Trade-offs and driving forces of land use functions in ecologically fragile areas of northern Hebei Province: Spatiotemporal analysis

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Abstract

Climate change, urbanization, and industrialization have caused severe conflicts in land use functions (LUFs) in Chinese ecologically fragile areas. The coordination of LUFs is of great significance to optimize national territory space. This study proposes an index system to assess LUFs and their conflict/coordination relationship at the grid-scale based on multi-source data characterizing land-use, geography and socio-economy. The geographic detector model is used to identify the driving forces associated with LUFs changes. Zhangjiakou City, a typical ecologically fragile area in North China, is selected as an empirical study area. The results show that during 1990–2015, land-use economic, social, and ecological functions greatly enhanced, especially the social function. Additionally, LUFs are spatially heterogeneous and clustered due to the terrain and socio-economic conditions. Among three LUFs, Land-use economic and social functions primarily display coordination. Land-use ecological and economic functions, as well as ecological and social functions, are coordinated in mountainous and hilly areas, while are conflicted in the Yang River valley. The driving mechanisms of multiple LUFs originate from spatially different coupling of natural conditions and anthropic activities, but economic development and social life are primarily responsible for LUFs changes. Policymakers are suggested to optimize ecological–living–production spaces by coordinating LUFs. Thus, this study can help mitigate LUFs conflicts and further improve the harmonization of ecological–living–production spaces.

1. Introduction

Land use functions (LUFs) refer to the private and public goods or services provided by diversified land uses (Pérez-Soba et al., 2008; Fan et al., 2018). As the land-use system’s feedback on the change of environment and human needs, LUFs study prioritizes human-earth system science concerning social and environmental issues (Meng et al., 2019). The prosperity of the Chinese economy and society has mostly been at the cost of overutilization and destruction of national territorial space (Liu et al., 2014; Jiang et al., 2020). With the national spatial planning proposal, China’s urban-rural planning system (dominated by production space exploitation) has turned to new national spatial development, in which ecological, living and production spaces are coordinated (Liu, 2018). The national territory space is essentially functional space determined by LUFs (Huang et al., 2020). Conflicts in LUFs have posed tremendous threats to ecological security and national territory space development.

In general, LUFs present connotations related to economic, social, and environmental fields, thereby divided into three subcategories: economic, social, and ecological functions (Pérez-Soba et al., 2008; Paracchini et al., 2011; Xue et al., 2019). Two methods are primarily applied into LUFs evaluation study. One is the land-use types merging (LUTM) method that merges land-use types with similar functions (Dai et al., 2018). The other is the multi-factor comprehensive appraisal (MFCA) method with an index system through statistical data (Pérez-Soba et al., 2008; Wang and Dong, 2015). However, the MFCA method assesses LUFs at the administrative units level, which is not detailed enough to support decision-making processes. Although the LUTM method can be used in greater detail at the grid level, it fails to accurately indicate the social and economic significance (Krovakova et al., 2015). Therefore, in this study, an effort has been made to propose a new index system to assess LUFs at the grid-scale.

LUFs present complex trade-offs relationships that reflect the state of coordination and conflict among LUFs (Willemen et al., 2010; Zhou et al., 2017; Zhang et al., 2019). Nevertheless, most of the existing researches focus on the trade-offs analysis of land ecosystem services (Lu
et al., 2014; Li et al., 2018). As LUFs involve more social and economic aspects, the quantity, pattern, transformation and coordination of LUFs were studied (Liu et al., 2016; Li et al., 2019) to understand the coordination or conflict relationship of LUFs. However, to our knowledge, bare have investigated the nonlinear relationship and the spatial pattern characteristics of multiple LUFs from the perspective of spatial heterogeneity.

There is increasing awareness that the mechanisms of how human–natural factors affect LUFs have become of considerable significance to sustainable land management (Callo-Concha and Denich, 2014; Liu et al., 2019a; Peng et al., 2016). Some scholars have constructed the framework to analyze the impacts of LUFs changes driven by policies (Purushothaman et al., 2012; O’Sullivan et al., 2015). Quantitative analysis of human–natural factors driving LUFs changes has been conducted based on statistical variables (Sun et al., 2017; Duan et al., 2020). It is found that spatial non-stationarity of LUFs is closely related to the complexity of human-natural factors. However, identifying the spatial heterogeneity of these factors and estimating their coupled contributions to LUFs changes is still challenging. A geographical detector model was first proposed by Wang et al. (2010) to identify the intensity of environmental factors’ effect on health outcomes. The model is a spatial variation analysis model based on the theory of spatial heterogeneity. It has been used to explore driving forces and their interaction in ecosystem service, and land-use research (Liu et al., 2019b; Qu et al., 2019). Therefore, we attempt to apply the geographical detector model for assessing the interaction of human–natural factors to better understand the spatial non-stationarity of LUFs.

Chinese ecologically fragile areas are an important part of the national territory space and are also key areas for the study of human-earth system dynamics (Liu, 2020). Rapid urbanization and industrialization have caused resource scarcity, ecosystem degradation, and LUFs conflicts (Peng et al., 2011; Long et al., 2018). Zhangjiakou City, in Hebei Province, China, is a demonstration zone of national-level ecology, where is an ecologically fragile area with slow economic development (Huang et al., 2019). Along with implementing of the Coordinated Development of the Beijing–Tianjin–Hebei Region strategy, and being the joint host of the 2022 Winter Olympics, the city has experienced unprecedented changes in the socio-economic system. As a result, the dramatic expansion of construction land threatened to local agricultural production and ecosystem functions. Therefore, optimizing the territory space, it is imperative to understand the trade-offs and the driving mechanisms of LUFs in Zhangjiakou City, and has reference meaning for other ecologically fragile areas. Correspondingly, we take spatial correlation into account when constructing LUFs trade-offs model to identify the complex relationships of LUFs. In addition, a geographical detector model was adopted to explore the interaction of human-natural...
factors driving LUFs changes. The objectives of the study are to (1) develop an integrated index system based on multi-source data characterizing land-use, geographic and socio-economic information for evaluating LUFs at the grid-scale; (2) analyze the spatiotemporal changes and coordination/conflict relationships of multiple LUFs in the change of land-use economic, social, and ecological factors; (3) investigate the driving factors and the effects of their interactions on the change of land-use economic, social, and ecological functions; and (4) propose policy implications for relieving LUFs conflicts and coordinating ecological-living–production spaces.

2. Materials and methods

2.1. Study area

Zhangjiakou City, located in the northwest of Hebei Province, is upstream (in terms of wind and water) of Beijing. The city contains 17 administrative counties (districts) in 2015, covering an area of 3.68 × 10^5 km^2 (Fig. 1). The terrain is divided into the Bashang Plateau and the Baxia Basin. It is an ecologically fragile area with severe drought and soil erosion (Wang et al., 2020). The Three North Shelterbelt and Grain for Green projects have been implemented in an attempt to improve the ecological environment.

Zhangjiakou City is part of the poverty belt around Beijing and Tianjin. Poverty-stricken villages and population account for 23.4% and 17.34% of those in Hebei Province, respectively. In recent years, Zhangjiakou City has become an important place for industrial relocation and functional decentralization from Beijing and Tianjin. The food processing, energy generation, metallurgy and mining, and equipment manufacturing are becoming dominant industries. However, economic development and ecological restoration have intensified ecology, agriculture, and urban land-use contradiction, resulting in conflicts in LUFs (Liu et al., 2018; Ma et al., 2020).

2.2. Methodology

2.2.1. Preparing the data

Multi-source data such as land-use, geographic, and socio-economic data are used for evaluating each land use function (LUF) (Table 1). Two Landsat-Thematic Mapper™ images from 1990 and 2000, and one Operational Land Imager (OLI) image from 2015 were interpreted to obtain land-use data. The interpretation accuracies (86.82%, 88.92%, and 86.38%) and the Kappa coefficients (0.84, 0.87, and 0.83) meet the cut-off values. The types of land use were divided into arable land, orchard land, forestland, grassland, urban–rural construction land, transportation land, water area, and unused land. The monthly meteorological data, collected from 20 meteorological stations, were spatially interpolated using a thin-plate spline algorithm, and then clipped by the city’s boundary. The Advanced Very-High Resolution Radiometer (AVHRR) Vegetation Index and Phenology (VIP)15 V004 normalized difference vegetation index (NDVI) layers were processed with a linear method and was then combined with monthly data for MOD13Q1 NDVI layers for a year using maximum value composites. The resolution of the monthly Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data was 250 m after project transformation. In addition, a map of total solar radiation, sunshine duration, temperature, and precipitation was obtained using the kriging interpolation method in ArcGIS 10.4. The grid method calculates the data’s attribute values in the geographic grid to realize the spatial fusion of multi-source data and model construction. A fishnet (1 km × 1 km) covering the whole administrative unit was produced in ArcGIS 10.4.

2.2.2. Developing an index system for evaluating LUFs

The land-use system is a complex functional system comprising natural, economic, and social subsystems; therefore, it has ecological, economic, and social functions (Kienast et al., 2009; Xie et al., 2010). From the perspective of human well-being, LUFs are the goods and services containing economic value as they serve social-economic needs of humanity (Zhang et al., 2019). The economic value of LUFs includes the commodity value and service value, and can be measured using the market price (de Groot et al., 2012). Therefore, LUFs valuation is the process of converting tangible products and invisible services into monetary value, which comprehensively describes the relationship between LUFs and human well-being. For economic function, the value means land and its appurtenances are utilized to exchange goods and develop the economy (Liu et al., 2018). Social function refers to the sufficient food and comfortable places provided by land use to meet the basic demands of human survival and development. Ecological function refers to the environmental conditions, ecological resources, and other services provided by land use (Zou et al., 2020).

Considering land-use conditions, economic development, people’s livelihood, and ecological protection in Zhangjiakou City, LUFs can be divided into economic, social, and ecological functions, from the aspects of material production, life security, and ecological conservation. In Zhangjiakou City, economic development is necessary to be promoted by improving the economic benefits of land use (Liu et al., 2018). Therefore, in terms of land-use economic function, two indicators of agricultural production and non-agricultural production are selected to represent the economic value produced by agriculture, and secondary and tertiary industry activities, respectively. The city is the main agricultural product supply base and ecological environment supporting area for the Beijing–Tianjin–Hebei region (Song et al., 2018). Ensuring the security of food and ecology is fundamental to provide better living conditions. Hence, for the social function, two indicators of food supply and residence support are selected to represent the service of land use to the people in the city.
ensure food security and space load. In terms of ecological function, it can be calculated by the two indicators of soil conservation and gas regulation, which indicates the services of soil and water conservation and clean air provided by land use, respectively.

The economic value of LUFs can be calculated using the direct market method, the indirect market method, and other monetization methods based on the results of physical quantity accounting (Campbell and Tilley, 2014; Huang et al., 2019). And the calculation methods for the LUFs indicators are shown in Table A1 in Appendix A. The indicators chosen in this study are of equal importance because they are indispensable products and services provided by land use in Zhangjiakou City, and play equally positive roles as an important part of each function. Thus, the corresponding indicators are given equal weighting to calculate the three individual functions using the comprehensive evaluation method. The formula is as follows:

\[
FUN_i = \sum_{j=1}^{2} IND_j W_{ij}
\]

where \( FUN_i \) is the value of LUFs, \( IND_j \) is the value of indictor \( j \) of LUFs, and \( W_{ij} \) is the weight of indictor \( j \) of LUFs (0.5).

2.2.3. Exploring coordination/conflict among LUFs

A complicated relationship of coordination or conflict exists in LUFs affected by different demands of interest (Zhang et al., 2019), which shows regional differences and dynamic changes. Consequently, a LUFs trade-offs analysis model referring to the Bivariate Local Moran’s I model (Anselin, 2017), is employed to analyze the relationships among LUFs (Ji et al., 2019). The Bivariate Local Moran’s I model is as follows:

\[
I_i = \frac{Z_i}{\sum_z n} \sum_j W_{ij}(y_j - \bar{y})
\]

where \( Z_i = x_i - \bar{x}, x_i \) and \( y_j \) are the different function values of grids \( i \) and \( j \), respectively. \( \bar{x} \) and \( \bar{y} \) are the mean values of different function values of all grids \( i \) and \( j \), respectively. \( n \) is the number of grids, and \( W_{ij} \) is the spatial adjacent weight matrix between each grid \( i \) and \( j \). According to the spatial clustering feature, the correlation of LUFs representing high–high or low–low value clusters is defined as the coordinated relationship. While the correlation of LUFs representing high–low or low–high value clusters is defined as the conflicted relationship.

2.2.4. Selecting initial driving factors behind LUFs changes

Building on previous studies (Callo-Concha and Denich, 2014; Sun et al., 2017; Liu et al., 2019b), and in line with the natural condition perspective and the anthropic activity perspective, 13 exploratory spatial variables concerning LUFs changes were selected (Fig. 2). Natural conditions constitute the prerequisites of the variation in LUFs. Thus, six variables are incorporated to represent environmental limitation and geographical location: altitude, slope, annual precipitation, traffic accessibility, urban center radiation, and water resource accessibility. Altitude and slope were extracted from the digital elevation model that represented terrain characteristics. Annual precipitation (hereafter referred to as “precipitation”) was spatially interpolated using a thin-plate spline representing regional meteorological characteristics. Traffic accessibility, urban center radiation, and water resource accessibility were the spatial distance to the nearest road, county town, and water area, respectively. They were calculated using the spatial analysis module of ArcGIS to represent the geographical location characteristics.

Given that anthropic activities have an important influence on the intensity of LUFs changes, seven variables were selected to represent economic development and social life: economic aggregation, industrialization, agricultural modernization, social investment, population, urbanization rate, and residents’ consumption. From an economic development perspective, the economic aggregation was indicated by grid handling GDP. Industrialization was taken as the proportion of industrial added value in the total GDP of the whole county; agricultural modernization was indicated by the total power of agricultural machinery in the whole county; and social investment was characterized by total investment in fixed assets in the whole county. Population was the total population in the whole county, urbanization rate was calculated from the proportion of the urban population in the total population, and residents’ consumption was the total retail sales of consumer goods in the whole county.

2.2.5. Identifying driving factors of LUFs changes using a geographic detector model

The geographical detector model could test the associations among the explanatory variables and the dependent variables by analyzing the spatial distribution consistency. The model includes four components: the factor detector, the risk detector, the ecological detector, and the interaction detector. In this paper, the factor detector and interaction detector were used to examine the spatial driving factors of each LUF (economic, social, or ecological function) change and the factors’ interaction effect. The factor detector model is as follows:

\[
Q = 1 - \sum_{i=1}^{N_1} \frac{N_i \sigma_i^2}{N}\]

where \( Q \) is the power of the driving factors, ranging from 0 to 1; the higher the \( Q \) value, the greater the effect the explanatory variables have. \( i = 1, \ldots, L \) is the number of explanatory variables to be divided (strata). \( N \) and \( N_i \) are the sample sizes of the whole study area and each stratum, respectively. \( \sigma^2 \) and \( \sigma_i^2 \) are the variances of each LUF change in the whole study area and each stratum, respectively.

The interaction detector can test the interaction of different factors, and to identify the interaction of two factors. The calculation method is as follows. First, the \( Q \) value of two driving factors \( X_a \) and \( X_b \) to \( Y \), namely \( Q(X_a) \) and \( Q(X_b) \), is calculated. Second, the \( Q(X_a \cap X_b) \) value is calculated when they interact. Third, \( Q(X_a), Q(X_b), Q(X_a \ast X_b) \),
and $Q(Xa \cap Xb)$ are compared, and their relationship divided into five categories (Table 2).

### Results

#### 3.1. Changes in LUFs in Zhangjiakou City from 1990 to 2015

##### 3.1.1. Changes in the total amount of LUFs

The overall magnitude of land-use economic, social, and ecological functions in Zhangjiakou City increased over the period 1990–2015 (Table 3). The value of land-use economic and social functions rose rapidly (by an annual average of 76.28% and 84.32%, respectively), amounting to 486.51 × 10^8 Chinese Yuan (CNY) and 2886.20 × 10^8 CNY in 2015, respectively. Further, the growth rates of the values of the economic and social functions during 2000–2015 were 2.14 times and 2.90 times the values in 1990–2000, respectively. The land-use ecological function increased slightly from 144.8 × 10^8 CNY in 1990–184.95 × 10^8 CNY in 2015 at an annual average of 1.11%.

##### 3.1.2. Changes in spatial patterns of LUFs

There was significant spatial heterogeneity among the three types of LUFs (Fig. 3). Land-use economic and social functions were similar in overall spatial pattern. Their high-value areas were centralized in the Yang River valley and the central area of each county, such as Xuanhua county, Xuanhua district, Huailai county, and Qiaodong district due to the strong economic development and abundant arable land. However, the low-value areas were concentrated in the eastern and southeast hilly areas, where there were poorer agricultural production conditions and living infrastructure, but more forests and grasslands. Noteworthy, the spatial distribution of the ecological function was opposite to that of the economic and social functions due to the socio-economic and natural conditions.

As shown in Fig. 4, most regions in Zhangjiakou City displayed an increase in the land-use economic function. The economic function growth contributed 83.01% of the total growth in 1990–2000 and 97.53% in 2000–2015. In terms of land-use social function, the proportion of regions with degradation (45.78%) was slightly higher than that of regions with improvement (43.28%) during 1990–2000. This was due to the drought taken place in 1999. Meanwhile, geographical location, such as traffic accessibility (0.451), urban center radiation (0.403), and water resource accessibility (0.390), were the strongest, it became weaker compared with that of 1990. To identify the factors affecting land-use economic, social, and ecological functions, the factor detector and interaction detector models were used to estimate the impact of the 13 factors in 1990–2000 and 2000–2015, respectively. In the models, the dependent variable was the change value of each function, whereas the explanatory variables were the 13 factors. The results show that all 13 driving forces had a significant effect on the change of each function at the 0.01 significance level.

#### 3.2. Analyzing coordination/conflict among LUFs

As illustrated in Fig. 5, during 1990–2015, the relationship between the land-use economic and social functions was mainly coordinated, and the area ratio in Zhangjiakou City increased from 28.38% to 33.70%. The coordination relationship occurred mainly in the Yang River valley and eastern mountains. It is worth noting that the spatial imbalance of land-use economic and social functions was still intensive, characterized by the area of the conflict relationship between them, which declined in 1990–2000 and increased in 2000–2015.

For land-use economic and ecological functions, the area of the conflict relationship contributed to 32.51% and 26.53% of the total area in 1990 and 2015, respectively, which were 1.22 times and 1.28 times the coordination relationship, respectively. However, the area ratio of the coordination relationship between land-use economic and ecological functions was 34.17% in 2000, which was 1.06 times the conflict relationship. Therefore, the conflict relationship between land-use economic and ecological functions was dominant in 1990 and 2015, while the coordination relationship was dominant in 2000.

In terms of land-use social and ecological functions, the coordination relationship prevailed in 1990, accounting for 42.04% of the total area. While the conflict relationship played a leading role in 2000 and 2015, the area proportion increased from 42.36% to 43.49%. Notably, the conflict relationship between economic and ecological functions and social and ecological functions mainly occurred in the Yang River valley and eastern mountains, while their coordination relationship was mainly in Bashang Plateau.

#### 3.3. Identifying driving factors associated with LUFs changes

To identify the factors affecting land-use economic, social, and ecological functions, the factor detector and interaction detector models were used to estimate the impact of the 13 factors in 1990–2000 and 2000–2015, respectively. In the models, the dependent variable was the change value of each function, whereas the explanatory variables were the 13 factors. The results show that all 13 driving forces had a significant effect on the change of each function at the 0.01 significance level.

##### 3.3.1. Driving factors of land-use economic function change

The detected factors within economic development and social life had much greater effects on the economic function change compared to environmental limitation and geographical location (Fig. 6). From 1990–2000, the leading driving factors (the top three Q values) were economic aggregation (0.845) > population (0.691) > urbanization (0.535), while the weakest determinant was water source accessibility (0.159). During 2000–2015, economic aggregation (0.753) showed the strongest effect, followed by industrialization (0.643) and population (0.476). Although the influence of the economic aggregation was still the strongest, it became weaker compared with that of 1990–2000. Meanwhile, geographical location, such as traffic accessibility (0.451), urban center radiation (0.403), and water resource accessibility (0.390), had an increasing influence on the change in the land-use economic function.

The interactions of 78 pair factors were bivariate enhanced or

### Table 2

<table>
<thead>
<tr>
<th>Description</th>
<th>Interaction</th>
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<tbody>
<tr>
<td>$Q(Xa \cap Xb) &lt; \min(Q(Xa), Q(Xb))$</td>
<td>Weak; univariate</td>
</tr>
<tr>
<td>$\min(Q(Xa), Q(Xb)) &lt; Q(Xa \cap Xb) &lt; \max(Q(Xa), Q(Xb))$</td>
<td>Nonlinearly enhanced; bivariate</td>
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<tr>
<td>$Q(Xa \cap Xb) = Q(Xa) = Q(Xb)$</td>
<td>Independent</td>
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</table>

Note: “*∩*” means interaction and “+” means combination.
nonlinear enhanced in influencing land-use economic function change during 1990–2015. The top three pairs of interaction effects can be concluded as follows: the interaction effect of economic aggregation and precipitation was the maximum value (0.995), followed by the interaction effect of population and urban center radiation (0.988), and aggregate and slope (0.986) in 1990–2000. Meanwhile, the interaction effect of urbanization rate and social investment was the strongest (0.998), followed by the interaction effect of economic aggregation and slope (0.978), and economic aggregation and precipitation (0.965) in 2000–2015.

### 3.3.2. Driving factors of land-use social function change

During 1990–2000, the driving factors related to economic development and geographical location contributed more to the spatial change of land-use social function (Fig. 7). Economic aggregation was the most influential factor, with a $Q$ value of 0.671, because economic development often had good spatial consistency with grain output and housing demand. Traffic accessibility (0.419) and water resource accessibility (0.412) were ranked second and third, respectively. Slope, with a $Q$ value of 0.059, had the weakest ability to explain the spatial change of the social function. In 2000–2015, the impacts of the social life and economic development factors were strengthened as a whole, with population, industrialization, and urbanization rate becoming the
The top three dominant driving factors in descending order with $Q$ values of 0.710, 0.497, and 0.496, respectively. Conversely, the explanatory power of environmental limitation and geographical location factors generally declined, in which traffic accessibility, with a $Q$ value of 0.020, decreased by 0.399, and became the weakest determinant.

The interactions of 78 pair factors were bivariate enhanced or nonlinear enhanced in influencing land-use social function change during 1990–2015. The top three pairs of interaction effects were as follows: in 1990–2000, the interaction effect of traffic accessibility and slope was the maximum value (0.972), followed by the interaction effect of economic aggregation and social investment (0.904), and economic aggregation and precipitation (0.904). Meanwhile, the interaction effect of urbanization rate and precipitation was the strongest (0.979), followed by the interaction effect of urbanization rate and industrialization (0.974), and economic aggregation and slope (0.965) in 2000–2015.

3.3.3. Driving factors of land-use ecological function change
Between 1990 and 2000, the driving factors belonging to environmental limitation and social life had a higher level for ecological function change compared with economic development and geographical location factors (Fig. 8). Social investment, with a $Q$ value of 0.735, had the most significant relationship with the ecological function change, because the growth of social fixed assets investment led to the spatial expansion of urban areas encroaching on the ecological space. Altitude (0.658) and residents’ consumption (0.636) were the second and third explanatory variables, respectively, while industrialization (0.094) was the weakest driving factor for ecological function change. In 2000–2015, the driving factors within environmental limitation and social life were still strong, but the leading driving factors changed. Specifically, the urbanization rate (0.808), slope (0.503), and population (0.478) became the top three driving factors, which was related to the acceleration of urbanization rate and implementation of ecological restoration projects such as Grain for Green. Industrialization was still the weakest factor, although its $Q$ value had increased to 0.125.

The interactions of 78 pair factors were bivariate enhanced or nonlinear enhanced in influencing land-use economic function change during 1990–2015. Specifically, in 1990–2000, the interaction effect of residents’ consumption and altitude was the maximum value (0.996), followed by the interaction effect of agricultural modernization and traffic accessibility (0.992), agricultural modernization, and social investment (0.990). Meanwhile, the interaction effect of urbanization rate and social investment was the strongest (0.998), followed by urbanization rate and precipitation (0.985), and urbanization rate and economic aggregation (0.984) in 2000–2015.

4. Discussion
4.1. Insights into LUFs changes and human–natural driving factors
LUFs in Zhangjiakou City have been improving, while the ecological functions improved at a much lower rate than the others. The fact reflected a more urgent need for the economic and social functions, such as
food, housing and income, which were consistent with the findings of Wang and Zhen (2017) and Meng et al. (2019) in other ecologically fragile areas. The following analysis of the trade-offs of LUFs also confirmed that the conflicts between socio-economic functions and ecological functions were increasing. Furthermore, the ecological functions presented different trade-offs with the social and economic functions in developed and backward regions, respectively, caused by the variability of natural environmental conditions and socio-economic development levels.

As shown in Fig. 9, the environmental limitation, especially topography (e.g., slope or altitude) decides the spatial pattern of LUFs, while economic development and social life (e.g., industrialization or urbanization) are the key forces affecting the multiple LUFs variations. Additionally, geographical location, determining the spatial suitability and rationality, becomes a core factor affecting land-use economic and social functions. The results are in accordance with those of Sun et al. (2017) and Liu et al. (2019b), who found that regional policies and economic factors were the leading factors of the space differentiation of LUFs. Urban centers have become ideal places for population concentration, and real estate and infrastructure construction are accelerating...
urban–rural construction land expansion with economic improvement. As a result, during 1990–2015, the total population in Zhangjiakou City increased from $422.68 \times 10^4$ to $469.01 \times 10^4$, the urbanization rate increased from 19.50% to 36.41%, and the built-up area increased by almost four times. The fact has promoted improvement in land-use economic and social functions. However, a large part of arable land, forestland, and grassland has gradually changed into non-agricultural land (e.g., industrial land and residential land), which will inevitably threaten the ecological environment (Liu et al., 2018).

In contrast to studies from the perspective of single human or natural

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factors, this study has presented empirical evidence for the strong coupling effect of natural conditions and socio-economic development on multiple LUFs changes. Climate conditions, such as precipitation, have a crucial impact on vegetation growth, especially crop productivity in ecologically fragile areas (Patrick et al., 2010; Muhammad et al., 2016; Siriwat et al., 2018). However, in this study, precipitation contributes little to the change in the economic and social functions, because of the increasing improvement of agricultural science and technology.
technology. Combined with other factors, topography and precipitation had a more substantial effect on land-use economic and social functions change. Therefore, land-use management policies for regional natural conditions and socio-economic development should be proposed to avoid irrational human interference and unsuitable natural environments.

4.2. Implications for coordinating ecological–living–production spaces

In the context of resource and environmental restrictions, a suitable territory space for human activities is limited due to scarce land resources, especially in China (Long and Qu, 2018). Specifically, artificial exploited land accounts for only 0.71% of the national land area, while it supports 24.58% of the population and 35.62% of the GDP (Tan et al., 2017). Following the report to the Eighteenth National Congress of the Communist Party of China, optimizing national territory space development is the primary measure of ecological civilization construction. Meanwhile, “the space for production is used intensively and efficiently, the living space is livable and proper in size, the ecological space is unspoiled and beautiful” are the specific requirements for coordinating ecological–living–production spaces (Huang et al., 2017).

As Fig. 10 shows, ecological–living–production spaces are dominant functional spaces formed via dynamic processes where limited land resources are redistributed quantitatively and spatially among various LUFs (Huang et al., 2020). LUFs are at the core of ecological–living–production spaces; therefore, the measurement and trade-offs of LUFs are key in identifying ecological–living–production spaces (Liu et al., 2018). Exploring driving mechanisms of LUFs is an effective way to comprehensively understand the complexity of human–natural factors influencing LUFs, and then mitigate LUF conflicts, and optimize ecological–living–production spaces by adopting relevant policies.

4.3. Limitations of this study and future research directions

In this study, three LUFs (economic function, social function, and ecological function) were identified by six representative indicators at a more detailed scale (grid level) than previous studies (county level) (Du et al., 2016; Sun et al., 2017). Although the selected indicators covered the key LUFs in Zhangjiakou City, these could not comprehensively reflect all the LUFs. For example, the culture/leisure function was difficult to quantify due to the lack of spatial information (Zhang et al., 2019). Additionally, limited to data sources and imperfect models, the six indicators were calculated using multi-source data at different scales, which inevitably generated uncertainties in the spatial valuation of LUFs. Therefore, establishing a comprehensive and quantifiable indicator system to spatialize LUFs is still urgently needed for further study.

Table A1

<table>
<thead>
<tr>
<th>Function</th>
<th>Indicator</th>
<th>Calculation</th>
<th>Explanation</th>
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<tr>
<td>Economic function</td>
<td>Agricultural production</td>
<td>GAOV&lt;sub&gt;i&lt;/sub&gt; = ∑&lt;sub&gt;i&lt;/sub&gt; (AVQ&lt;sub&gt;ijk&lt;/sub&gt; × ARL&lt;sub&gt;ijk&lt;/sub&gt;)&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>GAOV&lt;sub&gt;i&lt;/sub&gt; is the agriculture output value of grid i. AVQ&lt;sub&gt;ijk&lt;/sub&gt; is the individual output value of agriculture, forestry, animal husbandry, and fishery of town j. ARL&lt;sub&gt;ijk&lt;/sub&gt; is the area of arable land, forestland, grassland, and water area of town j. ARL&lt;sub&gt;ijk&lt;/sub&gt; is the area of arable land, forestland, grassland, and water area of grid i.</td>
</tr>
<tr>
<td>Non-agriculture production</td>
<td></td>
<td>G23&lt;sub&gt;i&lt;/sub&gt; = ∑&lt;sub&gt;j&lt;/sub&gt; GNV&lt;sub&gt;ijk&lt;/sub&gt; × Si × (1 + Li)</td>
<td>G23&lt;sub&gt;i&lt;/sub&gt; is the gross output value of secondary and tertiary industries of grid i. G23&lt;sub&gt;i&lt;/sub&gt; is the gross output value of the secondary and tertiary industry of county j. Si and Li are the total areas of nighttime light with a digital number value over 0 and urban-rural construction land area of county j. Si and grid i. Li is average nighttime light intensity of grid i.</td>
</tr>
<tr>
<td>Social function</td>
<td>Food supply</td>
<td>VG&lt;sub&gt;i&lt;/sub&gt; = GY&lt;sub&gt;i&lt;/sub&gt; × FG</td>
<td>VG&lt;sub&gt;i&lt;/sub&gt; is the value of food supply of grid i. FG is the market price of wheat. GY&lt;sub&gt;i&lt;/sub&gt; is the standard grain yield of grid i. NDV&lt;sub&gt;i&lt;/sub&gt; and ARE&lt;sub&gt;i&lt;/sub&gt; are the sum of the NDV&lt;sub&gt;i&lt;/sub&gt; value and arable land area of grid i, respectively. a and b are the regression coefficients of NDV&lt;sub&gt;i&lt;/sub&gt; and ARE&lt;sub&gt;i&lt;/sub&gt;, respectively, which are obtained from linear regression analysis of standard grain yield, NDV&lt;sub&gt;i&lt;/sub&gt; value, and cultivated land area in the township.</td>
</tr>
<tr>
<td>Residence support</td>
<td></td>
<td>VP&lt;sub&gt;i&lt;/sub&gt; = POP&lt;sub&gt;i&lt;/sub&gt; × RARE × CHS</td>
<td>VP&lt;sub&gt;i&lt;/sub&gt; is the value of residence support of grid i. RARE is per-capita living space. CHS is the per-area commercial housing price. POP&lt;sub&gt;i&lt;/sub&gt; is the population density of grid i. POP&lt;sub&gt;j&lt;/sub&gt; is the total population of town j. URP&lt;sub&gt;i&lt;/sub&gt; and URL&lt;sub&gt;j&lt;/sub&gt; are urban–rural construction land areas of town j and grid i, respectively. NER and URN&lt;sub&gt;i&lt;/sub&gt; are the total nighttime light intensities of urban–rural construction land of town j and grid i, respectively.</td>
</tr>
<tr>
<td>Ecological function</td>
<td>Gas regulation</td>
<td>VGR&lt;sub&gt;i&lt;/sub&gt; = VCO × CO&lt;sub&gt;i&lt;/sub&gt; × VO&lt;sub&gt;i&lt;/sub&gt;</td>
<td>VGR&lt;sub&gt;i&lt;/sub&gt; is the value of gas regulation of grid i. VCO is CO&lt;sub&gt;2&lt;/sub&gt; sequestration cost. CO&lt;sub&gt;i&lt;/sub&gt; is the amount of CO&lt;sub&gt;2&lt;/sub&gt; sequestration of grid i. NPP&lt;sub&gt;i&lt;/sub&gt; is the net primary productivity of grid i. O&lt;sub&gt;i&lt;/sub&gt; is the amount of O&lt;sub&gt;2&lt;/sub&gt; release of grid i. VO&lt;sub&gt;i&lt;/sub&gt; is the average cost of O&lt;sub&gt;2&lt;/sub&gt; afforestation and industrial oxygen production. AP&lt;sub&gt;i&lt;/sub&gt; is the amount of photosynthetically active radiation absorbed by grid i. O&lt;sub&gt;i&lt;/sub&gt; is the amount of photosynthetically active radiation absorbed by grid i. AP&lt;sub&gt;i&lt;/sub&gt; is the efficiency of solar energy utilization influenced by temperature stress, water stress, and the maximal light utilization efficiency of the vegetation in grid i (Liu et al., 2013).</td>
</tr>
<tr>
<td>Soil conservation</td>
<td>Soil fertility maintenance</td>
<td>VSR&lt;sub&gt;i&lt;/sub&gt; = V&lt;sub&gt;i&lt;/sub&gt; × Vo&lt;sub&gt;i&lt;/sub&gt;</td>
<td>VSR&lt;sub&gt;i&lt;/sub&gt; is the value of soil conservation function of grid i. Vo&lt;sub&gt;i&lt;/sub&gt; is the value of soil fertility maintenance of grid i. V&lt;sub&gt;i&lt;/sub&gt; is the value of land abandonment proportion of grid i. I&lt;sub&gt;3&lt;/sub&gt; is the value of sediment deposition alleviation of grid i. C&lt;sub&gt;i&lt;/sub&gt; is the pure content of nitrogen, phosphorus, and potassium in the soil. TF is the conversion coefficient from the pure amount of nitrogen, phosphorus, and potassium to fertilizer amount. F&lt;sub&gt;i&lt;/sub&gt; is the price of fertilizer. B is the annual income of forestry. P is soil bulk density. h is the surface soil thickness. C is the reservoir capacity cost. A&lt;sub&gt;i&lt;/sub&gt; is the amount of soil conservation of grid i. R&lt;sub&gt;i&lt;/sub&gt;, K&lt;sub&gt;i&lt;/sub&gt;, L&lt;sub&gt;i&lt;/sub&gt;, and S&lt;sub&gt;i&lt;/sub&gt; are the rainfall erosivity factor, soil erodibility factor, slope length, and steepness factors of grid i, respectively. C&lt;sub&gt;1&lt;/sub&gt; and P&lt;sub&gt;i&lt;/sub&gt; are the cover-management and support practice factors of grid i, respectively (Kumar et al., 2014).</td>
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</table>

Note: Standard grain yield is calculated from the yields of wheat, corn, millet, naked oats, and potatoes according to their yield ratio coefficients. The yield ratio coefficients of corn, millet, naked oats, and potatoes, obtained from farmland grading results in Zhangjiakou City, are 0.54, 1.41, 1.75, and 0.80, respectively.
research.

This study has highlighted the differences in the coupling mechanism of human–natural factors for multiple LUFs changes using spatial analysis techniques and a geographic detector model. However, the geographic detector model did not encompass all the possible driving forces in the LUFs changes. For example, policies and management measures were difficult to quantify. Future research needs to consider more comprehensive driving forces and further understand the coupling effect of human–natural factors on LUFs changes.

5. Conclusions

To investigate the spatiotemporal trade-offs and driving forces of LUFs in ecologically fragile areas, this paper selected Zhangjiakou City in Hebei Province as the study area. The results suggest that during 1990–2015, land-use economic, social, and ecological functions were greatly enhanced, especially the social function increased the most. Spatially well-developed regions such as the Yang River valley exhibited high economic and social functions, and low ecological function, whereas undeveloped regions with mountainous and hilly areas presented the opposite situation. Land-use economic and social functions displayed mainly coordinated. By contrast, land-use ecological function and other functions were coordinated or conflict in different regions. Moreover, the coupling influences of human–natural factors were different in the changes in the economic, social, and ecological functions. However, multiple LUFs changes were more strongly influenced by economic development and social life.

The conflicts among LUFs will become more intensive in Zhangjiakou City along with implementing the Coordinated Development of the Beijing–Tianjin–Hebei Region strategy and jointly hosting the 2022 Winter Olympics. Therefore, we should coordinate LUFs using properly land resources according to the local natural conditions and socio-economic development. Specifically, well-developed regions, such as the Yang River valley, should promote urbanization within the carrying capacity of natural resources. For Bashang Plateau, on one hand, wind and sand-blocking forest and water conservation forest should be constructed to protect farmlands and pasture. On the other hand, modern green animal husbandry and ecotourism agriculture should be developed to promote the local economy. In the shallow southern hills and deep mountains, greening barren hills and slopes should be implemented, and soil and water conservation forests and economic forests should be constructed.

The analytical framework developed in this study and findings from Zhangjiakou City contribute to profoundly understanding spatiotemporal features, interrelationships, and driving forces of LUFs. This study provides a valuable basis for further research and offers references for stakeholders and decision-makers for sustainable land use and harmonious ecological–living–production spaces in an ecologically fragile region.

Author statement

Liu Chao: conducted and performed research, and wrote the whole paper. Xu Yueqing: designed the structure of this paper and went through all sectional works. Lu Xinhai: designed the structure of this paper and went through all sectional works. Han Jing: revised and finalized the paper.

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Appendix A

See Table A1.

References


