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Mapping trade-offs among urban fringe land use functions to accurately support spatial planning

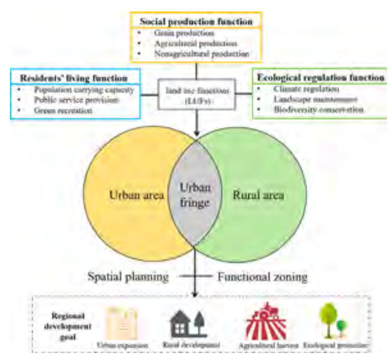
Yuefeng Lyu [a], Mengjing Wang [a,b,*], Yinuo Zou [a], Cifang Wu [a]

[a] Department of Land Management, School of Public Affairs, Zhejiang University, Hangzhou, Zhejiang 310058, China
[b] School of Landscape Architecture, Zhejiang Agricultural and Forestry University, Hangzhou, Zhejiang 311300, China

HIGHLIGHTS

- Identify and quantify nine sub-land use functions in urban fringe to accurately support spatial planning
- High-precision datasets suitable for local-scale research are used in this research
- Land use classification were more in line with the practical requirements of territorial spatial planning in China
- Provide a case reference for the efficient land use in urban fringe of second-tier cities in China

GRAPHICAL ABSTRACT



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ABSTRACT

The land use planning and management of urban fringe areas have become major governmental agendas under the background of continuing periurbanization processes. Quantifying land use functions (LUFs) and their interactions as rationales for spatial planning can aid in formulating a more effective and sustainable land use management system. Considering that most of the previous research on LUFs focused on large-scale regions, research on local-scale districts such as urban fringe is still limited. Therefore, the objective of this work is to map the spatial distribution of LUFs and their level of provision around an urban fringe area, so as to identify LUFs synergies and trade-offs in relation to urban expansion and environmental protection planning. To achieve this target, we have proposed an improved LUFs classification system that was suitable for small-scale regions. Fine scale multivariate datasets were used to meet the practical requirements of spatial planning. The urban fringe areas of Binzhou city in China was taken as a case study to quantify and analyze nine kinds of sub-land use functions. The interactions among LUFs and their cold-hot spots were measured through Spearman correlation analysis and bivariate local Moran's I respectively. The results demonstrated a heterogeneous spatial pattern of multiple LUFs and the diverse interactions among them. The social production function presented an obvious regional distribution, the residents' living functions were greatly affected by the radiation of the urban central areas, and the ecological regulation functions were closely related to the land use types. According to the LUFs clustering results, we proposed two spatial planning-zoning schemes based on the land use function and human utilization intensity. The integrative approach and the proposal of functional zones developed in this paper are applicable to provide a new perspective for spatial planning and peri-urban land use management.

* Corresponding author at: Department of Land Management, School of Public Affairs, Zhejiang University, Hangzhou, Zhejiang 310058, China.
E-mail addresses: lyf93520@163.com (Y. Lyu), mengjing_wang@126.com (M. Wang), crystalzzy1@163.com (Y. Zou), wucifang@zju.edu.cn (C. Wu).

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1. Introduction

With the acceleration of the urbanization and modernization, the urban structure continues to sprawl away from the city center and the fringe zones adjacent to build-up areas are gradually integrated into city (Galster et al., 2001; Irwin and Bockstael, 2007; Zhang et al., 2018). Taking China as an example, during the period from 2004 to 2014, China's urban built-up land area has increased by 78.5%, far exceeding the urban population growth rate of 46% (Bai et al., 2014). Under the rapid process of land urbanization, excessive rural land areas and ecological spaces in the urban fringe were transformed into construction land for the purposes of economic development and social activities (Yang et al., 2021; Yin et al., 2020; Liu et al., 2018), leading to a series of environmental problems, social contradictions and land use conflicts, such as farmland encroachment, greenery reduction, increased traffic jams, inefficient land use, land fragmentation, and degraded ecological system functions including water, air, biodiversity, etc.(Yew, 2012; Zhao, 2010; Tu et al., 2007), all of these problems pose great challenges to urban sustainability. Previous literature has illustrated that these negative impacts of peri-urbanization have not only emerged in China's large cities and metropolitan areas, but also existed in the second-tier cities and medium-sized cities (Yue et al., 2016; Gao et al., 2016). Thus, this issue has received increasing attention from the research community.

In actuality, the outputs provided by land use systems that directly or indirectly relate to any type of good or service to human society vary among different land use types (Turner and Daily, 2008). Previous studies have defined these contributions provided by the interactive land use systems as land use functions (LUFs; Assessment, M. E, 2005; Wiggering et al., 2006; Fan et al., 2018). With the continuous improvement of the theory of LUFs, the concept of LUFs has been expanded from the original agricultural system (Helming and Pérez-Soba, 2011) or agricultural production function (Andersen et al., 2013) to a composite framework integrating regional economic, social and environmental functions, characterizing a boarder concept than the well-known concept of ecosystem services (ESs, Kienast et al., 2009; Chao et al., 2018; Paracchini et al., 2011).

Numerous studies have provided evidence that LUFs vary among land use types, and the bundles of LUFs are not separated but interacted (Zhang et al., 2019; Sylla et al., 2020). These interactions are usually manifested in the form of trade-offs or synergies. The term trade-off means that an enhancement of one land use function will lead to a reduction in another land use function, while synergy represents a trend of simultaneous increases (Cao et al., 2020; Rodríguez et al., 2006). As a transitional zone between urban and rural areas, urban fringe areas are characterized by its complex, fragmented and dynamic land use system compositions (Geneletti et al., 2017), and the LUFs in these regions also present complex forms of trade-offs and synergies. For instance, intensive road networks are generally considered to be an important factor that leading to the fragmentation of agricultural and forested landscapes as well as to the degradation of ecosystem service functions. However, from another perspective, these traffic infrastructures also improve the well-being of residents to a certain extent by increasing landscape accessibility (Žlender and Ward Thompson, 2017). Therefore, It is necessary and meaningful to further evaluate and identify complex LUFs among urban fringe regions, as these efforts helps to lay a solid foundation for the spatial planning as well as for land use management and allow a scientific rationale for orderly land cover changes in peri-urban areas.

Previous empirical research on LUFs mainly focused on two directions. One is concerning the landscape multifunctionality of a specific administrative region, such as nationwide, urban agglomerations, province, city, country and so on (Leh et al., 2013; Queiroz et al., 2015; Peng et al., 2016; Chao et al., 2018; Sun et al., 2016). The other concentrates on the functions and interactions among specific land use type, such as farmland, forest, watershed, urban land or rural land (Peng et al., 2016; Barbier et al., 2010; Song et al., 2015; Fan et al., 2018). However, almost all these LUFs studies have been carried out on a relatively large spatial scales, small scale research is still limited, not to mention choosing local scale like urban fringe areas to conduct research, which probably limited by two main reasons. On the one hand, previous large-scale LUFs studies have often used remote sensing datasets such as terrain, precipitation, soil type, and run-off datasets, as research materials. However, due to the geographical homogeneity within a narrow scope, these parameters mentioned-above may not be able to significantly reflect spatially heterogeneous interactions on such a small scale. More refined datasets and a more scientific index evaluation system urgently need to be proposed for fine scale research. On the other hand, large scale research often uses administrative districts as basic units to conduct spatio-temporal analyze or regional comparisons of variety land use functions. Related differentiated management recommendations have mostly been put forward from the perspective of macro-administrative regional management. In contrast, local-scale research or non-administrative research, such as research on urban fringe areas, often uses grids or plots as the basic research unit. Therefore, the corresponding research results should be combined with specific spatial management instruments to propose more practical control measures.

Overall, we have fully considered the social-ecological complexity of land use systems in urban fringe areas and proposed a local-scale classification evaluation system to quantify and visualize diverse LUFs. It is worth mentioning that we abandoned the use of conventional remote sensing data and instead selected some fine patch features to represent certain individual land use functions. All the input datasets and output results in this study are based on fine scale to address the limitations of previous research. For the empirical research, Binzhou city, a typical second-tier city in the Yellow River Delta of China, was selected as an example. The results of LUFs trade-offs and synergies analysis provide research support for land use functional zoning and spatial planning in urban fringe and guide the city from disorderly expansion to sustainable development. The specific aim of this study comprise the following objectives: (1) identify and quantify multiple LUFs in an urban fringe area; (2) quantify the trade-offs and synergies among different LUFs;(3) provide solutions for land use strategies and for the spatial planning of urban fringe through high-accuracy LUFs mapping.

2. Materials and methods

2.1. Study area

The city of Binzhou (117°15′27″ ~ 118°37′03″E, 36°41′19″ ~ 38°16′14″N) is located on the Yellow River Delta Plain in northern of Shandong Province, only 120 km to the inlet of the Yellow River. The three specific reasons that we chose Binzhou are as follows:(1) China plans to increase the population urbanization rate at a pace of 1% per year and the overall number of rural migrants is expected to reach 400 million by 2035. Under population-resources-environmental carrying constraints, there is no doubt that medium-sized cities will replace urban agglomerations and large cities and will become hot spots for rapid urbanization and development. In the past decade, the annual growth rates of the GDP and population in Binzhou City were 8% and 5‰ respectively, which are much higher than the average speeds in China and in Shandong Province. This rapid development trend can represents the urbanization process of many second-tier Chinese cities in the coming future well. (2) With the tremendous social and economic achievements of the Yangtze River Basin since the turn of this century, it is reasonable to believe that the Yellow River Basin, as the other important natural economic belt in China, is going to be the next demonstration region for ecological civilization construction and sustainable development. Binzhou was listed in the “Yellow River Delta High-Efficiency Ecological Economic Zone” by the State Council of China in 2009, indicating that the coordinated development between economic construction and ecological protection will be the long-term spatial planning goal in this city. (3) We have participated in Binzhou Territorial Spatial Planning (2020–2035) as a planning team, which helped us to have a better understanding of the land use situation in this study area and allowed us access to detailed data.

The central urban areas of Binzhou located in Bincheng district, which consists of two parts: the northern main urban area and the southern high-tech development zone, with a total area of 164.46 km^2. Since the urban fringe is constantly evolving with the size of the city, the radiation intensity, relationship between urban and rural areas and many other factors (Gu et al., 1995), the definition of the urban fringe range has varied from case to case in previous studies. For instance, Friedmann (1966) defined the urban fringe area as the region approximately 10–15 km away from the inner city according to the commuting range of residents, and Bryant and Russwurm (1979) and Bryant et al. (1982) used the ratio of the agricultural population to the non-agricultural population to determine the urban fringe area to be within 6–10 miles of the city's outward extension. Chinese scholars have proposed that the range of urban fringe is between 8 and 30 km based on several case studies, such as Beijing (Li, 2005) Tianjin (Zhai and Zhang, 2006), Guangzhou, Shanghai (Gu et al., 1993) and Nanjing (Cui and Wu, 1990), etc. After taking economic construction, city positioning, built-up area, administrative boundaries and many other factors into consideration, we finally defined 10 km as a reasonable range for the urban fringe in this study. Through a 10 km buffer analysis, we superimposed the obtained surface and the administrative boundaries to determine the research area (Fig. 1).

2.2. Data collection

Multi-source datasets such as vector data, raster data and statistical data were used in this study (Table 1). Detailed descriptions of the data were as follows:

(1) Land use dataset: The land use vector data of 2019 were provided by the Bureau of Natural Resources and Planning of Binzhou City. Most notably, the data were interpreted from "The Third National Land Survey ", which was conducted by the China Natural Resources Administration since 2018 and has already been used as the latest land cover data for Binzhou Territorial Spatial Planning (2020–2035). According to the requirements of the parameter design and planning practices, we reclassified the original land use types into 11 major categories and 14 sub-categories based on the latest national current land use classification system (GB/T 21010–2017). Specifically, cultivated land, woodland (forest and garden), grassland, wetland, open water area, commercial land, public service land, industrial and mining land, residential land (urban residential land and rural residential land), transportation land (primary road and railroad) and unused land were included.

(2) Agricultural production dataset: A cultivated land quality evaluation and grading database of 2015 was also acquired from the Bureau of Natural Resources and Planning of Binzhou. Considering that Binzhou is located in the double cropping area of northern China, this dataset introduced the land use coefficient and land economic coefficient to represent the agricultural production capacities in summer (mainly corn) and winter (mainly wheat) at the patch level.

(3) Satellite image dataset: Landsat 8 OLI surface reflectance images with a spatial resolution of 30 m × 30 m were downloaded from the United States Geological Survey (USGS) (http://earthexplorer.usgs.gov/). The monthly normalized difference vegetation index (NDVI) from March to November was extracted from these remote-sensing images, and the maximum NDVI value of each pixel was calculated by the maximum value composite (MVC) method.

(4) Statistical dataset: Data related to economic development, population density and other aspects were collected from the statistical reports of townships in the study area. For some missing data, we used the average values representing Bincheng District published in the statistical yearbook (2019) as substitutes.

2.3. Evaluation system used to quantify LUFs

The chosen classification system is the foundation of LUFs identification. Moreover, the "production-living-ecology" (Xi et al., 2014; Zhou et al., 2017) and "economic-social-environmental"(Du et al., 2016; Xie et al., 2010) forms are the two most common classification forms. Although relevant scholars have realized the explicit form and implicit property of land use (Liu et al., 2015; Zou et al., 2020) and have proposed some more complex classification forms. The "production-living-ecology" classification form is still a widely accepted classification form for its direct interaction with land use types. In this study, we proposed a LUFs evaluation system with 3 primary function categories and 9 sub-functions from the perspective of the "production-living-ecology" classification form (Table 2). The data availability and indicator representativeness of the LUFs relative to the geographic and economic characteristics of urban fringe were the basic principles applied in this study.

The social production function of land use is designed to be represented by three aspects, namely the grain production, agricultural production and nonagricultural production. In particular: (1) The grain production indicator reflects the capacity of cultivated land to provide crop services (Maes et al., 2012). In this study, the agricultural land grading results of Binzhou city and the cultivated land plots in the urban fringe area were superimposed to determine the overall grain production capacity. (2) Traditional agricultural production usually involves agriculture, forestry, animal husbandry as well as fisheries. In this study, due to the scarce grassland resources and strict water-related environmental protection policies in the Lower Yellow River basin, only the forestry and fruit industries were taken into consideration. The output agricultural production value was calculated by multiplying the land economic coefficient obtained in the agricultural land grading results by the forest/garden area. (3) Although the land use types in peri-urban areas mainly include nonconstruction land, some industrial-mining land and commercial land areas were still scattered in the urban fringe area and towns, so the function of non-agricultural production should also be taken into account. The calculation principle of this factor was consistent with the above principle; non-agricultural production was calculated by multiplying the land use areas by the output value per unit area.

The residents' living function refers to the capacity of the land use system to provide residential space, security and entertainment for human beings, as this is the most basic function of land use systems (Geoghegan, 2002). Following this approach, the living function was quantified by three sub-categories, namely, the population carrying capacity, public service provision and green recreation in this study. More specifically: (1) Housing is the most basic function provided by land for mankind (He et al., 2011). In China, the construction standards of urban and rural residential land vary, and the population carrying capacity also shows great differences between urban and rural area. In this study, we calculated the population carrying capacity of urban fringe area by multiplying the area of urban/rural residential land and their respective criterion. (2) The public service accessibility is closely related to the quality of residents' living, so we visualized the coverage of public services through a buffer analysis using the basic standard of 300-meters coverage radius for public service provisions, according to (Barbosa et al., 2007). (3) Landscape aesthetics are considered to be an important part of cultural ecosystem services under the framework of the Millennium Ecosystem Assessment (MA) process of the United Nations. The beauty and aesthetic value of urban fringe areas, which were regarded as continuous spatiotemporal urbanization gradients from urban cores

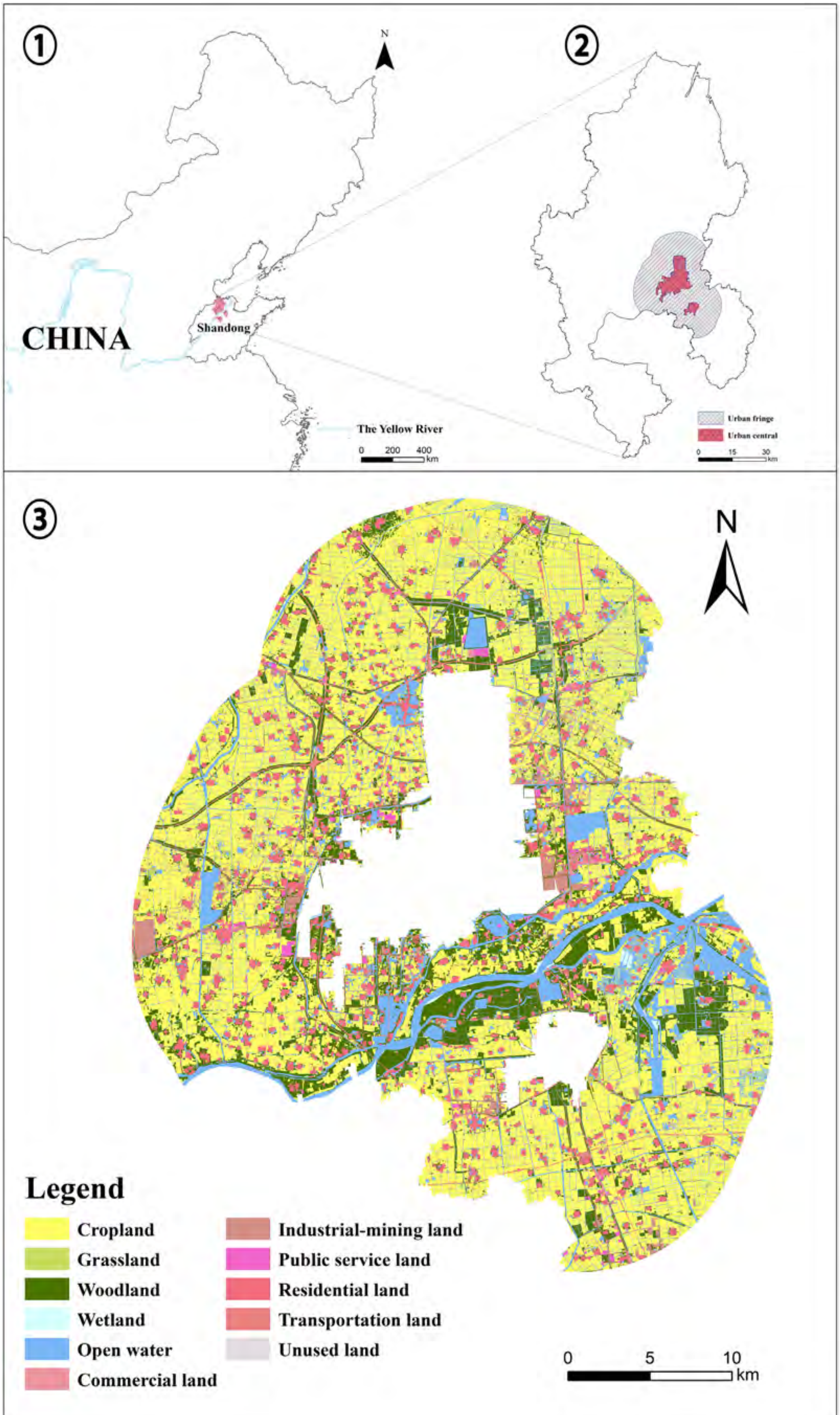

Fig. 1. ① The location of Binzhou city; ② the location of the central urban areas and urban fringe areas; ③ land cover map of the urban fringe in Binzhou city.

Table 1
Data categories and sources.

Description	Sources	Format
Land use status data (2019)	Bureau of Natural Resources and Planning of Binzhou City	Vector
Cultivated land quality evaluation and grading dataset (2015)		Vector
Landsat 8 OLI image	USGS (http://earthexplorer.usgs.gov/)	Raster
Statistical Yearbook (2019)	Bureau of Statistics of Binzhou City, Township Statistical Bureau in the study area	Spreadsheet

to (semi) natural areas (Spyra et al., 2020), not only exist with regard to support for parks, 'scenic drives,' and the selection of housing locations (de Groot et al., 2010), but are also closely related to the "amount or configuration of open space in agricultural or forested (land use/land cover) types"(Chan et al., 2011) in rural areas. To better quantify the aesthetic and leisure needs of residents, we followed the theoretical research method proposed by (Danie et al., 2012) for forested landscape aesthetics and evaluated this approach by multiplying the two indicators of the green recreation ability and traffic accessibility. In this study, the NDVI was used to quantify the ability of the land to provide a green recreation function at the plot scale. Moreover, the traffic accessibility was obtained by a multiple buffer analysis of expressways (with a range of 2500 m and a gradient of 500 m), urban roads (with a range of 1000 m and a gradient of 200 m) and rural roads (with a range of 250 m and a gradient of 50 m).

The ecological regulation function reflects the environmental conditions, ecological resources and other services provided by the land use (Liu et al., 2021). To better characterize the heterogeneity and multifunctionality of LUFs on a fine-scale, we discarded some conventional metrics that have often been used in the similar research and selected climate regulation, landscape maintenance and the ecosystem service capacity to represent the ecological regulation function in the studied urban fringe area. (1) Climate regulation helps alleviate the urban heat island effect and reduce air pollution, which is of great significance for urban ecological security (Chen et al., 2006). According to (Larondelle and Haase, 2013; Schwarz et al., 2011), the "surface emissivity" and "*f*-evapotranspiration" climate regulation indicators were chosen in this study. These specific parameters came from previous studies (see in Table S1, Schwarz et al., 2011). (2) Land use changes caused by urban expansion trigger strong changes in the landscape patterns, and fragmented patches will significantly affect the ecological processes and edge effects in the urban fringe systems. Therefore, we took the integrity of patches as a measure of landscape maintenance ability into the evaluation of land use ecological function (Mitchell et al., 2015; Langevelde and Frank, 2015). According to the research of (Munroe et al., 2005), four specific parameters that can reflect the fragmentation pattern of the landscape were selected, including the aggregation index (AI), meanpatch zize (MPS), largest patch index (LPI) and contagion (CONTAG). They were considered equally important and given the same weight in this study. All the results were exported through the mobile window module of Fragstat 4.2 software and eventually got superimposed in grid format. (3) The InVEST model quantifies habitat quality based on the relative impact and sensitivity of the habitat to threats, the distances between the habitats and the sources of threats, and the locations of protected areas (Sharp et al., 2018), which is regarded as a conventional method in the trade-off study of ecosystem service. Therefore, we used the habitat quality module of the Invest model to quantify the ecosystem service capacity in the research area. The specific research process and parameter design were obtained based on previous studies (see in Table S2, Chen et al., 2016; Wu et al., 2019).

Refer to the evaluation index system construction in the previous LUFs research, the weight distribution of individual land use function shows different characteristics with the change of the research unit type. Almost all LUFs studies that target administrative units assume that each land use function has the same status, whether the research scale is national (Leh et al., 2013; Queiroz et al., 2015), regional (Peng et al., 2016), provincial (Fan et al., 2018), prefecture-level city (Chao et al., 2018) or country (Sun et al., 2016). Correspondingly, those LUFs studies that target region that dominated by one specific land type tend to have more inclined weight settings, such as watershed (Peng et al., 2016), forest (Barbier et al., 2010), farmland (Song et al., 2015), and so on. In our research, we assume that each sub-land use function in residents' living function and ecological regulation function has the same status. As for the social production function, since the urban fringe is dominated by ecological land (mainly cultivated land and woodland), we use the expert scoring method to set the weights of the three sub-land use functions to 0.5, 0.3 and 0.2 respectively.

2.4. Data analysis and visualization

2.4.1. Gradient analysis

Aiming to determine whether there are trade-offs and synergies between different LUFs, we applied a Spearman's rank correlation analysis, a nonparametric measure of bivariate correlations that has been commonly used in previous research (Vallet et al., 2018). A positive correlation between a pair of LUFs implies synergy, while a negative correlation between two LUFs represents a trade-off.

As this study was conducted on a fine scale, it was carried out on the premise of the consensus that some land use functions are considered to be provided by specific land use types. For instance, the grain production function was all provided by cultivated lands, while the population carrying capacity was only related to residential lands, etc. When one plot didn't provide the specific corresponding land use function, its value was marked as "no data". The existence of a large number of missing values makes the correlation analysis less scientific. For this reason, we preprocessed the original data through a gradient analysis.

Rural–urban gradients have been commonly used to consider changes of ecological patterns and processes that occur due to urbanization (Andersson et al., 2009; Kroll et al., 2012). Along the boundary of

Table 2
Overview of land use function categories, indicators, descriptions and weights used in this study.

Primary functions	Sub-functions	Description	Weights
Social production function	Grain Production	Grain production per unit area	0.5
	Agricultural production	Output value of the forestry and fruit industries per unit area	0.3
	Non-agricultural production	Output values of nonagricultural industrial per unit area	0.2
Residents' living function	Population carrying capacity	Habitable population per unit area	0.33
	Public service provision	Accessibility of public services	0.33
	Green recreation	Accessibility of green leisure spaces	0.33
Ecological regulation function	Climate regulation	The ability to regulate the air temperature and air quality	0.33
	Landscape maintenance	Integrity of patches in the landscape pattern	0.33
	Biodiversity conservation	Habitat quality and degradation	0.33

the central urban areas, we created concentric buffer zones with an intervals of 250 m within 10 km of the urban fringe area. The statistical analyses were performed at the grid scale and the mean values of 40 intervals were calculated in ArcGIS 10.4 platform.

2.4.2. Spatial correlation analysis and hot/cold spot identification

Bivariate local Moran's I is the extension of local Moran's I and is characterized by a comparison between the observed value of one variable in a given spatial unit and another variable in the adjacent spatial unit; this index can reveal the spatial correlation between the two variables. In this study, bivariate local Moran's I was used to quantify the spatial heterogeneity of trade-off and synergy between land use functions. The calculation method is shown in the following equation (Zhang et al., 2019):

$$I_i = \left[Z_i / \left(\frac{\sum_i Z_i^2}{n} \right) \right] \sum_j w_{ij} (y_i - \overline{y}) \quad (1)$$

where $Z_i = x_i - \overline{x}$, x_i, y_i are the different functional values of grid cells i and j respectively; $\overline{x}, \overline{y}$ is the mean value of different functional values of all i and j points;

n is the number of all grid cells; W_{ij} is the spatially adjacent weight matrix between the i and j values of each grid cell in the research area.

In this study, a spatial weight matrix (based on the 95% confidence interval, i.e., a significance level, $P < 0.05$) was constructed by using the queen adjacency method to analyze the spatial correlation of production, living and ecology functions of land use in pairs. All these operations were implemented by Geoda 1.14.

2.4.3. Standardization and spatial mapping format

The indicators mentioned above were normalized by using min-max normalization, thus making the value of each indicator range from 0 to 100. The weight coefficients of each function category and sub-indicators was comprehensively determined by government policy makers and urban planners. Each quantitative evaluation result of LUFs was eventually exported as a spatial map through ArcGIS 10.4 platform. Considering that all input datasets were composed of vector data and 30 m × 30 m raster data, finally we uniformly converted these export results into raster format with a grid resolution of 30 m × 30 m and transformed them into the China Geodetic Coordinate System 2000(CGCS2000).

3. Results

3.1. Spatial characteristics of sub-land use functions

The nine land use sub-functions in this study were separately calculated and visualized on the maps, which were unevenly distributed (Fig. 2 spatial distribution of nine sub-land use functions). Some LUFs demonstrated relatively similar spatial patterns, while others exhibited almost the opposite distributions. For example, both grain production (A) and agricultural production (B) presented a distribution pattern with high values in the south and low value in the north, which might be affected by the joint effects of local light distribution, irrigation conditions, soil fertility and many other factors. Coincidentally, the spatial representations of climate regulation (G) as well as biodiversity conservation (I) showed similarity, the reason might be that different land use types generally have similar air control and biodiversity maintenance characteristics. Similarly, high intensity built-up land have worse heat absorption capacities than ecological lands and thus also pose greater threats to the habitat quality. Moreover, green recreation (F) and landscape maintenance (H) showed a clearly inverse distributions. The intensity of land use by humans in the urban fringe areas gradually weakened from the urban cores to the seminatural areas, indicating the impact of human activities on landscape maintenance. While transportation infrastructure, public services and other facilities have brought convenience to residents, they have also damaged the integrity of ecological patches to a certain extent. In summary, the nine selected LUFs were spatially clustered and associated rather than randomly distributed.

3.2. Trade-offs and synergies among sub-land use functions

3.2.1. Gradient characteristics of sub-land use functions in urban fringe areas

Fig. 3 directly visualizes the standardized value of land use for each sub-function and its development trend with the distance to the urban central areas. From the perspective of the function type, the green lines illustrated a higher and more stable trend on the map, indicating that the supply capacity of the corresponding ecological regulation function in the urban fringe was stronger than the other two primary functions, and was not significantly influenced by the spatial location.

The other important aspect to be noticed was the fluctuations of the value of each sub-land use functions along the horizontal axis as well as their interactions. The results demonstrated that the value of the GP curve continued to rise with an increasing distance from the urban development boundary. In contrast, five other curves including those of AP, NAP, RC, PP and GR represented the downward trends to varying degrees. These trends could be attributed to the strong radiation effect in the central urban central areas. Districts closer to the city center often have better infrastructure and road conditions, which was undoubtedly more conducive to the expression of living functions and to certain production functions.

3.2.2. Pairwise relationships among sub-land use functions

The resulting coefficients obtained from the Spearman rank correlation analysis (Table 3) were used to further analyze the relationships between nine sub-land use functions. Among 36 pairs of relationships between selected sub-functions, 15 pairs were positively correlated, whereas the other 21 pairs were negatively correlated. On the one hand, the results in the table confirmed the conclusions of Fig. 3 that the value of AP, NAP, RE, PP and GR values were synergistic with each other and all negatively correlated with GP to varying degrees. On the other hand, certain ecological regulation functions (i.e., CR, LM, and BC) demonstrated strong trade-off relationships with residents' living functions. Taking LM as an example, the correlation coefficients between it and the residents' living sub-functions were −0.68, −0.81 and −0.67. A reasonable explanation for this result is that ecological function values are strongly related to land use types. According to (Sylla et al., 2020; Liu et al., 2018), nonconstruction lands tend to have better performances in characterizing the ecological regulation functions, while living function were mainly determined by the presence of construction land. This can also be used to explain the synergies between these ecological regulation functions and grain production function, as a result of cultivated land belong to non-construction land and thus have ecosystem services capabilities.

3.3. Spatial patterns and cold-hotspot identification of LUFs

According to the weight settings that mentioned above, we carried out spatial superposition calculations on the three primary land use functions and used the natural-break-point classification method (Jenks method) to divide the results into 7 intervals (Fig. 4). The standardized results of the social production function ranged from 0 to 68.20. The social production capacities of most grids was relatively low, and the proportion of areas with medium and below medium production capacity accounted for 26.4% and 63.4% of the total, respectively. Only a small number of grids had a high production capacities, and these were mainly located in the western and southern parts of the study area and away from the inner city. The evaluation results of residents' living

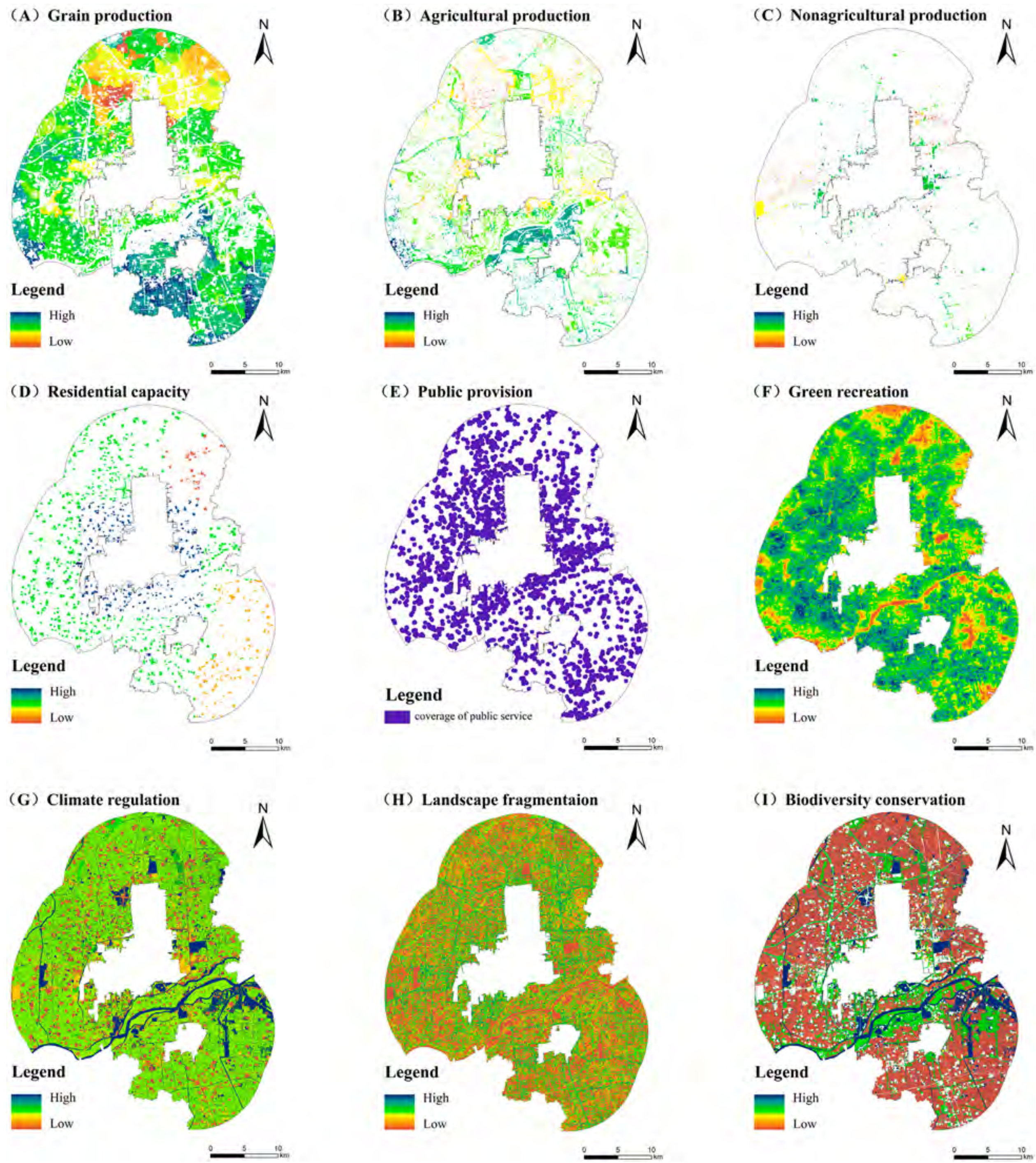

Fig. 2. Spatial distribution of nine sub-land use functions.

functions showed different spatial patterns. Since the central urban area had the largest population, the densest road networks and the best public services, districts located near the northern main urban area and the southern high-tech development zones generally had high living function values. The periphery of the urban fringe area was composed of cultivated land, and the lower level of development in these areas made their living function values much weaker. For ecological regulation functions, approximately 77.2% of the total area revealed medium or about-medium values. The area with the best ecological regulation function in the urban fringe area was located between the two well-developed districts because this region contained abundant open water and woodland terrains.

Although a standardization approach was adopted to unify the dimensions of the primary land use functions, there was still a lack of comparability among the multiple functions (i.e., the social production, residents' living, and ecological regulation functions). The existing results were still unable to determine the relative importance or dominant position of these functions on the same grid unit, causing difficulties in the implementation of land use zoning and spatial planning. Therefore, we introduced the bivariate local Moran's I index to further reveal the trade-off and synergy between these primary functions. As shown in the Fig. 5, the difference between the locations of the cold and hot spots once again demonstrated that distinctly positive and negative relations existed among these three primary land use functions.

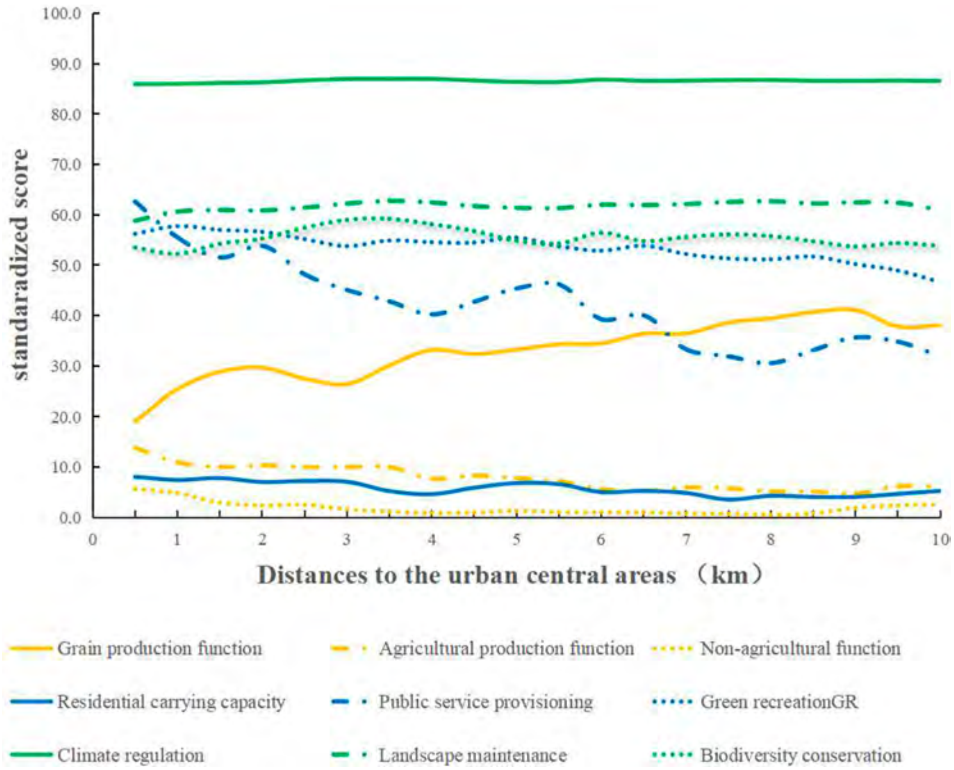

Fig. 3. Standardized LUFs values along the urban-rural gradient considered in this study.

4. Discussion

4.1. Applications of LUFs in land use functional zoning

Although functional zoning is not a novel approach for geographers or landscape ecologists (Cao et al., 2020), it is still uncommon to delineate land use functions in urban fringe, especially at fine scales. According to the standardized value of each land use function and the results of the spatial trade-offs and synergies analysis, the present research divided grids with similar attributes into several functional zones to provide a reference for differentiated planning design and policy guidance.

Determining the classification principle and priority levels is the necessary prerequisite for land use functional zoning. Urban fringe is regarded the interface between urban and non-urban ecosystems, most of the time, this area undertakes the important responsibility of the social-ecological connection most of the time (Zhu et al., 2017). Additionally, approximately 78.5% of the land in the local urban fringe is non-construction land that provides ecological functions to some extent. Obviously, under the sustainable urban development trend in China, the Binzhou government is committed to giving top priority to the maintenance of ecology functions of land use. Furthermore, there are a large number of villages and agricultural land scattered on the urban fringe of Binzhou city, and the planning and management of these land use types will significantly influence the livelihood of the agricultural population as well as the path of local urbanization development in the coming future. In addition to the ecological protection function, the related production function has also been regarded as a major agenda by local policy makers. Overall, this study clarifies that the priority relationships among these three types of land use functions follow the following order: ecology function > production function > living function. In other words, when a plot reflects a high-high synergy relationship between the production and ecological functions, we are more inclined to dominate this plot with ecological activities and measures. With this principle, we established a set of systematic classification rules (Fig. 6) and divided the urban fringe land into 6 specific functional zones (Fig. 7, Table 4), including agricultural production zone (APZ), multifunctional agricultural zone (MAZ), ecological

Table 3
Spearman rank correlation coefficients of land use sub-functions.

	GP	AP	NAP	RC	PP	GR	CR	LM	BC
GP	–	−0.94**	−0.59**	−0.88**	−0.90**	−0.86**	0.210	0.56**	−0.11
AP		–	0.67**	0.86**	0.87**	0.82**	−0.34	−0.61**	−0.01
NAP			–	0.75**	0.67**	0.44	−0.60**	−0.68**	−0.52*
RC				–	0.88**	0.76**	−0.53*	−0.81**	−0.22
PP					–	0.89**	−0.49*	−0.67**	−0.16
GR						–	−0.36	−0.54*	−0.01
CR							–	0.80**	0.86**
LM								–	0.55*
BC									–

* Significant at the 95% confidence level.
** Significant at the 99% confidence level.

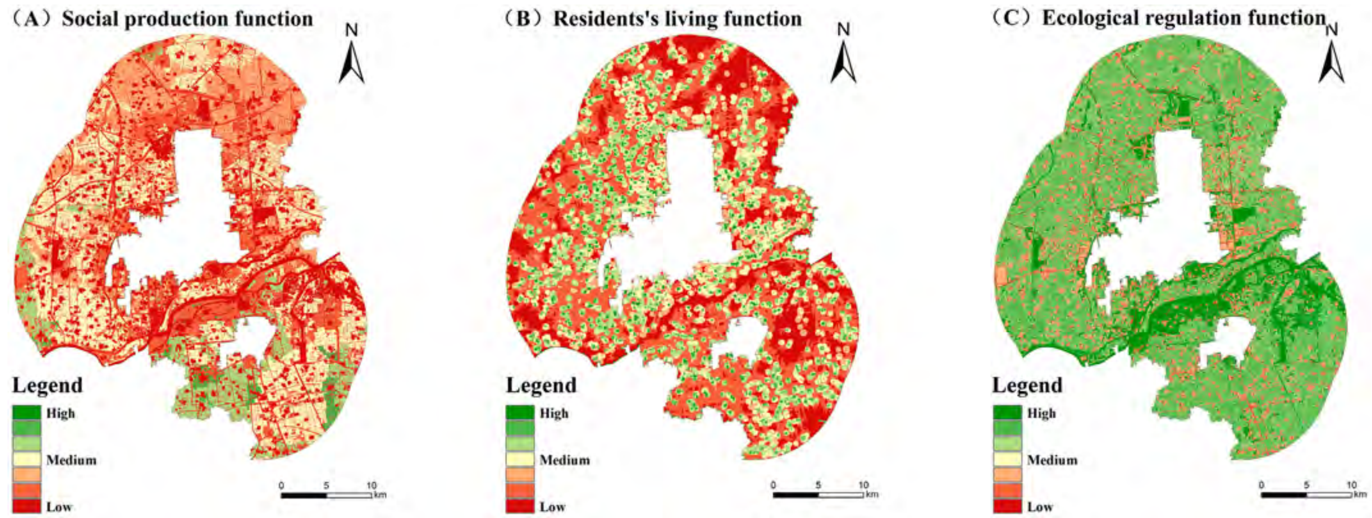

Fig. 4. The spatial pattern of the three primary land use functions.

conservation zone (ECZ), ecological recreation zone (ERZ), urbanization development zone (UDZ) and land reserve zone (LRZ).

Due to the multiple driving factors of urban development, economic efficiency, and China's unique "Cultivated Land Requisition Compensation Balance" land use policy, the encroachment of ecological land by construction land has been and will be the main land use activity occurring in regions with relatively high land value, such as urban fringe areas, over a long period of time. Therefore, policy makers and city planners are truly concerned about the location, pattern, intensity and economic-ecological consequences of construction land and high-intensity land use types during the process of urban expansion. Based on the land use functional zoning scheme obtained above, we suggest that the urbanization development zone (UDZ) and land reserve zone (LRZ) are suitable for containing high-intensity human development and utilization activities. Medium-intensity human activities or suitable development construction could be established in the agricultural production zone (APZ), multifunctional agricultural zone (MAZ) and ecological recreation zone (ERZ). As the ecological conservation zone (ECZ) is the main supply center of ecosystem services, conservation and protection activities are encouraged in this zone. By extracting the types of ecological land and construction land and superimposing them with the land use functional zoning map, we have drew another functional partition map of human activities and utilization intensities in the studied urban fringe area (Fig.8, Table 4).

4.2. Implications for land use planning and management

Identifying distinct functional zones is an effective approach to integrated land use planning and management (Bennett, 2016). Adopting diverse control measures for different functional divisions is an important way to improve the overall land use efficiency and contributes to the allocation optimization and sustainable development of land resources in urban fringes.

From the perspective of land use functions, different land use development directions should be determined according to the corresponding functional characteristics of the land area. Both the agricultural production zone (APZ) and multifunctional agricultural zone (MAZ) are important agricultural production bases in Binzhou city. Due to the severe soil salinization problem in the Yellow River Delta, appropriate improvement measures should be incorporated into the planning and management system to better maintain the functions of cultivated land. For instance, efforts such as the promotion of water-

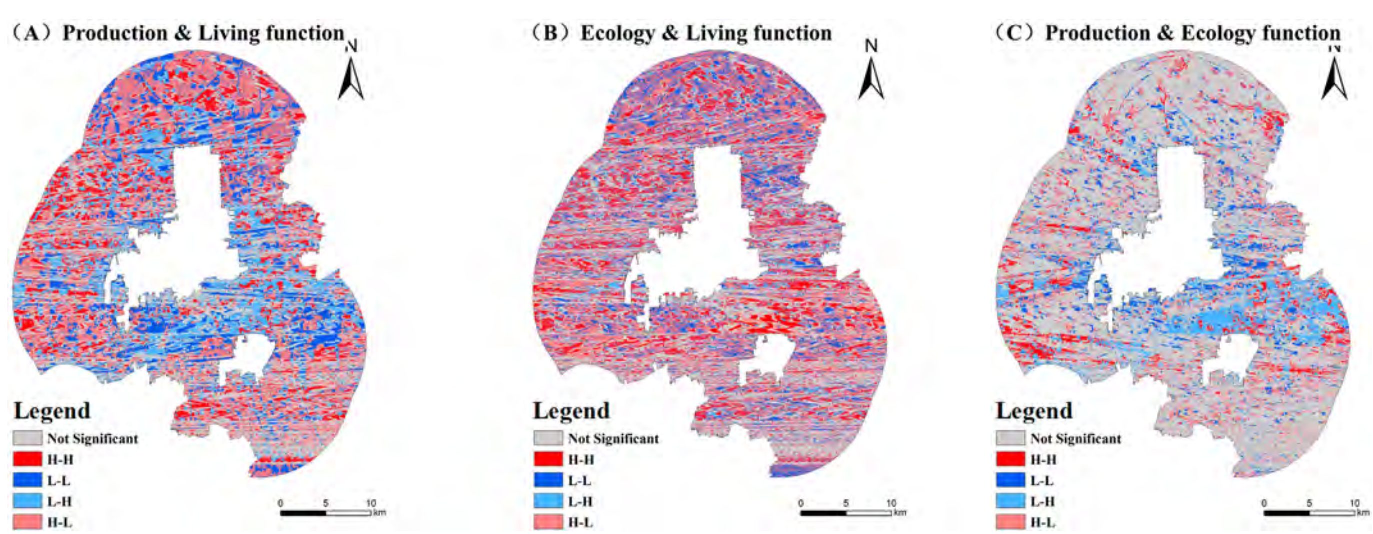

Fig. 5. Spatial distribution of trade-offs and synergies between the three primary land use functions.

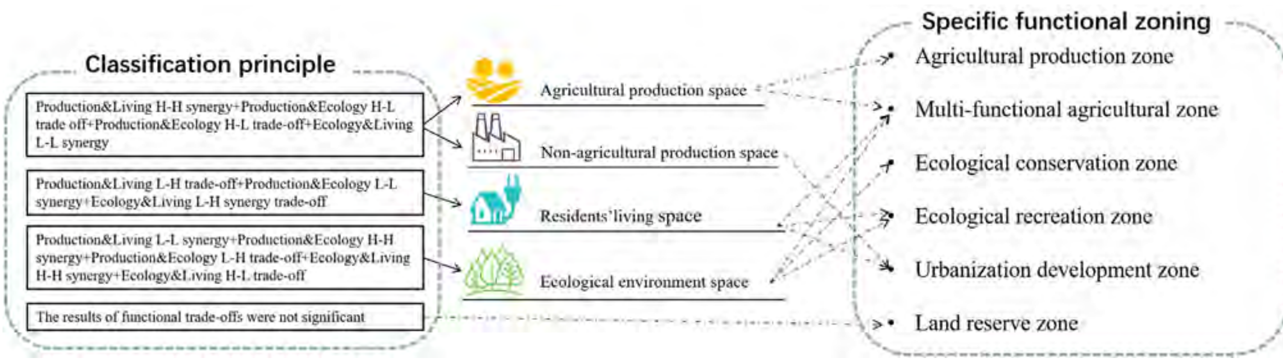

Fig. 6. Classification principle of land use function zoning.

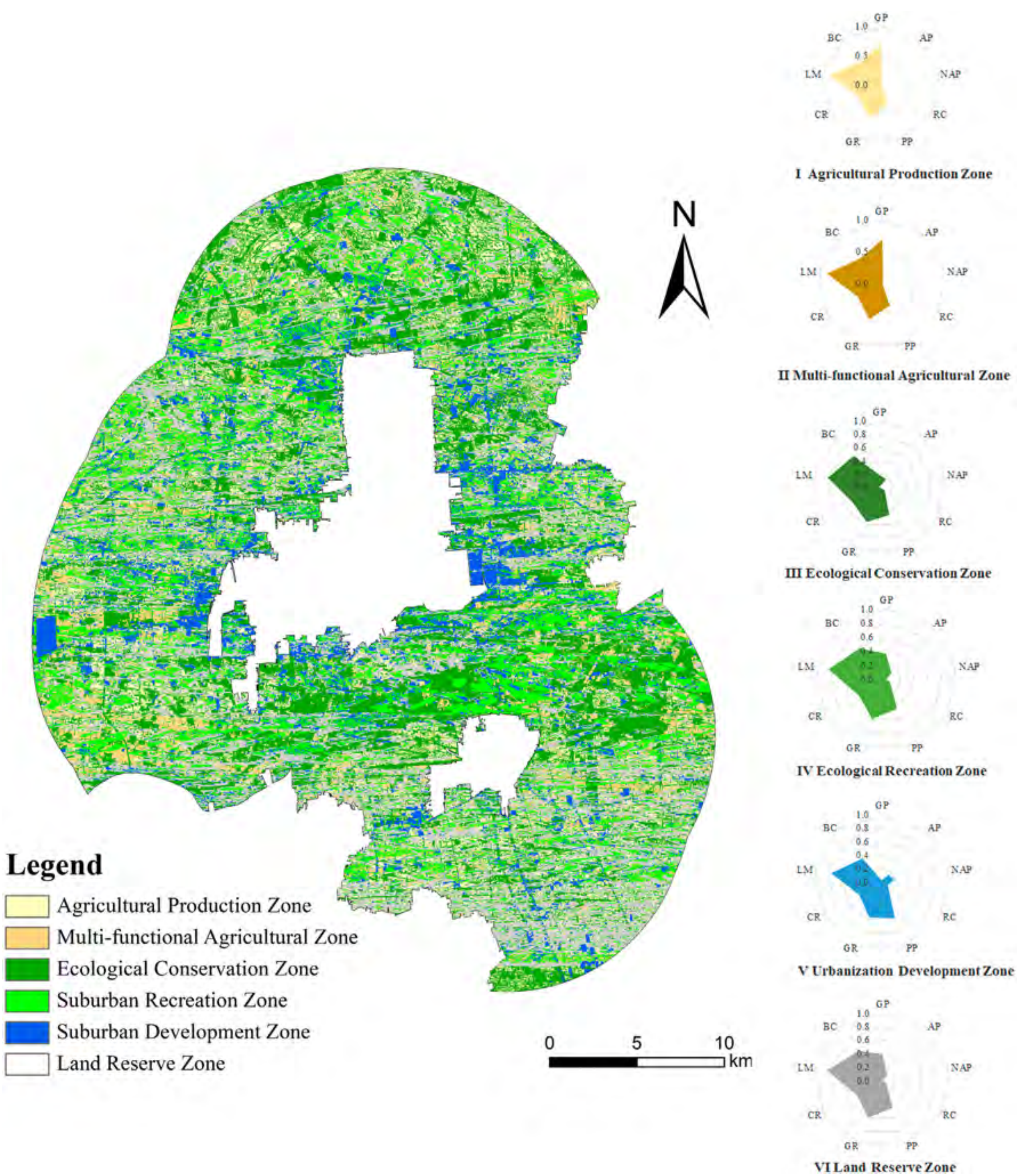

Fig. 7. Land use function zoning of the urban fringe in Binzhou city. The radar chart shows the average value of each function in each functional area, and the values were standardized by the z-score and are displayed on a scale from 0 to 1 .

Table 4
Description of two functional partition schemes.

Zoning principle	Name	Characteristic description	Area ratio (%)
Land use functional zoning	APZ	Districts with good production capacities related to cereals, corns, vegetables and other agricultural products.	12.1
	UDZ	Suitable for socioeconomic human activities and construction	10.7
	ECZ	Provides a series of high quality ecosystem services for residents	25.8
	MAZ	Illustrate a certain degree of advantages in terms of living functions or ecology functions on the basis of agricultural production	10.5
	ERZ	Represent good ecology and living functions and can provide natural landscape leisure resources for residents	17.1
	LRZ	Does not show obviously functional tendencies and can be flexibly adjusted in the future planning	23.8
Utilization intensity zoning	PDZ	Living dominated trade-offs among production, living and ecology functions	26.6
	MDZ	Complex trade-offs and synergies among production, living and ecology functions	36.9
	RDZ	Ecology dominated trade-offs among production, living and ecology functions	21.2
	CZ	High-intensity development and construction area	15.3

(The abbreviations in this tables are as follows: APZ represents the agricultural production zone; UDZ represents the urban development zone; ECZ represents the ecological recreation zone; MAZ represents the multifunctional agricultural zone; ERZ represents the ecological recreation zone; LRZ represents the land reserve zone; PDZ represents the priority development zone; MDZ represents the moderate development zone; RDZ represents the restricted development zone; and CZ represents the construction zone.).

saving facilities and planting techniques, the introducing of salt-tolerant crop varieties, and the encouragement of comprehensive land consolidation projects would help to demonstrate the synergies among various land use functions. The ecological conservation zone (ECZ) plays an important role in providing diverse ecosystem service functions in complex urban system. In this zone, the occupation of ecological space for nonecological use must be strictly limited, and the exploitation of this zone must be prohibited. In the ecological recreation zone (ERZ), land fragmentation caused by urban expansion and development generally results in a trade-offs between living functions and ecology functions. Seeking a balance between residents' well-being and ecological protection will be the long-term focus of the government. Encouraging the planting of green belts on both sides of the main road represent a simple but practical approach, that can weaken the barrier presented by roads to species migration and increase the connectivity among important habitats (Kong et al., 2010). The urbanization development zone (UDZ) is of vital importance for scientifically managing the quantity, intensity and standards of construction land. More compact urban growth should be promoted through the intensive use of current construction land resources; this measure would contribute to reducing the total expanded urban area and minimizing the negative influence of urban sprawl on multiple land use functions. As the land reserve zone (LRZ) has not been characterized to contain specific land use functions at present, disordered development and construction activities would not be conducive to enhancing the multifunctional value of the land in this zone. Formulating elastic, detailed planning tools and flexible land use management policies will contribute to the long-term goal of sustainable urban development and will also represent a reasonable attempt to scientifically address uncertain challenges in the coming future.

Under the utilization intensity zoning scheme, it is necessary for natural resource management departments to integrate differentiated management tools, especially for complex districts such as urban fringe where farmlands and woodlands occupy the dominant land use type positions. First, as a policy tool, planning is a vital step for controlling land use. Adhering to the concept of "planning first" helps to the macroscopic land use zoning layout and makes the planning and determination of land functions more scientific and reasonable. Besides, strengthening the spatial concept transmission and index decomposition of planning at different administrative levels (such as city, countries, townships and villages) is conducive to coordinated regional development, especially for those cross-administrative areas or non-administrative areas like urban fringe. Second, appropriate access standards or boundaries are an important prerequisite for differentiated management. Constructing a composited standard system including constraint indicators (such as the farmland area and forest occupancy rate), development indicators (such as the development intensity and plot ratio) and comprehensive indicators (such as the air quality and biodiversity) contributes to the realization of functional land utilization partitions. Last but not least, farmers, urban residents, governments, developers and other groups are all important participants in the urban fringe development and utilization processes (Allen, 2003). Thus, land use intensity governance must reach a challenging consensus among very different needs associate with diverse stakeholders (Hudalah et al., 2007). The approaches to LUFs trade-offs and partition management by governments require improved multisubject coordination in order to address different development requirement levels (Spyra et al., 2020; Dupont, 2007).

4.3. Limitations and future projections

Although the LUFs trade-off and functional zoning schemes developed in this study have good applicability and scientific bases, there are still some shortcomings in this study; these shortcomings are described as follows. First, for the purpose of functional partitioning and high-precision mapping, this study only selected land cover data representing 2019 for analysis. Therefore, the LUFs trade-offs discussed in this study can only be regarded as a static identification of land use multifunctionality in the single year of study. Further discussion regarding spatial-temporal dynamic LUFs changes might be carried out in follow-up research. Second, all the evaluations conducted in this study were carried out within 10 km of the urban built-up areas, meaning we only considered the radiative impact of the urban center on the urban fringe. However, the wider rural areas outside the urban fringe could also affect the LUFs of the urban fringe to a certain extent, and these influences were ignored by default in this study. Third, although we have tried our best to select indicators and parameters that were suitable for fine-scale research, some inaccuracies and uncertainties still remained in the functional quantifications. For example, the Invest model is a commonly used method in habitat quality evaluations, but this model has been confirmed to have systematic errors when comprehensively calculating threat factors (Sharp et al., 2018). In addition, our team comprehensively determined the indicators, parameters and weights used in this research, and although expert judgment was used, biases may have been introduced in the final results. Finally, this study only proposed an ideal functional zoning scheme from the perspective of LUFs identification. However, there is still a long way to go from academic research to planning in practice due to countless limited factors that must be considered in real applications. For example, "basic farmland protection policies" and "ecological red line control" are typical constraints that cannot be ignored in the process of urban expansion in China. Discussing these nonfunctional constraints is necessary to benefit land use function mapping in the future.

Despite the limitations described above, our research provides a typical fine-scale LUFs identification case reference for land use management and spatial planning in urban fringe areas under the background of rapid urbanization. Regarding the research prospects of fine-scale

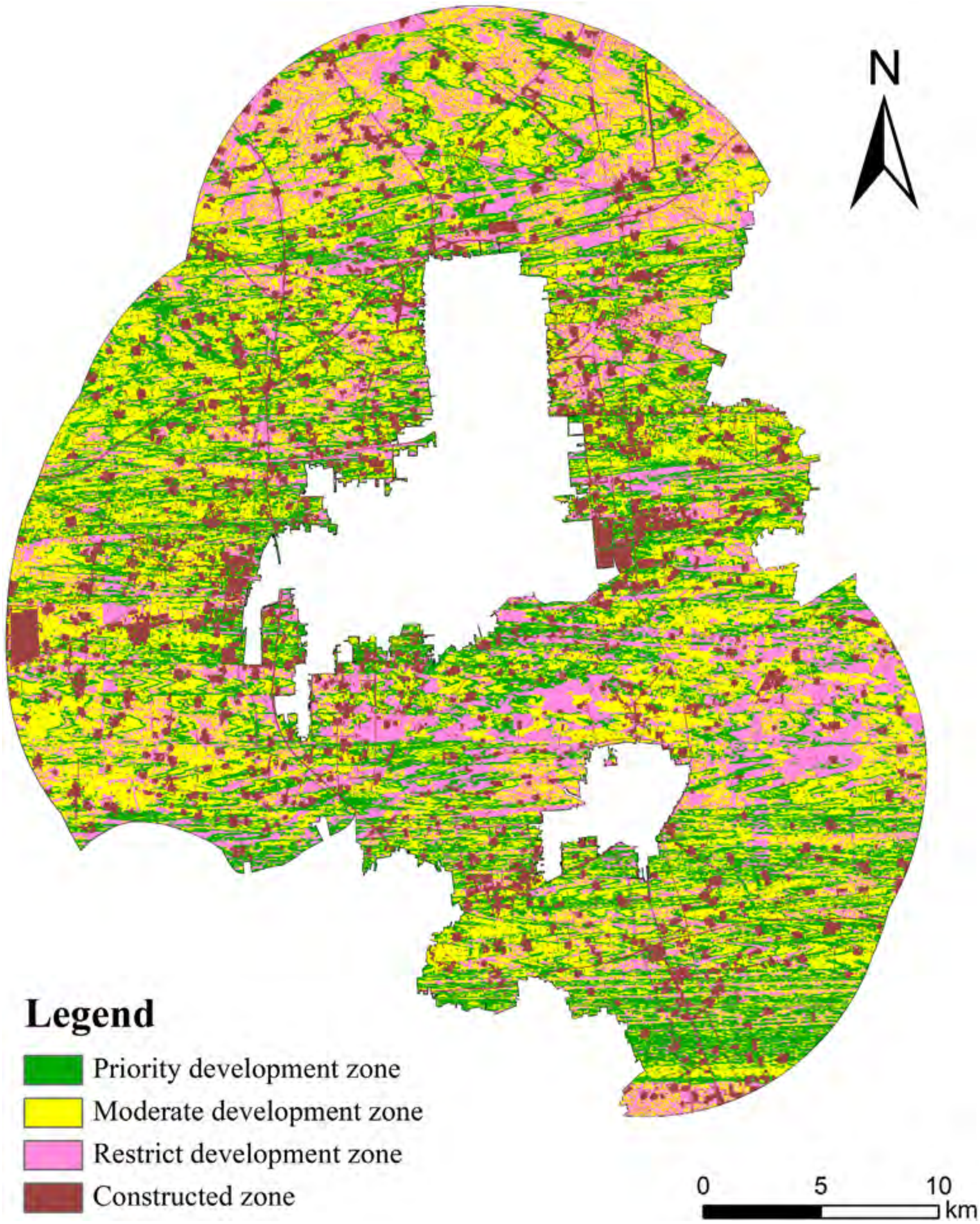

Fig. 8. Utilization intensity zoning of the urban fringe in Binzhou city

LUFs research, there are still two important directions worth exploring in the future. One direction is the innovation of data materials and evaluation indicators. A variety of high-resolution satellite data, synthetic aperture radar (SAR) data and point of interest (POI) data have already been widely used to study urban problems, and these data can also provide new perspectives for LUFs research. The other direction involves integration with appropriate policy tools. Fine-scale LUFs research can guide land use patterns and human activities in much smaller areas than that considered in this research. Therefore, this type of research should be combined with more practical spatial control policies and measurements to highlight its accuracy advantages.

5. Conclusion

The multifunctionality of land has been widely recognized; however, the potential of land to provide functions unrelated to socioeconomic development has often been neglected by urban planners and policymakers. In this study, we established a novel evaluation system to identify and analyze LUFs at the local scale. In addition, we selected an urban fringe area as the research area and integrated the evaluation results with spatial planning. To our knowledge, these combinations have rarely been seen in past research. The results demonstrate that diverse LUFs are spatially clustered and associated rather than randomly distributed. Based on the hot/cold spot analysis results, we eventually divided the urban fringe area into different planning zones from the perspective of the corresponding land use functions and human utilization intensities and proposed differentiated management suggestions for the sustainable development of these zones.

Competition and conflict under high land use intensities cause the trade-offs and synergies among land use functions and landscape ecosystem services to be popular issues in academic research (Westerink et al., 2013). On the one hand, LUFs are good quantitative factors for distinguishing the structures, combinations and dynamic trade-offs of functions among different land use systems (Slee, 2007). On the other hand, due to administrative divisions, governance structures and other realistic factors, urban-rural transitional zones such as urban fringes rarely appear as a target object for spatial tools. The concept of LUFs can provide a rational foundation for spatial governance and land use planning. The empirical results of the Binzhou case considered in this study provide relevant insights into how LUFs trade-offs can contribute to supporting spatial planning and land use management, thereby better establishing the coordinated development of urban-rural areas, especially in developing countries such as China, where land availability is limited.

CRediT authorship contribution statement

Yuefeng Lyu: Methodology, Visualization, Writing – original draft. **Mengjing Wang:** Conceptualization, Writing – review & editing. **Yinuo Zou:** Writing – review & editing. **Cifang Wu:** Supervision.

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 presented in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.149915.

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