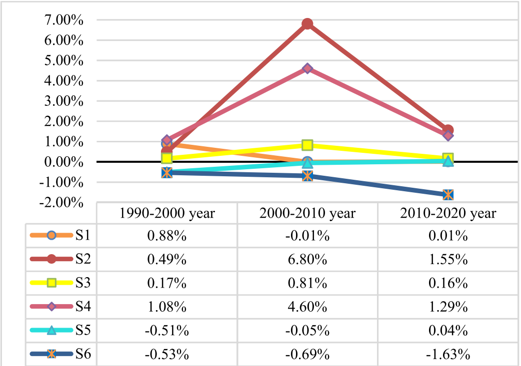
4.1. Analysis on PLES' pattern

The PLES in the investigation area are mainly ecological space and production space, from the data of 2020, the two types of space account for 38.43% and 58.09% of the whole region, respectively, among which the green ecological space and agricultural production space are the most prominent, percentage is 55.71% and 38% of the total area (Fig. 3). As can be seen from Table 2 and Fig. 4, evidently, it is discernible that the most significant spatial changes in the single spatial dynamic attitude across the region are industrial production and urban living space, which are memorably higher than the single spatial dynamic attitude of blue ecological space, rural living space, agricultural production space and green ecological space; among them, industrial production space and urban living space have obvious land expansion; green ecological space and blue ecological space both have a tendency to decline.

This study is based on a single spatial dynamic index (Formula 1) and combines the following two dimensions for specific analysis: (1) Based on the time dimension can clarify the development track of PLES in the investigation area. From Fig. 3, we can see that 2000–2010 is the most prominent period of all kinds of spatial changes. During this period, the single spatial dynamic degree shows: industrial production space > urban living space > rural living space > blue ecological space > green ecological space > agricultural production space, among them, the first three types of space are expanding, the last three types of space are shrinking. Compared with the single space dynamic degree of all kinds of space in each period, the change of industrial production space and urban living space is still intense. This phenomenon is due to the northeast region as a typical old industrial base and an essential resource reserve area in China. The progress of the region's development has been relied on natural resources, iron ore and forests, for example. The development process of green industrial structure is relatively slow, thus gradually forming an industry-oriented development. From the perspective of geographical location, the three northeastern provinces of China have a superior geographical location and borders with many countries. At the same time, they have land ports and sea ports, which greatly contributes to the development of industry. (2) Based on the spatial dimension can depict the pattern distribution of PLES in the investigation area. It can be clearly seen from Fig. 3 that the region with the most dramatic changes in industrial production space is the Bohai Rim Economic Circle in Liaoning Province; the expansion of urban living space is chiefly manifested in the capital cities of the three provinces and their surrounding areas; the rest space changes are dispersed. Considering the historical trajectory of Chinese regional development, the Bohai Rim economic circle is the third uplift zone of Chinese economic development after the Yangtze River Delta and the Pearl River Delta economic circle. In the long-term development, the Bohai Rim economic circle has become the most active region in the three northeastern provinces with its unique geographical advantages and accumulated development system. Urban living space is the most obvious trend of expansion in the study period. Explaining this phenomenon from the field of economics is due to the long-term development of the region, which will first form a siphon effect through the trickle-down effect, over time, due to the uneven and uncoordinated development, the polarization phenomenon will occur, and then the urban living space will continue to expand based on the original location to obtain greater space to carry the driving force needed for regional development: population and resources.

Table 2
Markov transfer matrix and single space dynamic degree of PLES from 1990 to 2020, and 2020 space proportion.

Year/Space Change/hm^2		2020 year						
		Production Space		Living Space		Ecological Space		Total
		S1	S2	S3	S4	S5	S6	
1990 year	S1	249233.00	1143.55	5638.67	2205.50	15705.19	2239.66	276165.55
	S2	65.48	504.35	39.44	134.93	90.52	424.34	1259.06
	S3	3655.28	118.01	13828.26	480.83	555.93	99.40	18737.71
	S4	136.16	17.90	145.16	3234.18	28.50	14.22	3576.11
	S5	45128.64	630.06	1199.72	399.23	414250.51	2436.17	464044.32
	S6	2500.94	221.41	78.50	77.76	9117.42	13542.30	25538.33
	Total	300719.50	2635.26	20929.74	6532.42	439748.07	18756.09	789321.07
2020 year proportion		38.10%	0.33%	2.65%	0.83%	55.71%	2.38%	/
Single land use dynamic degree		0.30%	3.64%	0.39%	2.76%	−0.17%	−0.89%	/



Note: S1, S2, S3, S4, S5 and S6 represent Agricultural Production Space, Industrial Production Space, Rural Living Space, Urban living space, Green Ecological Space and Blue Ecological Space Respectively.

Fig. 4. Dynamic change of PLES in investigation area from 1990 to 2020.
Note: S1, S2, S3, S4, S5 and S6 represent Agricultural Production Space, Industrial Production Space, Rural Living Space, Urban living space, Green Ecological Space and Blue Ecological Space Respectively.

4.2. *Analysis on driving force of PLES's change*

Before driving force analysis, land demand forecasting needs to be carried out. Firstly, extract the expansion land, and bring the two years of the target period into the model to obtain the expansion land of the PLES of the certain period; secondly, forecast the land demand, to augment the authenticity of the outcomes, the accuracy calculation and comparison are carried out before predicting the distribution of PLES in 2030 and 2060, the specific operation is as follows: By 1990 and 2000 PLES' data and 2000 and 2010 PLES' data predicting the distribution of PLES in 2010 and 2020. By comparing with the actual situation, in addition to the large spatial changes such as industrial production space, the predicted value in 2010 is in agreement with the actual value by 91.58%, and the predicted value in 2020 is in agreement with the actual value by 95.25%. Accuracy exceeds 90%, then through the PLUS model （Formula 2）to predict 2030 and 2060 distribution of PLES. This section has two prediction methods: Linear Prediction and Markov Chain Prediction, to make the results more real and reliable, combine the two prediction methods and through the mean method obtain the distribution of PLES in 2030 and 2060. It is worth mentioning that the similarity between Linear Prediction and Markov Chain Prediction is 95.91%. Thus, it can ensure the authenticity of the results of this study.

Next, proceed Land Expansion Strategy Analysis (LEAS). Based on the above-mentioned spatial expansion land data and each driving factor data, by the random forest algorithm and set sampling rate parameter to the highest accuracy of 0.01. Following that, the

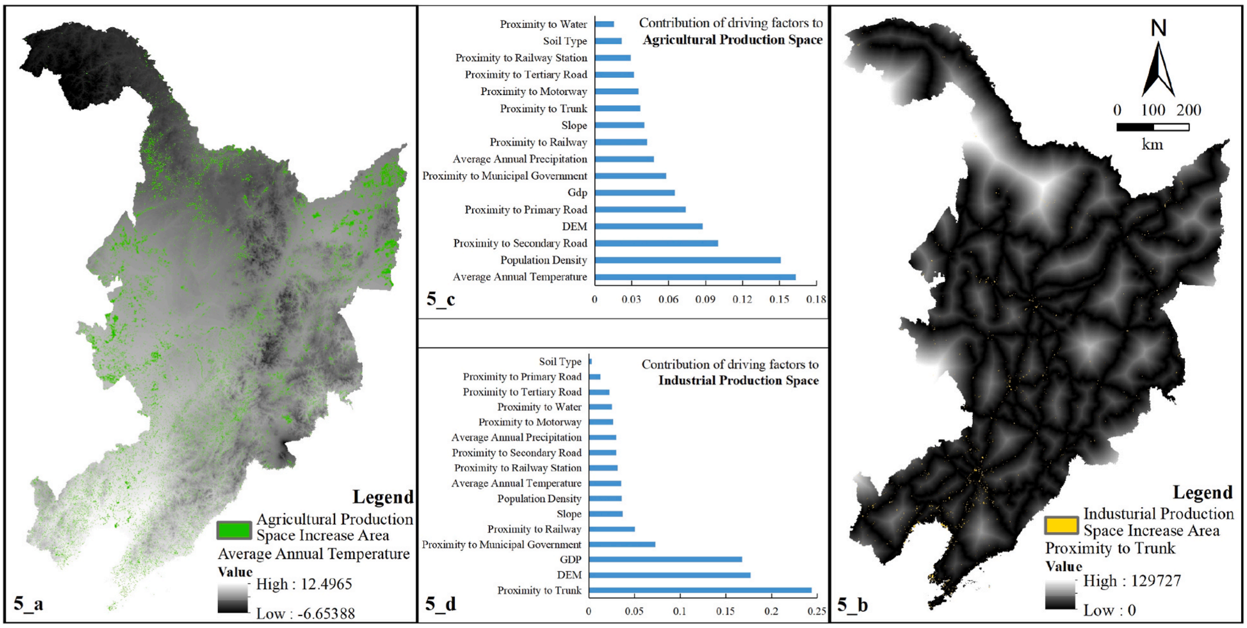


Fig. 5. 5_a is the spatial expansion map of agricultural production space; 5_b is the spatial expansion map of industrial production space; 5_c is the drivers contribution bar chart of agricultural production space; 5_d is the drivers contribution bar chart of industrial production space.

development probabilities of different spaces in each period and the contribution rates of each driver are obtained.

From Figs. 5–7, it can be apparently seen that from investigation period, the coverage of new agricultural production space is wider. Results display that the annual average temperature, population density and proximity to secondary road are the leading driving forces affecting the change of agricultural production space. The specific performance is as follows: the new agricultural production space is principally distributed in the area with higher annual average temperature, the area outside the three provincial capital cities, and the area near the tertiary road. Compared with the agricultural production space, the new industrial production space is more aggregated, and the research results show that the proximity to trunk, elevation and GDP are the main contributing factors of the new industrial production space. Specifically, it is shown that: the closer the area to the trunk, the lower the elevation and the sparser the population density, the more concentrated the new industrial production space. The chief drivers of new rural living space are proximity to tertiary roads, population density and slope, which are general added in areas closer to tertiary roads and areas far away from cities and with gentle slope. The driving factors that contribute the most to the new urban living space are the proximity to the railway station, the population density and the proximity to the railway line. The new urban living space is concentrated in the area closer to the railway station, the area with higher population density and the area closer to the railway line. From the data results, the contribution rate of the first two is significantly higher than the third driving force. The coverage of the newly added green ecological space has obvious gradient, decreasing from southwest to northeast. It can be seen from the visual map that it is mostly concentrated in areas with high annual average temperature, low elevation and sparse population density. The distribution of the new blue ecological space is relatively insignificant, it distributed in areas with higher annual average temperature, lower altitude and closer to the water system, in general.

From a perspective concerning the effects of driving forces on spatial land expansion, the annual average temperature is the most direct influencing factor on the expansion of agricultural production space and ecological space. Population density is the dominant driving force for the expansion of agricultural production space and the two types of living spaces, which are closely related to human lives. In addition, population density is also the first driving force for the expansion of green ecological space, actual performance is the expansion of green ecological space has the highest probability of occurring in regions where population density is lower. Response to this, there are two reasons: one is that the green ecological space will be damaged by human behavior; the second is that the areas with high population density are generally the administrative center and development center of the region. The space of this kind of area is tight and not suitable for green ecological space. The leading drivers of industrial production space and two types of living space, which need to communicate with outside, are related to the distance from the road, extremely. The trunk is mainly used to connect paramount transportation hubs including national roads, provincial roads, and important industrial and mining enterprise production areas and relevant public places and significant locations. For industrial production space, its essential diplomatic demand is transportation, hence closer the proximity to the trunk, the more convenient its transportation. The tertiary road plays a role in connecting local counties and towns, as well as remote suburbs or other functional areas, and is also the first driver of rural living space. For the old industrial city, the railway station is generally the first development area of the city, and the subsequent expansion of town space is basically around the area, so the proximity to the railway station is the main driving power of urban expansion.

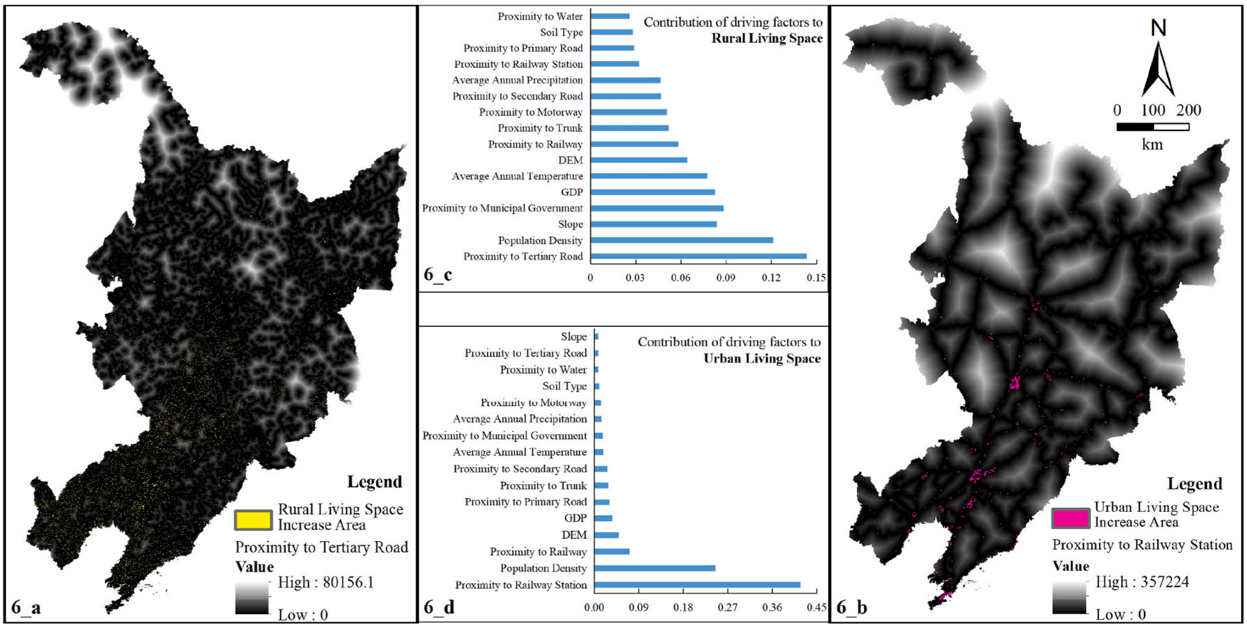


Fig. 6. 6_a is the spatial expansion map of rural living space; 6_b is the spatial expansion map of urban living space; 6_c is the drivers contribution bar chart of rural living space; 6_d is the drivers contribution bar chart of urban living space.

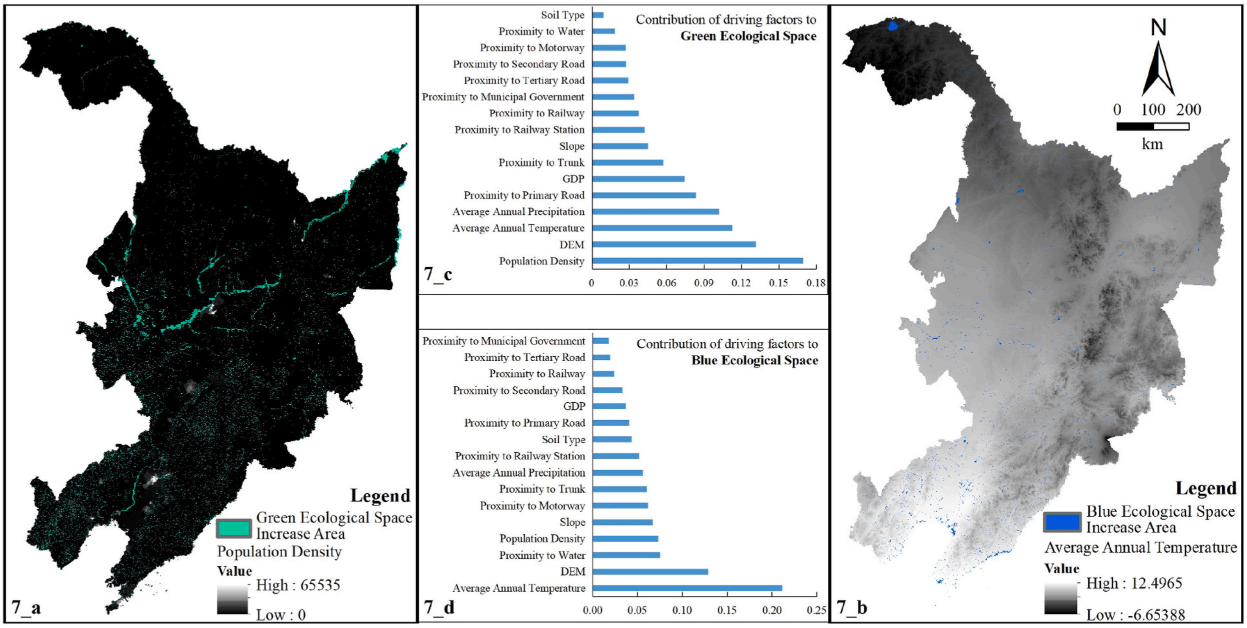


Fig. 7. 7_a is the spatial expansion map of green ecological space; 7_b is the spatial expansion map of blue ecological space; 7_c is the drivers contribution bar chart of green ecological space; 7_d is the drivers contribution bar chart of blue ecological space.

4.3. Analysis on prediction of PLES

After the accuracy comparison based on Markov Chain and Linear Prediction, the final simulation value is brought into the CARS model by using the mean value method of the two to predict the pattern of PLES in 2030 and 2060 in the investigation area, this part is predicted by formula 7, then simulate the layout of future space, so as to improve the prediction ability and explanatory power of future PLES.

Drawing on the theoretical of Ecological-Protection-Development, combined with the foregoing, this study set the constraint

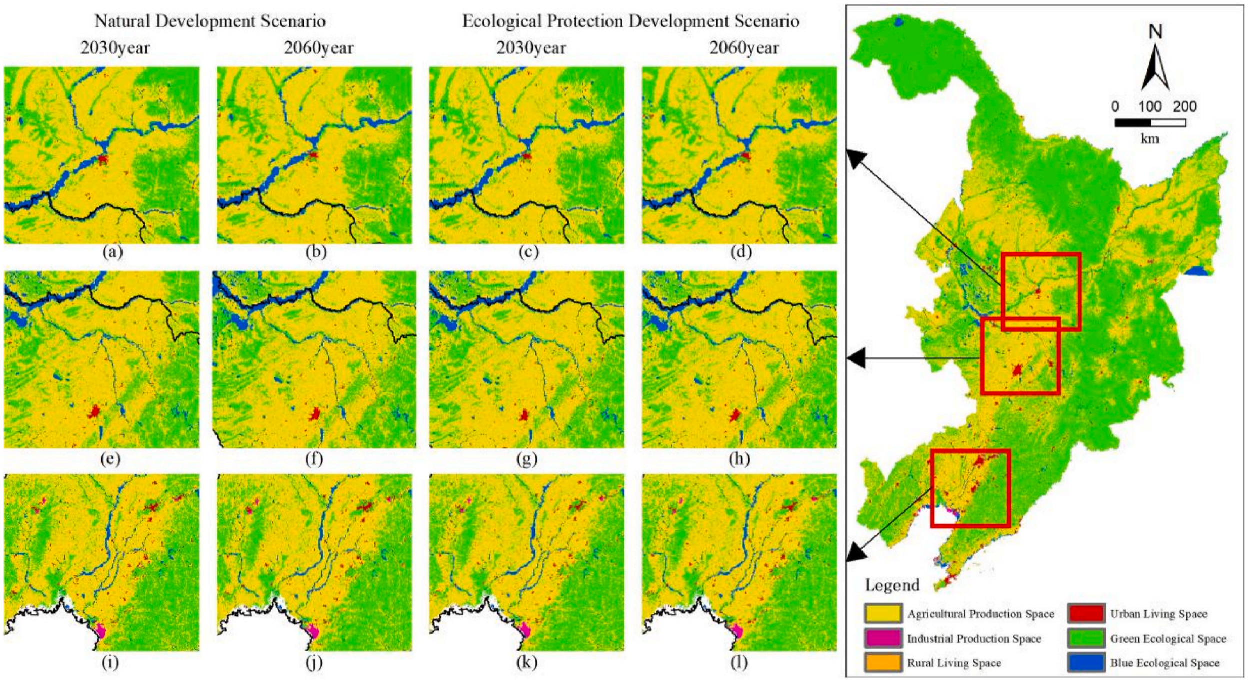


Fig. 8. Prediction of PLES pattern distribution in 2030 and 2060.

conversion area for agricultural production space and two types of ecological space, the remaining three types for unconstraint conversion area. Obtain the pattern distribution map of the PLES in 2030 and 2060 under the Ecological-Protection-Development concept, and make comparison between it with the Natural-Development Scene.

The observation can be deduced from a visual analysis of Figs. 8 and 9 that the urban living space land under the two development scenarios is relatively attenuated, while the two types of ecological space land increase significantly in the forecast years. View of time, the variation in PLES under the two scenarios is not very obvious. The reason for this is that the ecological civilization construction has been one of the overall layouts in China for nearly 10 years, and the relevant policies and strategic deployments have been well developed and implemented, which further indicates that the ecological civilization construction in China has achieved a stage victory. On the other hand, considering the investigation period of this research is the rapid development epoch of Chinese reform and opening up, and enters a new century. After a long period of development and social system reform, the regional development pattern has been basically stable, so the change range and circulation of spatial land use are relatively slow.

4.4. Analysis on spatial correlation of PLES' carbon stock

This paper takes grid as research unit, considering the actual area of investigation area and visualization effect, it was finally decided to divide the study area into 10 km × 10 km grid units through the Create Fishnet of ArcGIS, and then obtain the carbon stock value of each unit grid via the Zonal Statistics. In order to make the research results more objective and real, this research employed secondary land use data to derive carbon density values and subsequently estimate carbon stock, obtained the carbon stock data of each period through the Carbon Module (Formula 3-7) within the InVEST software, and then analyzed the spatial correlation.

In the aspect of spatial correlation, carbon stock' Moran'I values (Formula 8) in the three northeastern provinces from 1990 to 2020 exhibit a totality high measure of above 0.7, which denotes a robust level of interdependence; Moran'I values of carbon stocks in 2030 and 2060 are also greater than 0.7, which means the spatial pattern layout of carbon stock in the investigation area shows a more noticeable clustering. From Fig. 10, the $\text{Getis} - \text{Ord } G_i^*$ (Formula 9) appearance that over the last three decades, it is apparent that the investigation area layout has exhibited distinct differences in distribution with regards to the high and low values of carbon stock. The areas of high-value agglomeration are primarily concentrated within the border regions of the research domain, especially in the border areas between northern Heilongjiang and Russia border area, as well as the western part of the investigation area bordering North Korea. View of the layout of the PLES pattern, above area is mainly a green ecological space concentration area. The locale where in low-value accumulations are predominantly found is primarily situated in the vicinity at the confluence of the research site and the Inner Mongolia Autonomous Region, which is the chief concentration area of agricultural production space and urban living space. The regions with vast changes in the spatial correlation of carbon stock are the northwestern, central, western and southeastern region of the investigation area. Generally, carbon stock has a strong spatial correlation in the investigation region, and is connected to the

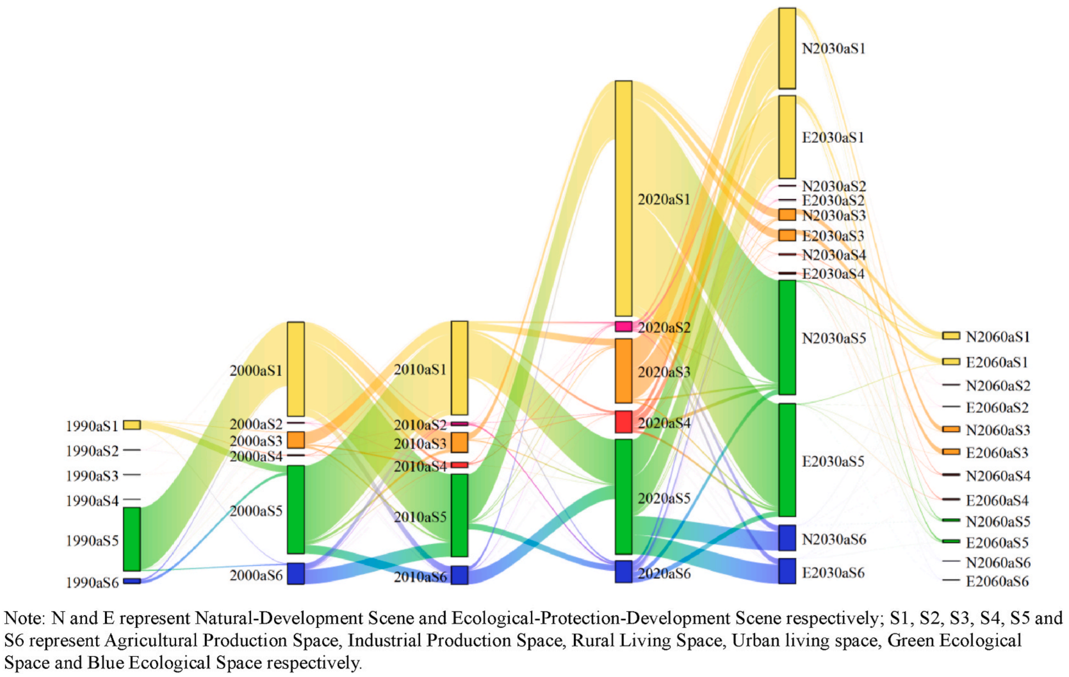


Fig. 9. The flow of PLES in the study area.
Note: N and E represent Natural-Development Scene and Ecological-Protection-Development Scene respectively; S1, S2, S3, S4, S5 and S6 represent Agricultural Production Space, Industrial Production Space, Rural Living Space, Urban living space, Green Ecological Space and Blue Ecological Space respectively.

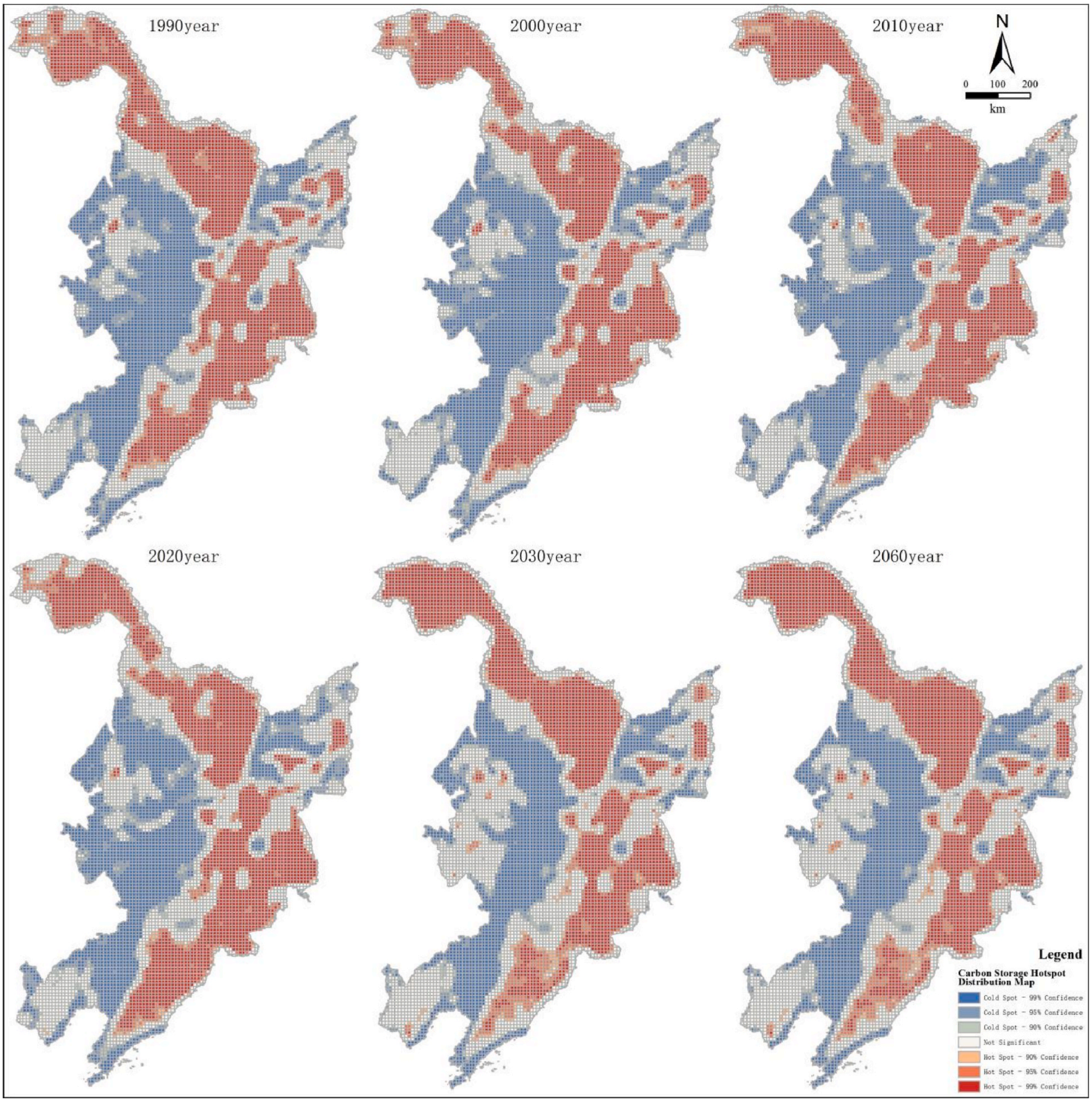


Fig. 10. Hotspot map of carbon stock in PLES of study area.

distribution of PLES intimately. The overall structure shows that overall layout of the high-value-area around the low-value-area.

5. Discussion

This research employs the PLES as the fundamental unit of investigation, and highly combines and applies the PLES spatial structure and the PLUS model, which not only enriches the research system of the PLUS model, but also provides new ideas to carry out territorial spatial research, prediction and simulation research of territorial space, and is conducive to promoting the research related to territorial spatial planning and spatial governance. And the study of carbon stocks' spatial correlation can accelerate the realization of the "double carbon" strategic goal, with a view to actively addressing environmental issues such as global warming.

Overall, the investigation area had the largest share of green ecological space and agricultural production space during the investigation period, and it is predicted that it will be the same trend in 2030 and 2060, which further illustrates that the three northeastern provinces of China are and will be an essential guarantee area and strategic area for China's agriculture and forest resources. Because the three northeastern provinces of China are located between 38°*N* and 52°*N* latitude, this dimension belt will face a cold winter of about 3–4 months in one year, hence, the climatic rivers will freeze, which is not conducive to vegetation survival and agricultural production. Therefore, temperature has emerged as a critical determinant in the process of spatial land conversion in the investigation area. This is consistent with the research conclusions of Yang Xiaojing et al. [22] and Wang Peijuan et al. [74]. They all believe that climate has an important impact on agricultural production in the three northeastern provinces. In addition, the population loss in the three northeastern provinces is serious, and human resources have become one of the scarce resources in the region. This is also evidenced by the study of Lian Xiaomei et al. [75]. Her results show that the current population agglomeration in the study area significantly lags behind the economic agglomeration. Meanwhile, the behavior subject of space land is human, and the relevant policy issuers of space land are also human, the service objects of space land include human. That is to say, the alteration of population structure is bound to variation in space land, analyse from this angle, population density will inevitably become a noteworthy driver in its development. From the research results of Duan Chengrong et al. [17], it is clear that the three northeastern provinces are currently in the stage of negative population growth with a net migration of population, thus inevitably leading to the adjustment of spatial land use. From the prediction results in the Natural-Development scene and the Ecological-Protection-Development scene in 2030 and 2060 respectively, the spatial land pattern in the two scenes is not much different, which in turn shows that the achievement of ecological civilization construction in China has been well achieved.

It can be seen that adhering to ecological civilization is the bottom-line thinking of development, and taking the road of sustainable development is the fundamental way of development. Because the resource-based cities in the study area of the three northeastern provinces account for 58.33%, if the region wants to achieve development, it is necessary to consider the special attributes of resource-based regions. Taking into account the development prospects and existing development conditions of the study area, if we continue to pursue the rapid development of the economy, it must be a radical development at the expense of the city. However, the current development is based on the concept of ecological protection and sustainable development. Therefore, avoiding over-aggressive development and adhering to the slow development model, that is, adhering to a long-term ecological protection development concept is a feasible way for the current development of the three northeastern provinces. Thus, under the guidance of the Dual-Carbon strategy, in order to achieve the Dual-Carbon Strategy goal as soon as possible, the three northeastern provinces of China should follow the pace of national development, break the path of industrial development dependence, innovate new development areas, attract new talents, and retain the labor force. Relatively, weakening the dominance of industry in the study area, bringing into play the land resources advantages. Not only that, but it is also imperative to fortify the crucial standing of the three northeastern provinces in the context of national ecological advancement whilst steadfastly remaining committed to the path of ecological civilization. With a view to enhancing PLES' land use efficiency in the three northeastern provinces, form a new development pattern of production development, affluent life and well ecology, and then revitalize the strategic role of the three northeastern provinces in the new developmental epoch of the country, provide scientific reference for the three northeastern provinces in land space planning and space governance, as well as provide reference for the relevant development of other regions.

6. Conclusion

Depend on the perspective of PLES, this research comprehensively used InVEST model, PLUS model and ArcGIS spatial analysis method to disclose the pattern distribution of the PLES spatial correlation and the spatial correlation of carbon stock in the three northeastern provinces from 1990 to 2020. Then, affirmed the contribution rate of each driving factor to every spatial changes, as well as predicted the pattern distribution and spatial correlation of carbon stock in the study area in 2030 and 2060. The key findings are summarized as follows.

(1) The aspects of spatio-temporal pattern distribution in PLES: the types of PLES in the study area are mainly ecological space (58.09%) and production space (38.43%), among which green ecological space (55.71%) and agricultural production space (38.10%) are the most prominent. Industrial production space (3.60%) and urban living space (2.76%) expanded significantly. The green ecological space (−0.17%) and the blue ecological space (−0.89%) showed a declining trend. However, during the period from 2010 to 2020, the green ecological space was different from the previous period, showing a significant expansion trend. By the period, 2000–2010 is the most dramatic period of spatial transformation of all types and it is reflected that this period is the period of the greatest development changes in the investigation area.

(2) The investigation of the impetus behind the evolution of PLES: the annual average temperature has the most direct impact on the agricultural production space expansion and green and blue ecological space. Population density is not only the main driving force of agricultural production space and two types of living space which are closely related to human life, but also the first driving force of green ecological space expansion. The proximity to the road is the most important driving force for industrial production space and two types of living space, which need to communicate with the outside. And the key drivers are: proximity to trunk, proximity to the tertiary roads and proximity to railway.

(3) In the prediction and analysis of PLES: the land use of urban living space in the predicted year is relatively attenuated in the Natural-Development and Ecological-Protection development scene, the land use of two types of ecological space increases significantly. Under two scenarios, PLES' pattern in the predicted year is relatively stable and the change range is not noticeable, which manifests the success of China's ecological construction in recent years.

(4) In the exploration of the spatial correlation within the carbon stock of PLES: carbon stock' spatial correlation is apparently and has a close correlation with the distribution of PLES. The distribution of high-value area and low-value area showed discernible heterogeneity, the former phenomenon exhibits a noticeable concentration within the northern and eastern perimeters of the examined territory, whereas the latter display is primarily distributed in proximity to the intersection with the Inner Mongolia

Autonomous Region, the spatial land use types in this area are complex and with a high space development intensity. The layout of the study area shows that carbon stock's high value area around the low value area.

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Author contribution statement

Li Qiang: conceived and designed the experiments; performed the experiments. Pu Yuchi: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper. Gao Wei: contributed reagents, materials, analysis tools or data

Data availability statement

Data associated with this study has been deposited at http://www.Resdc.cn; http://www.Resdc.cn; https://www.openstreetmap.org;http://guihuayun.com/.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18923.

References

[1] S.L. Piao, Y. He, X.H. Wang, F.H. Chen, Estimation of China's terrestrial ecosystem carbon sink, Methods, progress and prospects 52 (6) (2022) 1010–1020.
[2] X. Chuai, et al., Carbon neutrality check in spatial and the response to land use analysis in China, Environ. Impact Assess. Rev. 97 (2022), 106893.
[3] A. Goldstein, et al., Protecting irrecoverable carbon in Earth's ecosystems, Nat. Clim. Change 10 (4) (2020) 287–295.
[4] C. Yue, P. Ciais, R.A. Houghton, A.A. Nassikas, Contribution of land use to the interannual variability of the land carbon cycle, Nat. Commun. 11 (1) (2020).
[5] S.L. Piao, C. Yue, J.Z. Ding, Z.T. Guo, Perspectives on the role of terrestrial ecosystems in the "carbon neutrality" strategy, Sci. China Earth Sci. 52 (7) (2022) 1419–1426.
[6] G.S. Zhou, Z.M. Zhou, L. Zhou, Y.H. Ji, Advances in the carbon sink potential of terrestrial ecosystemsin China, Chin. Sci. Bull. 31 (67) (2022) 3625–3632.
[7] P. Hamel, R. Chaplin-Kramer, S. Sim, C. Mueller, A new approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA, Sci. Total Environ. 524–525 (2015) 166–177.
[8] Y. Li, Z. Liu, S. Li, X. Li, Multi-Scenario simulation analysis of land use and carbon storage changes in changchun city based on FLUS and InVEST model, Land 11 (5) (2022) 647.
[9] G. Sharma, L.K. Sharma, Climate change effect on soil carbon stock in different land use types in eastern Rajasthan, India, Environ. Dev. Sustain. 24 (4) (2022) 4942–4962.
[10] T. Toru, K. Kibret, Carbon stock under major land use/land cover types of Hades sub-watershed, eastern Ethiopia, Carbon Bal. Manag. 14 (7) (2019).
[11] H.Z. Pan, T. Yang, Y. Jin, S. Dall'Erba, G. Hewings, Understanding heterogeneous spatial production externalities as a missing link between land-use planning and urban economic futures, Reg. Stud. 55 (1) (2021) 90–100.
[12] P.H. Verburg, J. van de Steeg, A. Veldkamp, L. Willemen, From land cover change to land function dynamics: a major challenge to improve land characterization, J. Environ. Manag. 90 (3) (2009) 1327–1335.
[13] Q. Hao, H.N. Liang, K.Z. Yang, Z.M. Feng, X.Y. Wang, Q.Q. Lu, Innovation of theory and technical method of territory spatial planning in the era of eco-civilization, J. Nat. Resour. 37 (11) (2022) 2763–2773.
[14] J.P. Xi, Building on Past Achievements and Launching a New Journey for Global Climate Actions- Statement at the Climate Ambition Summit, People's Daily, 2020.
[15] T. Rong, P. Zhang, H. Zhu, L. Jiang, Y. Li, Z. Liu, Spatial correlation evolution and prediction scenario of land use carbon emissions in China, Ecol. Inf. 71 (2022), 101802.
[16] X.T. Zheng, S.P. Guang, H.G. Ren, R.L. Xu, B. Xiang, Application of using knowledge graph to explore the knowledge pedigree of the environmental researches in northeast land, Journal of Geo-information Science 23 (6) (2021) 1002–1016.
[17] C.R. Duan, D.Y. Sheng, Study on inter-provincial migration in three provinces of northeast China since 1953—based on survival ratio method, Population Journal 44 (4) (2022) 14–28.
[18] Y.X. Zhang, X.H. Tang, S. Zhou, Study on adjustment and optimization of manufacturing industry structure under multi-constraint of environment, economy and employment—taking northeast China as an example, Reform of Economic System (3) (2019) 86–93.
[19] S.W. An, R.P. Li, Strategic choice of the Northeast revitalization under the background of high-quality development, Reforma 2018 (7) (2018) 64–74.
[20] C.J. Wang, X.M. Li, Y.S. Xie, P.R. Chen, Y. Xu, Strategic path of revitalization development of northeast China under new era, Bull. Chin. Acad. Sci. 35 (7) (2020) 884–894.
[21] W.Y. Dai, F.Q. Jiang, W.L. Huang, L.H. Liao, K. Jiang, Study on transition of land use function and ecosystem service value based on the conception of Production, Living and Ecological Space: a case study of the Fuzhou New Area, J. Nat. Resour. 33 (12) (2018) 2098–2109.

[22] X.J. Yang, Z.X. Xu, D.P. Zuo, S.Y. Cai, Assessment on the risk of agricultural drought disaster in the three provinces of Northeast China, Acta Geograph. Sin. 73 (7) (2018) 1324–1337.
[23] H.Q. Zhang, E.Q. Xu, H.Y. Zhu, An ecological-living-industrial land classification system and its spatial distribution in China, Resour. Sci. 37 (7) (2015) 1332–1338.
[24] D.Y. Kong, H.G. Chen, K.S. Wu, The evolution of "Production-Living-Ecological" space, eco-environmental effects and its influencing factors in China, J. Nat. Resour. 36 (5) (2021) 1116–1135.
[25] J.L. Liu, Y.S. Liu, Y.R. Li, Classification evaluation and spatial-temporal analysis of "production-living-ecological" spaces in China, Acta Geograph. Sin. 72 (7) (2017) 1290–1304.
[26] Q. Ma, Z.R. Wang, Y.H. Zhao, Evolution of spatial-temporal pattern and functional measurement of "production-living-ecological" space in Xi'an, China, Mt. Res. 39 (5) (2021) 722–733.
[27] M.J. Chen, Q.R. Wang, Z.K. Bai, Z.Y. Shi, Transition of "Production-Living-Ecological" space and its carbon storage effect under the vision of carbon neutralization: a case study of Guizhou Province, China Land Science 35 (11) (2021) 101–111.
[28] Q.K. Yang, X.J. Duan, L. Wang, Z.F. Jin, Land use transformation based on Ecological-production-living Spaces and associated eco-environment effects: a case study in the yangtze river delta, Sci. Geogr. Sin. 38 (1) (2018) 97–106.
[29] Z.X. Ji, Y.Q. Xu, A. Huang, Z.H. Lu, Y.M. Duan, Spatial pattern and evolution characteristics of the production-living-ecological space in the mountainous area of northern hebei province: a case study of zhangjiakou city, Acta Sci. Nauralium Univ. Pekin. 58 (1) (2022) 123–134.
[30] Z.Y. Ling, Y.S. Li, W.G. Jiang, C.M. Liao, Y.R. Ling, Dynamic change characteristics of "Production-Living-Ecological Spaces" of urban agglomeration interlaced with mountains,rivers and sea : A case study of the Beibu Gulf urban agglomeration in Guangxi, Econ. Geogr. 42 (2) (2022) 18–24.
[31] B. Feizizadeh, T. Lakes, D. Omarzadeh, A. Sharifi, T. Blaschke, S. Karimzadeh, Scenario-based analysis of the impacts of lake drying on food production in the Lake Urmia Basin of Northern Iran, Sci. Rep.-UK. 12 (1) (2022) 6237.
[32] L. Sankarrao, D.K. Ghose, M. Rathinsamy, Predicting land-use change: intercomparison of different hybrid machine learning models, Environ. Model. Software 145 (2021), 105207.
[33] X. Wu, A. Lin, Y. Li, H. Wu, L. Cen, H. Liu, D. Song, Simulating spatiotemporal land use change in middle and high latitude regions using multiscale fusion and cellular automata: the case of northeast China, Ecol. Indicat. 133 (2021), 108449.
[34] M. Zhao, Z. He, J. Du, L. Chen, P. Lin, S. Fang, Assessing the effects of ecological engineering on carbon storage by linking the CA-Markov and InVEST models, Ecol. Indicat. 98 (2019) 29–38.
[35] J. Jokar Arsanjani, M. Helbich, W. Kainz, A. Darvishi Boloorani, Integration of logistic regression, Markov chain and cellular automata models to simulate urban expansion, Int. J. Appl. Earth Obs. 21 (2013) 265–275.
[36] I. Santé, A.M. García, D. Miranda, R. Crecente, Cellular automata models for the simulation of real-world urban processes: a review and analysis, Landsc. Urban Plann. 96 (2) (2010) 108–122.
[37] D. Guan, H. Li, T. Inohae, W. Su, T. Nagaie, K. Hokao, Modeling urban land use change by the integration of cellular automaton and Markov model, Ecol. Model. 222 (20–22) (2011) 3761–3772.
[38] M.W.A. Halmy, P.E. Gessler, J.A. Hicke, B.B. Salem, Land use/land cover change detection and prediction in the north-western coastal desert of Egypt using Markov-CA, Appl. Geogr. 63 (2015) 101–112.
[39] S. Mansour, M. Al-Belushi, T. Al-Awadhi, Monitoring land use and land cover changes in the mountainous cities of Oman using GIS and CA-Markov modelling techniques, Land Use Pol. 91 (2020), 104414.
[40] S. Wang, X. Zheng, Dominant Transition Probability: Combining CA-Markov Model to Simulate Land Use Change, Environment, Development and Sustainability, 2022, p. 2022.
[41] H. Omrani, B. Parmentier, M. Helbich, B. Pijanowski, The land transformation model-cluster framework: applying k-means and the Spark computing environment for large scale land change analytics, Environ. Model. Software 111 (2019) 182–191.
[42] X. Liu, et al., A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects, Landsc. Urban Plann. 168 (2017) 94–116.
[43] X. Liang, Q. Guan, K.C. Clarke, S. Liu, B. Wang, Y. Yao, Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: a case study in Wuhan, China, Comput. Environ. Urban Syst. 85 (2021), 101569.
[44] X. Li, J. Fu, D. Jiang, G. Lin, C. Cao, Land use optimization in Ningbo City with a coupled GA and PLUS model, J. Clean. Prod. 375 (2022), 134004.
[45] X. Li, Z. Liu, S. Li, Y. Li, Multi-Scenario simulation analysis of land use impacts on habitat quality in tianjin based on the PLUS model coupled with the InVEST model, Sustainability-Basel. 14 (11) (2022) 6923.
[46] H.L. Tian, J.H. Zhu, X. He, X.Y. Chen, Z.J. Jian, C.Y. Li, X.Y. Guo, G.S. Huang, W.F. Xiao, Projected biomass carbon stock of arbor forest of three provinces in northeastern China based on random forest model, Sci. Silvae Sin. 58 (4) (2022) 40–50.
[47] Y.L. Zhu, K. Hu, S. Sun, Y.H. Liu, J.X. Liang, Research on the spatiotemporal variation of carbon storage in the coastal zone of Liaoning Province Based on, InVEST Model. Geoscience. 36 (1) (2022) 96–104.
[48] X. Zhang, Y.X. Li, C.Y. Lv, L. Xia, Y.S. Guo, Y. Wang, C.C. Xu, B. Sun, Research progress on application of ecosystem service functions based on InVEST model, Ecological Science 41 (1) (2022) 237–242.
[49] H.Y. Li, The Evaluation on Ecological Effects of the Project of Returning Farmland to Forest in Liaoning Province, Based on Remote Sensing and InVEST Model, Jilin University, 2019.
[50] L. Xu, N.P. He, G.E. Yu, A dataset of carbon density in Chinese terrestrial ecosystems (2010s), China Scientific Data 4 (1) (2019) 90–96.
[51] C.H. Zhang, L.Y. Wang, Q.W. Song, X.F. Chen, H. Gao, X.Q. Wang, Biomass carbon stocks and dynamics of forests in Heilongjiang Province from 1973 to 2013, China Environ. Sci. 38 (12) (2018) 4678–4686.
[52] Y.D. Pan, R.A. Birdsey, J.Y. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, A large and persistent carbon sink in the world's forests, Science 333 (6045) (2011) 988–993.
[53] J.Y. Fang, A.P. Chen, C.H. Peng, Q. S, L.J. Ci, Changes in forest biomass carbon storage in China between 1949 and 1998, Science 292 (5525) (2001) 2320–2322.
[54] A. Huang, Y.Q. Xu, L.H. Lu, C. Liu, Y.B. Zhang, J.M. Hao, H. Wang, Research progress of the identification and optimizationof production-living-ecological spaces, Prog. Geogr. 39 (3) (2020) 503–518.
[55] S. Cho, B. Mccarl, Major United States land use as influenced by an altering climate: a spatial econometric approach, Land 10 (5) (2021) 546.
[56] Q. Li, Y.C. Pu, Y. Zhang, Study on the spatio-temporal evolution of land use in resource-based cities in three northeastern provinces of China, An Analysis Based on Long-Term Series.Sus 14 (20) (2022), 13683.
[57] G.Y. Jiao, X.Z. Yang, Z.Q. Huang, X. Zhang, L. Lu, Evolution characteristics and possible impact factors for the changing pattern and function of "Production-Living-Ecological" space in Wuyuan county, J. Nat. Resour. 36 (5) (2021) 1252–1267.
[58] X.Y. Liang, L.H. Yuan, L.X. Ning, C.Q. Song, C.X. Cheng, X.Y. Wang, Spatial pattern of habitat quality and driving factors in Heilongjiang Province, J. Beijing Normal Univ. (Nat. Sci.) 56 (6) (2020) 864–872.
[59] L. Zhu, J.M. Cheng, J. Jin, L.C. Fei, J. Cheng, Space differentiation patterns and influencing factors of "Ecological-Living-Industrial" land use structure-based on the panel data of 284 cities, Chinese Journal of Agricultural Resources and Regional Planning 39 (8) (2018) 105–115.
[60] D. Liu, L.L. Qu, L.N. Li, Spatial-temporal characteristics of land use change in the northern border transect of Heilongjiang Province, China Journal of Beijing Normal University(Natural Science) 57 (3) (2021) 417–423.
[61] F. Luo, A. Pan, Z.S. Chen, Y.H. Wang, Spatiotemporal pattern change of cultivated land and its driving factors in Yibin City, Sichuan Province during 1980-2018, Bull. Soil Water Conserv. 41 (6) (2021) 336–344.
[62] Q. Li, J.S. Xiao, K.Z. Yang, On the Theoretical system of territorial spatial planning in the era of ecological civilization, Urban Stud. 28 (6) (2021) 41–49.
[63] J. Xiong, K. Lu, Z.Y. Jiang, Y. Zhag, Q.L. Fu, Y. Jin, Study and thoughts on territorial spatial planning under the goal of "carbon emissions peak and carbon neutrality, Urban Planning Forum (4) (2021) 74–80.

[64] Y. Zhou, X.H. Li, Y.S. Liu, Land use change and driving factors in rural China during the period 1995-2015, Land Use Pol. 99 (2020), 105048.
[65] J.N. Wang, W. Wang, C. Zhang, S. S, Y.Y. Wang, Z.H. Sun, B.L. Wu, Spatial and temporal changes and development predictions of urban green spaces in Jinan City, Shandong, China, Ecol. Indicat. 152 (2023), 110373.
[66] Y. Yu, B. Guo, C.L. Wang, W.Q. Zang, X.Z. Huang, Z.W. Wu, M. Xu, K.D. Zhou, J.L. Li, Y. Yang, Carbon storage simulation and analysis in Beijing-Tianjin-Hebei region based on CA-plus model under dual-carbon background, Geomatics, Nat. Hazards Risk 1 (14) (2023), 2173661.
[67] Y. Zhang, X.G. Li, Y.L. Wen, Forest carbon sequestration potential in China under the background of carbon emission peak and carbon neutralization, J. Beijing For. Univ. 44 (1) (2022) 38–47.
[68] L. Ma, T.T. Jin, Y.H. Wen, X.Q. Wu, G.H. Liu, The research progress of InVEST model, Ecol. Econ. 31 (10) (2015) 126–131.
[69] Peter Kareiva, Natural Capital: Theory & Practice of Mapping Ecosystem Services, Oxford University Press, USA, 2011.
[70] L. Li, J.F. Li, X.L. Wang, S.J. Sun, Spatio-temporal evolution and gravity center change of carbon emissions in the Guangdong-Hong Kong-Macao greater bay area and the influencing factors, Heliyon 9 (6) (2023), e16596.
[71] R. Haining, S. Wise, J.S. Ma, Exploratory spatial data analysis in a geographic information system environment, Journal of the Royal Statistical Society. Series D (The Statistician) 3 (47) (1998) 457–469.
[72] T. Lin, M.Z. Yang, D.F. Wu, F. Liu, J.H. Yang, Y.J. Wang, Spatial correlation and prediction of land use carbon storage in guangdong province based on InVEST-PLUS model, China Environ. Sci. 42 (10) (2022) 4827–4839.
[73] Y. Dou, X. Luo, L. Dong, C.T. Wu, H.W. Liang, J.Z. Ren, An empirical study on transit-oriented low-carbon urban land use planning: exploratory Spatial Data Analysis (ESDA) on Shanghai, China, Habitat Int. 53 (2016) 379–389.
[74] P.J. Wang, L.J. Han, G.S. Zhou, H. Liang, The effects of climate warming on different cultivars of spring maize under climate warming in Northeast China and the adaptation countermeasures, J. Nat. Resour. 30 (8) (2015) 1343–1355.
[75] X.M. Lian, J.H. Wu, Dynamics of spatial pattern between population and economies in Northeast China, Population Journal 40 (1) (2018) 45–55.