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Trade-offs/Synergies in Land-use Function Changes in Central China from 2000 to 2015

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Abstract: To solve the problems caused by irrational land-use, studying the functions of land-use, its changing characteristics, and the relationship between each land-use function will be beneficial for achieving sustainable land development. In this research, we constructed an evaluation framework of multiple land-use functions (LUFs) based on sustainable land-use theory. Specifically,, we classified the multiple LUFs into three types: agricultural production function (APF), living function (LVF), and ecological service function (ESF). We then spatialized the economic and social data, and implemented the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model and RUSLE (Revised Universal Soil Loss Equation) model to evaluate each sub-LUF (crop production, aquatic production, woodlands production, livestock production, living space, life quality, water supply, soil conservation, climate regulation, biological conservation) in central China in 2000 and again in 2015. Moreover, by analyzing the changes to LUFs and the relationships between each LUF change, we were able to discern patterns of LUF change in central China. The results show that: 1) 42.12% of total territory in the study area increased their APF from 2000 to 2015, while 43.41% of the lands increased their ESF yet only 8.98% of the lands increased their LVF; 2) in Hubei and Hunan, there was more land with an increase of APF than in Anhui or Jiangxi. The APF in Jiangxi exhibited the greatest decline over time period, the LVF increased more in the provincial capital cities than in other regions, and the ESF expanded more in Jiangxi than in the other provinces; and 3) the changes in APF were significantly and positively correlated with changes in LVF. Additionally, changes in ESF were negatively but non-significantly correlated with changes in APF and LVF.

Keywords: land planning; land-use function (LUF); trade-offs; synergies; central China

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1 Introduction

The increasing number of industries and populations concentrated in cities is speeding up the expansion of construction land, which is displacing agricultural space (Lu et al., 2015) and destroying the ecological environment (Dai et al., 2019). This mounting imbalance in land-use (Su et al., 2011) has exacerbated the conflict between urban, agricultural, and environmental spaces, resulting in severe soil erosion, air pollution, and habitat degradation. Suitable land planning and management are critical for achieving the goal of Sustainable Development (SDGs)of the United Nations by 2030, from the aspect of economic, environmental, and social sustain-

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able development. As the basis of the 'population-society-environment' mega-system, the sustainable use of land resources is of great significance. In order to promote this goal, the International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions Programme on Global Environmental Change (IHDP) have jointly developed the Global Land Project, which aims to measure, model, and understand land system use and change from the perspective of coupled human-social–ecological systems. How to regulate land development (Lowe et al., 1993), promote the optimal allocation of resources (Wu, 2019), and reconcile land-use conflicts (Bax et al., 2019) between development and nature protection has become a major scientific issue for the sustainable development of different regions and countries worldwide, including China.

Land-use (LU), being one of the major determinants of global environmental change, is at the core of land planning and land management, with significant implications for ecosystems, climate change, and human vulnerability (Polasky et al., 2011). LU patterns include both explicit and implicit forms (Long and Qu, 2018). The former is the spatial distribution and landscape structure of differing land-use/land-cover (LULC), which can be observed via field surveys or remote sensing monitoring (Dadashpoor et al., 2019). A tremendous amount of research has explored changes to LULC. Land-use functions (LUFs), the implicit forms of LU, refer to the ability of the land to provide goods and services to meet human needs, which depends not only on the land resources but also on how people use the land and what humans need from the land. The approach of multifunctional land-use (MLU) takes synergy effects of LUF into consideration, which aims to improve land-use intensity and efficiency and strike a balance in the relationship between scarce land and increasing social development.

A rational land-use system should maximize ecological functioning while also satisfying human wellbeing. The classification methods vary among studies because they were doing under different social background and aimed to solve different problems. Normally, an evaluation of MLU will consider three dimensions, namely ecological function, economic function, and social function. The land's ecological function often refers to the ability of local land to keep soil from eroding, to store carbon, and to provide habitat for animals and plants. The economic function evaluation of land is based on its local resources, while the social function of land is its ability to living space that makes people feel comfortable. These three land-use functions interact with each other. For example, a place with a sound ecological environment could provide humans with a better living environment. In China, when farming on fragmented and uneven land, farmers are unable to use agricultural machines to enhance the farming efficiency and farmland management practices (Zhou et al., 2019). Agricultural land consolidation addresses this problem by pooling the fragmented land parcels, which collectively improves the agricultural functioning of that land (Liu et al., 2016). Farmland consolidation also adds to the economic function of land by promoting the capitalization of land resources and changes the ecological function of land by both reducing land fragmentation and modifying biodiversity on land. Notably, an MLU function evaluation not only considers non-commodity services (e.g., climate regulation (Yang et al., 2013), habitats (Lewis, 2009), and water-related ecosystem services (Chen et al., 2018), but it also integrates the commodity services which address human needs (e.g., provisioning of agricultural products or living space).

Current studies on MLU evaluation tend to focus on a certain scale unit, like a nation, a province, or a city, but few researchers have tried to evaluate multiple provinces with similar social eco-environmental background and sharing the same national development policy. Moreover, the data of most existing studies are sourced from socio-economic statistics and their unit of inquiry was at county-level, instead of combing multiple data sources and take finer-scale resolution grid as the evaluation unit. Further, few studies have yet answered how multiple land-use functioning changes temporally (over years) or sought and examined trade offs/synergies for the respective LUF changes. Understanding the relationship of such changes in each LUF is imperative for land-use zoning and devising land-use policies to facilitate sustainable land-use practices.

Central China (i.e., Hubei Province, Hunan Province, Anhui Province, and Jiangxi Province) is one of the major grain production areas in China. It is rich in ecological resources and types of natural landscapes, with several national nature reserves, scenic spots, forest parks, and geological sites, such as Dongting Lake in northwest Hunan Province, Poyang Lake in the northern Jiangxi, Shennongjia in the eastern Hubei, and the Huangshan Mountains in the southern Anhui. These four provinces are similar in terms of climate, natural resource endowment, economic status, and agricultural system. Given this background, these four provinces were treated as one component of the pilot sites used by the Ministry of Natural Resources of the People's Republic of China for monitoring and survey of cultivated land resources (Ministry of Natural Land and Resources of People's Republic of China, 2015–2018). The speed of urbanization speed in this area has been fast in recent decades. The urbanization rate jumped from 45.8% in 2000 to 56.6% in 2015 in Hubei, from 29.7% to 50.9% in Hunan, from 27.7% to 60.0% in Jiangxi, and from 28.0% to 50.5% in Anhui (National Bureau of Statistics of Anhui Province, Hubei Province, Hunan Province, Jiangxi Province, 2011–2016). By 2015, the amount of per capita arable land in this region dropped to 713 m^2 (National Bureau of Statistics of China, 2016), close to the warning line (533 m^2) set by the United Nations; this has caused resource constraints that increasingly tighten and threaten food security there. Forests and grasslands have been reduced in coverage by 20.18 × 10^5 km^2, while soil erosion, soil pollution, air pollution, and biodiversity degradation are still persistent major problems (Xu et al., 2020). In short, irrational human activities have altered the structure of land-use, resulting in drastic changes in the LUFs.

In this research, we addressed three key questions: 1) what is the spatial patterning of changes in LUFs—agricultural production function, living function, and ecological services function—in central China from 2000 to 2015? 2) In what way do the changes to the respective LUFs interact with each other? 3) What are the drivers for the spatial heterogeneity of changes in LUFs? Compared with prior research, this study offers a more detailed understanding of the relationship of LUF changes in central China, which is helpful for policy makers to identify the spatial heterogeneity of local land-use problems, to pursue the twin goals of economic benefits and environment preservation.

2 Materials and Methods

2.1 Study area

Central China (Hubei Province, Hunan Province, Anhui Province, Jiangxi Province) is situated in the middle reaches of the Yangtze River, located between 24°29′N–34°62′N and 108°47′E–119°06′E. The corresponding administrative area covers 70.47 × 10^4 km^2. The terrain of this area is mainly that formed by plains, hills, and mountains (Fig. 1), where a subtropical mon-

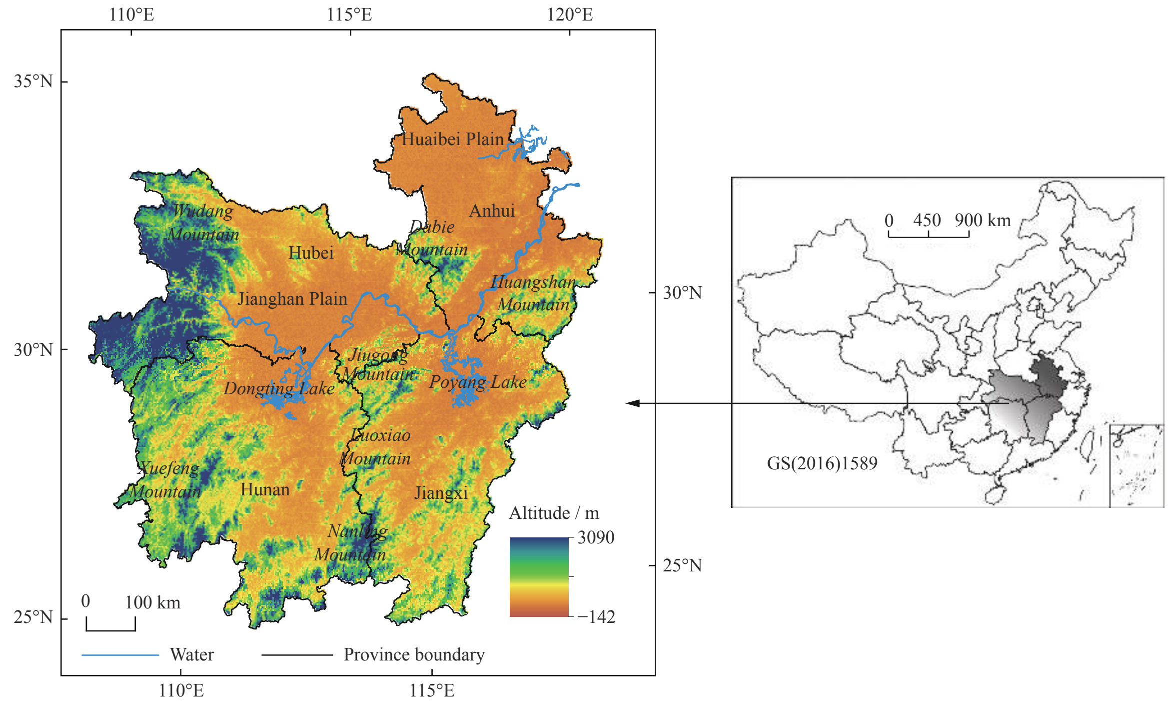

Fig. 1 Maps showing the location and elevation of central China

soon climate prevails, with four distinct seasons. Here, the annual precipitation is 800–1600 mm and the yearly average temperature is 15℃ to 20℃; most crops are grown twice per year.

2.2 Data sources

Agricultural output value in 2000 and 2015 was each obtained from the China Statistical Yearbook (National Bureau of Statistics of Anhui Province, Hubei Province, Hunan Province, Jiangxi Province, 2001–2016) and China Statistical Yearbook for Regional Economy (National Bureau of Statistics of China, 2001–2016). The root depth data (2000, 2015) came from The Big Earth Data Platform for Three Pole (http://poles.tpdc.ac.cn); the data for soil types (1990), leaf area index (2000, 2015), environmental protection areas in 2013, and road network in 2002 and 2015 were sourced from National Earth System Science Data Center (http://www.geodata.cn). The data for LULC coverage in 2000 and 2015 (1 km × 1 km), population density in 2000 and 2015 (1 km × 1 km), the normalized difference vegetation index (NDVI) for 2000 and 2015 (500 m × 500 m), net primary productivity (NPP) for 2000 and 2015 (1 km × 1 km), and digital elevation model (DEM) were obtained from the Data Center for Resources and Environmental Sciences (RESDC) (http://www.resdc.cn). Finally, the gauge daily meteorological data (wind direction, wind speed, precipitation and air pressure, temperature) of 2000 and 2015 were from Meteorological Data Center of China Meteorological Administration.

2.3 Classification of LUFs and research workflow

Land has multiple functions. Focusing on the economic goals of the SDGs, the functions of land include poverty eradication, hunger eradication, decent work and economic growth, responsible consumption and production, among others. Land-use function could also be divided into biomass versus non-biomass supply function. The biomass production function corresponds to land for agriculture, forestry, animal husbandry and fishery, while land for the non-biomass production function is mainly industrial land, mining land, storage land, and commercial land. In China, the land-use type in land-use planning is normally classified into three major types (Fig. 2): the agricultural space, living space, and ecological space. Following this land-use classification, the MLU functioning can also be classified, accordingly, into three dimensions: agricultural production function, living function, and ecological function. These three the dominant functions are closely related to the goal of sustainable land-use, and they have been adopted by the academic community.

The steps of this research went as follows (Fig. 3): 1) we first classified LUFs into three aspects: the agricultural production function, living function, and ecological service function; 2) next, we assessed the LUFs and their changes from 2000 to 2015, by spatializing the economic and social data and by using the InVEST and RUSLE models; 3) we determined the spatial correlation between the LUFs; and 4) finally, we summarized the spatial patterns of LUF changes and analyzed the reasons for these changes.

2.4 Evaluation framework of LUFs and trade off/synergy analysis among LUF changes

2.4.1 Evaluation methods of land-use functions

(1) Agricultural production function

Agricultural space, for which the primary objective is ensuring the survival and development of human beings, has the function of agricultural production, mainly the provisioning agricultural products and services. Due to real-world problems, such as the multi-appropriateness of land-use and the diversity of production, it is difficult to refine the production capacity of land-use through one or even several indicators. The indicators currently used for the analysis of agricultural functioning include the agricultural GDP (Fan et al., 2019), agri-

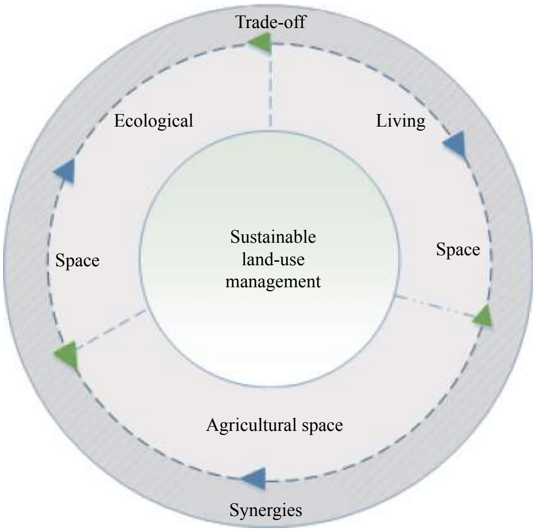

Fig. 2 Trade off/synergies between agricultural space, living space, and ecological space

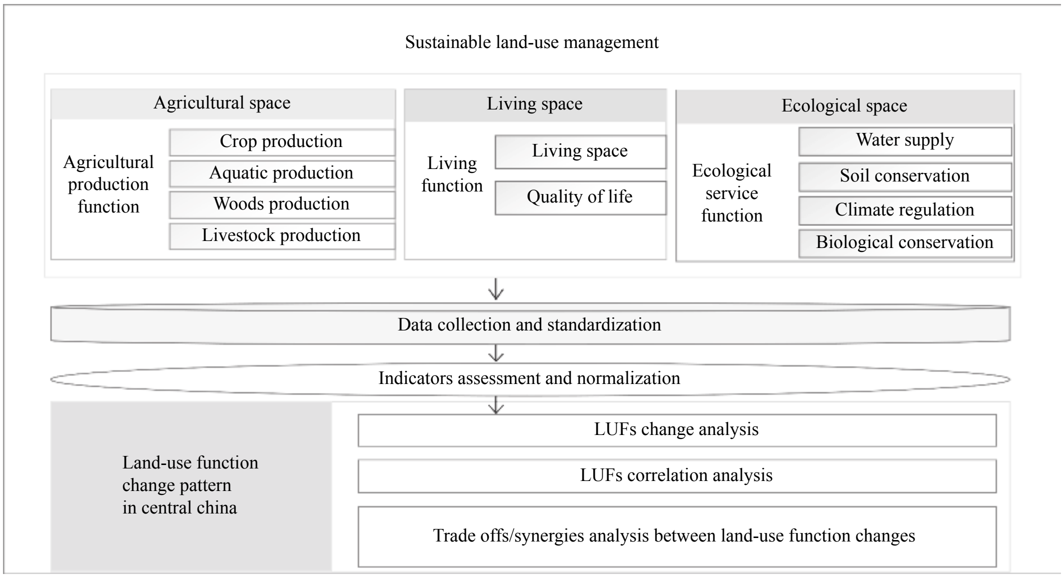

Fig. 3 Research workflow used in this study

cultural production output, per capita livestock, land settlement rate (Cheng et al., 2017), and NPP (Zhang et al., 2019). In central China, the agricultural area is distributed on the plain and alongside the water area (Fig. 1), where the fishery industry is well developed. Both aquatic products and animal husbandry are also essential components of regional agricultural production. Moreover, the government is encouraging farmers to develop the forestry industry. Therefore, this paper subdivides the agricultural production function (APF) into four sub-functions: crop production, livestock production, aquatic production, and wood production. Referring to Fan's research (2019), we use the corresponding agricultural outputs as the indicators for APF.

(2) Living function

This dimension focuses on the social goals of the SDGs, including the targets of good health and well-being, quality education, gender equality, clean water and sanitation, industrial innovation and infrastructure, sustainable cities and communities, and so on. Living space offers people a place to live, which is also associated with the psychological wellbeing of its citizens (Hu and Coulter, 2017). Accordingly, its main indicators are population density (Zhang et al., 2019), freight volume per 10 000 people, passenger volume per 10 000 people, proportion of tertiary industry personnel, proportion of land for urban and village settlements (Lin et al., 2010), traffic land density (Zhang et al., 2019), number of hospital beds per 10 000 people (Cheng et al., 2017), and total retail sales of social consumer goods per capita (An et al., 2018). Data of each indicator were obtained from statistical yearbooks, road vector data, and DMSP-OLS Nighttime Lights Time Series. Given the strong correlation between transportation, medical care, population density, service industry, and GDP, and the difficulty of obtaining consistent statistical yearbook data for all four provinces, we chose the living space and quality of life as indicators of the living function of the land. We divided the built-up land area by the population density to represent the population pressure of land; the greater the population pressure, the less space there is for each person. We divided the gross domestic product (GDP) by the population to represent the quality of life. We assumed that the higher the GDP, the better the local public services and the more money a person has at their disposal, so a better life can be afforded. Since these indicators have been widely used in other studies (e.g., Ramesh et al., 2009), our results could be compared with similar research findings.

(3) Ecological function

The function of ecological space is to maintain environmental security and provide ecological goods and services. The environmental objectives of the SDGs are the main ones, which entail specific objectives, such as cheap and clean energy, climate action, underwater organisms, and terrestrial organisms, to name a few. The land-use system is influenced by natural elements such as water, soil, air, and living things, and has various ecological service functions, notably those of water yield, soil erosion control, climate regulation, and biodiversity maintenance. The commonly used indicators are habitat quality, water yield, carbon sequestration, soil erosion, agricultural fertilizer input intensity, land degradation index, per capita water resources, habitat abundance index, and total ecological service value (Li et al., 2019). The corresponding data for analysis are often obtained in various ways, such as from meteorological stations, hydrological stations, statistical yearbooks, and field surveys.

The classification of land-use functions in different regions is not necessarily unique, and the dominant land-use function should be selected according to local conditions, by considering regional characteristics as well as development goals and stages. In central China, water sources in the form of lakes and rivers, including Dongting Lake, Poyang Lake, Chaohu Lake, Xiangjiang River, Hanjiang River, Ganjiang River, and Huaihe River, constitute a vital part of the local ecology. One also finds wetlands and forests harboring rich biodiversity. Yet land-use patterns incorporating serious human disturbance significantly affect the regional hydrology, soil, climate, and biology, which is concerning because the ecosystems in central China are sensitive and fragile (Song and Deng, 2017). We selected four indicators corresponding the four subsystems of the earth system (hydrosphere, geosphere, atmosphere, and biosphere) to represent the ecological function of land, namely water yield, soil conservation, carbon storage, and habitat quality.

A. Water yield

The water supply is represented as the water yield, this derived from the InVEST-Water Yield model. It estimates the annual average quantity of water produced by a watershed, defining water yield as the amount of water lost from the landscape, whose calculated sum and averages are based on the principle of water balance at the sub-watershed level. The annual water yield $Y(x)$ for each pixel on the landscape x is determined as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \quad (1)$$

where $AET(x)$ is the actual annual evapotranspiration for pixel x, and $P(x)$ is the annual precipitation received by pixel x.

Here we followed the procedure described by Yang et al. (2019). That research work was located in South China (Xiangjiang River Basin), which is of great reference value to our present work because Xiangjiang River is within our study area, which also has subtropical monsoon climate. The annual precipitation was interpolated by Kriging interpolation and calculated from the daily rainfall data, using Python 3.6. The reference evapotranspiration value was calculated using the Hargreaves Equation (Hargreaves and Allen, 2003). Soil depth data were taken from the published dataset of soil properties for land surface modeling over China (Shangguan and Dai, 2019). The plant available water fraction ($PAWF$) was calculated as follows:

$$\begin{aligned} PAWF = {} & 57.509 - 0.132 \times sand - 0.003 \times (sand)^2 - 0.055 \times \\ & silt - 0.006 \times (silt)^2 - 0.738 \times clay + 0.007 \times \\ & (clay)^2 - 2.688 \times OM + 0.501 \times (OM)^2 \end{aligned} \quad (2)$$

where the $clay$, $sand$, $silt$, and OM terms are the proportion of clay, sand, silt, and organic matter in the soil, respectively.

B. Soil conservation

Researchers around the world use the Soil Erosion Index to measure the effectiveness of soil conservation (Morgan et al., 1984). Soil erosion changes the landscape and disrupts the carbon cycle at multiple scales (Ito, 2007), and it also reduces crop yield and biomass production. With more soil erosion, less soil is conserved. The most common models employed for assessing soil erosion are the InVEST Sediment Delivery Ratio Model (Li et al., 2014), the Soil and Water Assessment Tool (SWAT) model (Abdelwahab et al., 2018), and the Revised Universal Soil Loss Equation (RUSLE) model (Prasannakumar et al., 2012). Each model has its advantages and disadvantages. The RUSLE model is effective when making a large regional evaluation (Shinde et al., 2010). In the present study, we calculated the RUSLE by referring to work by Lu et al. (2015). The RUSLE relates the rate of soil loss in tons per acre per year (A) to the erosive power of the rain (R), the soil erodibility (K), the land slope and length (LS), the degree of soil cover (D), and conservation practices (P), as shown below.

$$A = R \times K \times LS \times D \times P \quad (3)$$

C. Carbon sequestration

Soil carbon sequestration relates to the climate, plants, and agriculture (Lal, 2004). According to earlier research (Liu et al., 2015), we used the annual NPP as the main indicator to calculate carbon sequestration. Carbon sequestration is calculated this way:

$$CS = NC \times \beta \times \sum NPP \tag{4}$$

where *NC* is the content of carbon (C) in carbon dioxide (CO_2), which is 27.27%, and β = 1.63. Hence, for every gram of biomass produced by a plant, 1.63 g of carbon dioxide is absorbed and 1.19 g of oxygen is released.

D. Habitat quality

The habitat quality in the InVEST model refers to the ability of the ecosystem to provide conditions appropriate for the fauna individual and population persistence. These parameters are identical to those used in previous research (Li et al., 2021).

2.4.2 Trade-off/synergy analysis in LUF changes

We unified all data in terms of the administrative boundaries (2015), map projection (Gauss-Krüger projection), and geo-coordinate system (GCS_China_Geodetic_Coordinate_System_2000). We used the 'Create Fishnet' tool in ArcGIS 10.7 to create a 0.1° × 0.1° grid, and all data were unified under this grid by using Zonal Statistics. To normalized the index in Table 1 by using the min-max normalization procedure. Then, the 'Raster Calculator' tool in ArcGIS 10.7 was used to subtract the values of each LUF indicator (primary index and subindicators) in 2015 from its counterpart in 2000. Next, we used the 'Band Collection Statistics' tool in ArcGIS 10.7 to obtain a matrix of Pearson's *r* correlation coefficients between the changes of each LUF indicator, and analyzed the spatial relationship between the LUF changes in the study area. The correlation between two layers is a measure of dependency between them, and its value can range from +1 to –1: a positive correlation means they are synergistically related, and the opposite is true for a negative correlation. Finally, we used the average variation in the agricultural production function, livelihood function, and ecological services function as their respective threshold to calculate deviations from each primary index. That is, when the change in the cell is greater than the average change in the study area, it means that it has a positive effect on the enhancement of that particular local land-use function, which is recorded as '+'; otherwise, it has a negative effect, this recorded as '–' (Fig. 4; Table 2). We used the spatial 'Overlay Function' in ArcGIS 10.7 to identify spatial patterns of the trade-offs and synergies among temporal changes to agricultural production function change, living function change, and ecological service function.

3 Results and Analyses

3.1 Sub-land-use function changes from 2000 to 2015

The changes in each sub-LUF of the APF (agricultural production function), LVF (living function), and ESF (ecological service function) from 2000 to 2015 all show obvious spatial heterogeneity (Fig. 5). Similar to ecosystem services, the trade-offs and synergies between land-use functions and their changes can be identified and gauged by their correlation coefficient values (Table 3). A positive correlation indicates that two types of LUFs either increase or decrease at the same time, while a negative correlation indicates a trade-off relationship in which a given land-use function diminishes with the enhancement of another LUF. From 2000 to 2015, most places in Hunan Province experienced an increase in crop, aquatic, wood, and livestock production levels, except in western Hunan Province where the amount of woodlands production has fallen (Figs. 5a–5d). The places undergoing a reduction in primary production were mainly distributed in the north of Anhui Province and in Jiangxi Province's north and central parts. In Hubei Province, except for crop and aquatic production declining in its northern part, the sub-agricultural production function of other parts has risen. The overall sub-land-use-function with respect to LVF in the central China has evidently increased, except for some decreases in living space detected in the northern Anhui Province and eastern Hubei Province (Figs. 5e, 5f). However, the water supply function in central China is in decline (Fig. 5g), which is driven by climate change impacts, that is warmer temperatures hasten evaporation accompanied by less precipitation. The soil conservation function of most places in central China went unchanged from 2000 to 2015 (Fig. 5h), but this function did decrease in the plain areas, namely Huaibei Plain and Jianghan Plain in Hubei Province, due to intensive human activities there. The area where the climate regulation function has declined was clustered mostly in the western mountainous area of Hunan Province (Fig. 5i). Lastly, human activities also led declines in the biological conservation function in densely populated areas (Fig. 5j).

Table 1 Indicators of land-use functions in central China used in the present study

Primary functions	Sub-functions	Indicators	Description	Methods	Weights
Agricultural production function (APF)	Crop production (CP)	Agricultural output / (10000 yuan (RMB)/km^2)	The capacity to produce and supply agricultural plants	$A_1\times\frac{F_1}{S_1}$	0.25
	Aquatic production (AQ)	Fishery output / (10000 yuan (RMB)/km^2)	The capacity to produce and supply fish products	$A_2\times\frac{F_2}{S_2}$	0.25
	Woods production (WP)	Woods output / (10000 yuan (RMB)/km^2)	The capacity to produce and supply forest products	$A_3\times\frac{F_3}{S_3}$	0.25
	Livestock production (LS)	Livestock production output / (10000 yuan (RMB)/km^2)	The capacity to produce and supply livestock products	$A_4\times\frac{F_4}{S_4}$	0.25
Living function (LVF)	Living space (LP)	Population density/built-up land area / (person/km^2)	Provision of housing. The higher the indicator score, the less space available for each person	GIS overlay	0.50
	Life quality (QL)	GDP/population / (10000 yuan (RMB)/person)	Providing a high quality of life. The higher the GDP per capita, the higher the quality of life a place can provide to residents		0.50
Ecological service function (ESF)	Water supply (WY)	Water yield / (mm/km^2)	Capacity of water supply services	InVEST Water Yield model	0.25
	Soil conservation (SC)	Soil erosion / (kg/km^2)	The capacity to mitigate soil erosion	RUSLE model	0.25
	Climate regulation (CR)	Carbon sequestration / (kg/km^2)	The capacity to mitigate climate change	$NC\times\beta\times\sum NPP$	0.25
	Biological conservation (BC)	Habitat quality	The capacity for biodiversity conservation.	InVEST Habitat Quality model	0.25

Notes: A_1, A_2, A_3, and A_4 represent the area of cultivated land, water, forest, and grassland in the 1 km × 1 km grid, respectively. F_1, F_2, F_3, and F_4 denote the respective gross output value of agriculture, fisheries, forestry, and animal husbandry in the county-level administrative unit of the study area (each value is based on 1990 constant prices of China). S_1, S_2, S_3, and S_4 respectively represent the cultivated land, water area, forest area, and grassland area in the county-level administrative unit of the study area. The NC is the content of carbon (C) in carbon dioxide (CO_2), which is 27.27%; β is 1.63, that is, plants need to absorb a fixed amount of 1.63 g of CO_2 for every 1 g of dry matter (biomass) they produce

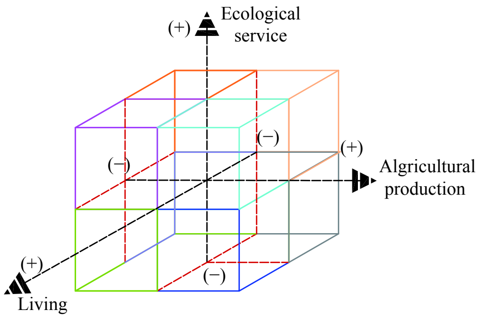

Fig. 4 Potential trade-offs/synergies in land-use function (LUF) changes illustrated by octants

3.2 Primary land-use function changes from 2000 to 2015

The mean values for the changed APF, LVF and ESF in the four provinces of central China were 0.074, 0.030, and –0.070, respectively, with corresponding standard deviations of 0.089, 0.033, and 0.054. These results indicate a general weakening of the ESF in the study area alongside a trend of strengthening APF and LVF. Spatial variability was greatest for changes in APF and least for those in ESF. In Hunan and Hubei, the increase in land area over time under APF exceeded that of Jiangxi or Anhui. Furthermore, the APF expansion in Jiangxi was less than the average increase for the entire study area. The rise in LVF in the capital city of each province was higher than the overall provincial average. In Jiangxi, the increase of ESF was higher than in the other provinces. The changes in APF were positively and significantly correlated with changes in LVF ($r = 0.028$; $P < 0.05$), while the changes in ESF were negatively, but not significantly, associated with those in LVF and APF (Table 4).

3.2.1 Agricultural production function changes

The APF in both Hunan Province and Hubei Province clearly rose from 2000 to 2015, whereas it declined in northwestern Anhui Province and northwestern and central Jiangxi Province (Fig. 6). Nonetheless, the overall trend for APF was that of increasing, which agrees with findings of Jin et al. (2019). Among the four subfunctions (Figs. 5a–5d), the agricultural production function decreased in several parts, such as Haozhou, Fuyang, and Chuzhou in northern Anhui; Xiangyang, Suizhou, Jingzhou, and Xianning in the north of Hubei; and Yichun in eastern Jiangxi. At the same time, the agricultural function in other parts of central China displayed an increasing trend. The fish supply function increased in the Yangtze River and Hanjiang River, Dongting Lake District, and Poyang Lake in Jiangxi Province; conversely, it was unchanged or even declined in other parts. The forest production function

Table 2 Description of trade offs/synergies in land-use function (LUF) changes

Characteristics of changes to the LUFs	APF	LVF	ESF	Description
Overall function enhancement (OFE)	+	+	+	The agricultural production function, living function, and ecological service function have ball increased eyond their respective average level from 2000 to 2015
Production function enhancement (PFE)	+	–	–	The agricultural production function has increased more than the average level from 2000 to 2015, while both the living function and ecological service function have changed less than or equal to the average level
Living function enhancement (LFE)	–	+	–	The living function has increased more than or equal to the average level from 2000 to 2015, while both the agricultural production function and ecological service function have changed less than or equal to the average level
Ecological function enhancement (EFE)	–	–	+	The ecological service function has increased more than the average level from 2000 to 2015, while both the agricultural production function and living function have changed less than or equal to the average level
Production function weakening (PFW)	–	+	+	The agricultural production function has decreased more than or equal to the average level from 2000 to 2015, whereas the living function and ecological service function have increased beyond the average level
Living function weakening (LFW)	+	–	+	The living function has decreased more than or equal to the average level from 2000 to 2015, whereas the agricultural production function and ecological service function have increased beyond or equal to the average level
Ecological function weakening (EFW)	+	–	–	The ecological service function has decreased more than or equal to the average level from 2000 to 2015, whereas the agricultural production function and living function have increased beyond or equal to the average level
Overall function weakening (OFW)	–	–	–	The agricultural production function, living function, and ecological service function have all decreased beyond or equal to the average level, from 2000 to 2015

Notes: APF, agricultural production function; LVF, living function; ESF, ecological service function

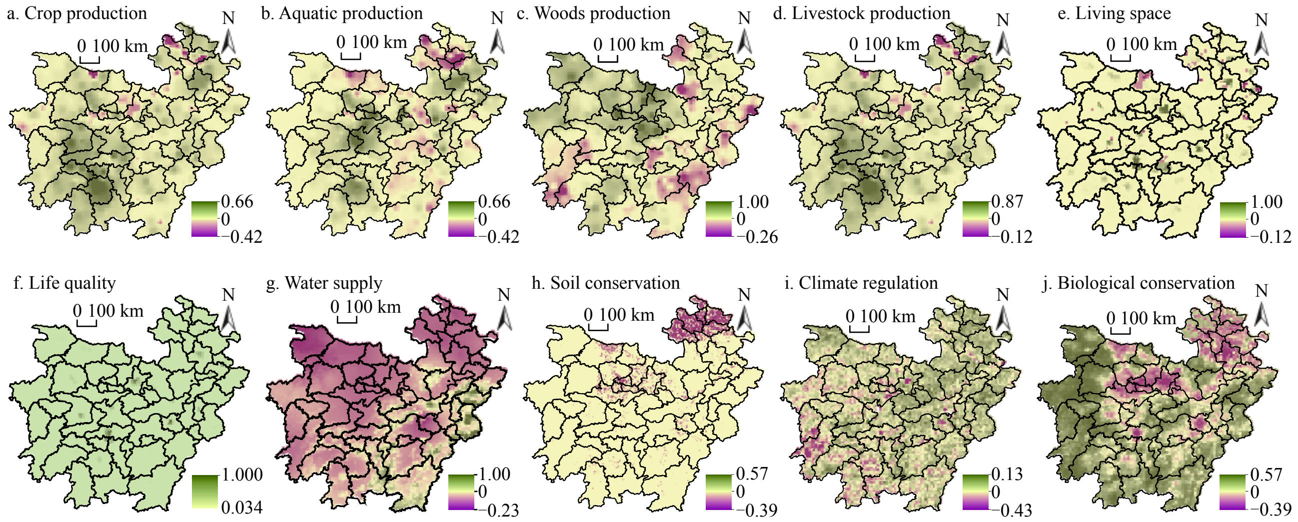

Fig. 5 Sub-land-use function changes from 2000 to 2015 at the city-level in central China

Table 3 Matrix of Pearson correlation coefficients for sub-land use function (LUF) changes from 2010 to 2015 in central China

Sub-LUF	CP	AQ	WP	LS	LP	QL	WY	SC	CR	BC
CP	1.00									
AQ	0.43^{*}	1.00								
WP	0.20	0.08^{*}	1.00							
LS	0.52	0.39	–0.21	1.00						
LP	–0.03	–0.04	–0.05	–0.09	1.00					
QL	–0.14	–0.21	–0.25	–0.55	0.98^{**}	1.00				
WY	$–0.19^{*}$	$–0.38^{**}$	$–0.49^{***}$	$–0.70^{**}$	$–0.19^{*}$	–1.09	1.00			
SC	–0.04	0	0.02	0.01	0.01	0.02	0	1.00		
CR	0.38^{**}	–0.42	0.18	$–0.86^{*}$	$–0.26^{**}$	–1.28	$–1.35^{**}$	0.02	1.00	
BC	$–0.65^{**}$	0.03	–0.17	$–0.75^{**}$	0.21	–0.71	–1.81	0.13	–1.68	1.00

Notes: *** $P < 0.001$, ** $P < 0.01$, and * $P < 0.05$; CP, crop production; AQ, aquatic production; WS, woods production; LS, livestock production; LP, living space; QL, life quality; WY, water supply; SC, soil conservation; CR, climate regulation; BC, biological conservation

Table 4 Matrix of Pearson correlation coefficients for the primary LUF changes in central China

Primary LUF	APF	LVF	ESF
APF	1.000		
LVF	0.028^{*}	1.000	
ESF	–0.120	–0.140	1.000

Notes: * $P < 0.05$; APF, agricultural production function, LVF, living function, ESF, ecological service function

weakened across the whole area of central China, except for Xiaogan, Xianning, and Shiyan. The livestock function increased significantly in most parts of Hunan Province and also in southern Anhui Province.

3.2.2 Living function changes

From 2000 to 2015, the living function in the study area increased (Figs. 5e, 5f), a result consistent with research by Yu et al. (2019). The most pronounced increase in the quality of life was distributed in provincial capitals and economically developed cities, such as Yichang, Xiangyang, Hengyang, Huaihua, Maanshan, Xinyu, and Shangrao. Even though the living space function changed very slightly, the major cities also were characterized by an increase, including those of Wuhan, Yichang, Hefei, Huaibei, Changsha, Changde, Nanchang, and Xinyu, among others, which was due to the expansion of built-up land area. For example, according to statistical data published in 2002, by the Hunan Statistics Bureau and Jiangxi Statistics Bureau, the average dwelling area of Changsha was 44.6 km^2 and that of Nanchang was 28.2 km^2. By 2015, this dwelling acreage had increased to 51.8 km^2 in Chang-

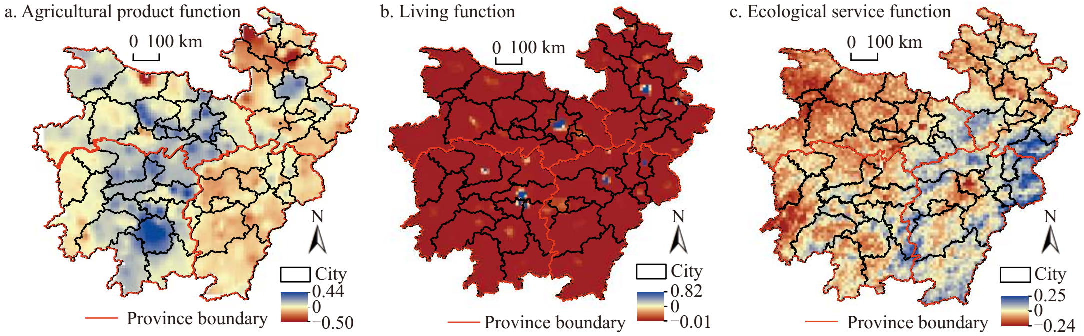

Fig. 6 Primary land-use function change anomalies from 2000 to 2015 in central China

sha and 52.2 km^2 in Nanchang. With more buildings, the city's residential capacity inevitably became greater. This finding is consistent with that reported by Liu et al. (2014) and Ye et al. (2017).

3.2.3 *Ecological service function changes*

From 2000 to 2015, differential changes ensued in the water supply function, climate regulation, and biological conservation function (Figs. 5g–5j). Among them, the water supply function in the study area exhibited the greatest decline, dropping by –0.23, which is consistent with Sun et al. (2006) and Liu et al. (2016). However, the water yield did increase in the northeast and south of Jiangxi Province, the intersected mountainous regions between Jiangxi and Hunan Provinces, and the intersected mountainous regions between Hunan and Anhui Provinces. The biological conservation function changes were obvious in the northeastern and southern parts of Jiangxi Province, in the intersected mountainous areas between Jiangxi and Hunan, and for the lakes of each province. The decline in the soil conservation function was concentrated in the grain production areas of central China, such as the Jianghan Plain, Xiangyang City, and Suizhou City in Hubei Province; the Huaibei Plain in Anhui Province; Dongting Lake in Hunan Province; and Poyang Lake in Jiangxi Province, where arable farming practices have destroyed the soil layer and increased soil erosion. The soil erosion in mountainous areas decreased over time, which is similar to what was found by Deng et al. (2012). In most areas, the climate regulation function and biological conservation function were improved, an outcome closely linked to the policy of returning farmland to forest (Song et al., 2014). Still, the climate regulation function was reduced in Huaihua City in Hunan Province. Habitat quality declined in the urban agglomeration of Wuhan City as well as Hefei City, which suggests urban sprawl affects the habitat of wildlife (Ke et al., 2018; Zhu et al., 2020).

3.3 Land-use function change pattern in central China

In this study, we divided the LUF changes pattern in central China into eight types (Fig. 7; Table 2). The uncoordinated expansion of urban space, agricultural space, and ecological space will bring about challenges in achieving a balanced development of the local environment and economy and society.

(1) The overall function enhancement (OFE), which accounted for 1.41% of the total study area, was mainly distributed on the Dongting Lake Plain on Hunan Province and on the Jianghan Plain in Hubei Province, including the suburban and rural areas of Yueyang, Changde, and Yiyang cities in Hunan Province; the Wangcheng District of Changsha City; and Jingzhou City in Hubei Province.

(2) The production function enhancement (PFE), this accounting for 21.69% of the total study area, was mainly distributed in the rural regions of Shiyan, of Xiangyang's southwestern part, and in eastern parts of Suizhou and Jingzhou in Hubei Province; in Yueyang, Changde, Hengyang, and Shaoyang in Hunan Province; and in the Hefeiand Maanshan Anhui Province. All of these places are essential agricultural product producing areas in China, distinguished by suitable natural conditions for agriculture, a strong capacity for the processing and circulation of agricultural products, and the integrated production of grain, fishery, and forestry industries.

(3) The living function enhancement (LFE), which accounts for 5.38% of the total study area. It was mainly

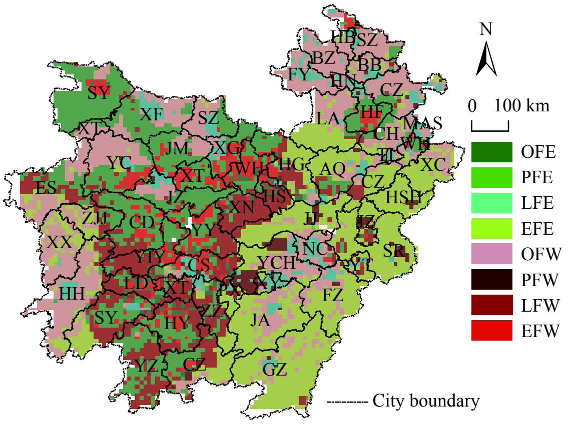

Fig. 7 Trade-offs/synergies of LUF changes in the central China. OFE, overall function enhancement; PFE, production function enhancement; LFE, living function enhancement; EFE, ecological function enhancement; OFW, overall function weakening; PFW, production function weakening; LFW, living function weakening; EFW, ecological function weakening. AQ, Anqing; BB, Bengbu; BZ, Bozhou; CD, Changde; CH, Chaohu; CZ, Chenzhou; CZ, Chizhou; CZ, Chuzhou; EZ, Ezhou; ES, Enshi; FZ, Fuzhou; FY, Fuyang; GZ, Ganzhou; HF, Hefei; HY, Hengyang; HH, Huaihua; HB, Huabei; HN, Huainan; HG, Huanggang; HSH, Huangshan; HS, Huangshi; JA, Ji 'an; JM, Jingmen; JZ, Jingzhou; JZ, Jingdezhen; JJ, Jiujiang; LA, Lu 'an; LD, Loudi; MAS, Ma'anshan; NC, Nanchang; PX, Pingxiang; SR, Shangrao; SY, Shaoyang; SY, Shiyan; SZ, Suizhou; TL, Tongling; WH, Wuhu; WH, Wuhan; XT, Xiantao; XN, Xianning; XT, Xiangtan; XX, Xiangxi; XF, Xiangfan; XG, Xiaogan; XY, Xinyu; SZ, Suizhou; XC, Xuancheng; YC, Yichang; YCH, Yichun; YIY, Yiyang; YT, Yingtan; YZ, Yongzhou; YY, Yueyang; ZJJ, Zhangjiajie; CS, Changsha, ZZ, Zhuzhou

distributed in the main urban areas of cities, including Suizhou, Xiangyang, Changsha, Nanchang, Ji'an, and Xinyu, among others.

(4) The ecological function enhancement (EFE), this accounting for 26.73% of the total study area, was mainly distributed in Jiangxi Province—except Nanchang, Yichun, Xinyu, and Ji'an (JA)—in addition to the southern mountainous regions, such as the Huangshan and Dabie Mountains in Anhui Province, Xuefeng Mountains in western Hunan Province, and Dabie Mountains in the southwest of Hubei Province.

(5) The production function weakening (PFW) accounted for 2.19% of the total study area. It was mainly distributed in the rural regions of Yichun and Jingdezhen in the northwestern part of Jiangxi Province, as well as in the suburbs of Huanggang, and Chenzhou. These areas are located in the mountains, and are influenced by policies such as returning farmland to forest (Song et al., 2014), which decreased the APF in these areas.

(6) The living function weakening (LFW) accounted for 13.08% of the total area. This was mainly distributed in the Dabie Mountains area and the south of Chenzhou in Anhui; the southwest of Enshi and the Jiu Gong Mountain area in Hubei; and Xuefeng Mountains, Nanling Mountains, and Luoxiao Mountains in Hunan, where there are abundant agricultural products and forest.

(7) The ecological function weakening (EFW) accounted for 5.94% of the total stud area. It was mainly distributed in urban areas, where the expanding built-up land has destroyed the local ecosystem, leading to ecological degradation, but in the process the living function of converted land has been improved (e.g., urban areas of Wuhan, Qianjiang, Changsha, and Hefei).

(8) The overall function weakening (OFW) accounted for 23.58% of the total study area. This was mainly distributed in Suizhou and Xiangyang in northern Hubei Province, Yichang in western Hubei Province, Huaihua and Xiangxi Autonomous Prefecture in western Hunan Province, the Northern Plain of Anhui Province, and the Nan Change Urban Agglomeration in central Jiangxi Province. The ecological environment is particularly vulnerable in these OFW areas.

4 Discussion

Land-use function change is influenced by multiple factors, including physical and socio-economic factors, which could occur through many visible or invisible mechanisms. Indigenous factors including geographic factors and economic status will determine the starting point and the potential of the land use functions. Meanwhile, external drivers, including governmental nature resource management policies and economic activities, can have an impact on the direction and speed of changes in the LUFs.

4.1 Insights into the spatial heterogeneity and the trade offs/synergies of LUF changes

Densely populated cities feature an intensive road network and buildings, because all transportation and buildings are linearly or nonlinearly linked to GDP growth. Nevertheless, the artificial impervious surface created is a disturbance that poses a dangerous threat to animals, displaces ecological land, and pollutes the environment. As the urban realm expands in tandem with industry development, either cropland or ecological land (or both) were replaced with built-up areas; this land-use conversion phenomenon is most obvious in the rural suburbs of provincial capital cities, as readily observed in Fig. 7. The results of our analysis are similar to other findings on land-use function dynamics in central China reported by other researchers. For example, previous studies have indicated that the livestock pollution (Li and Tan, 2015) in Xiangyang (Li et al., 2015), the livestock pollution in Shaoyang (Guo et al., 2012), which have increased the APF and LVF but reduced the ESF. Car factories in Suizhou (Liu et al., 2020) and car factories in Shiyan (Li et al., 2018) negatively impact the soil, water bodies, and atmosphere. Such human activities drive declines in ESF decline, as illustrated in Fig. 5 and Fig. 7 of our study. To mitigate that, in recent years the national government has focused on environmental-friendly economic development (Song et al., 2014). Local governments have encouraged the integration of primary and tertiary industries, advised non-agricultural enterprises to set up along traffic corridors, and ensured the reasonable layout of natural scenic areas, forest parks, and protective green belts, with the aim of promoting the sustainable integration of agricultural, urban, and ecological spaces. The ecological environment of the suburbs may rise because of increased financial investments in constructing an environmentally friendly urban area. The spatial distributions of augmented LVF and ESF are shown in the PFW in Fig. 7; this result agrees with the findings of Tan et al. (2019) and Deng et al. (2020), which demonstrated that people transformed abandoned land into ecological land which improved the ESF and LVF of land in Changsha.

In conclusion, urbanization inevitably interferes with the agricultural function and ecological service function of land. Nonetheless, this high price of urbanization could be avoided were policy makers to formulate appropriate land use policies and countermeasures in view of local conditions and the socio-economic development phases. To ensure the prudent implementation of such regional measures, the government should not only explore the feedback mechanism of the LUF and land resources management but also be aware of the trade offs/synergies effect among changes in each LUF.

4.2 Uncertainties and challenges for further research

Several uncertainties in this study should be highlighted. Firstly, due to the limited availability of data at a large scale, the indicators of land-use functions are insufficient in that they could not fully quantify the integrated meaning of agricultural production, living condition, and ecological environment. For example, water pollution is a serious environmental issue in central China. Since laws for environmental protection were implemented, many industry operations that polluted water resources have closed down. This activity has arguably changed the ecological quality of water area in central China, but it would require much time and cost much to quantify the spatial heterogeneity of water quality. Likewise, people enjoying a high quality life not only have a high income or large space to live in per capita, but are also provided with cultural and leisure services, which is related to mental pleasure and this could hardly be quantified on large scale. Moreover, the indicators of agricultural function and living function in this study are coarse grained. For example, the agricultural output statistics can only reflect regional differences in agricultural output, which could be easily influenced by extreme weather, such as flooding and drought events. External factors also jointly influence the agricultural output in a particular year, including market prices and government policies, and so on. The quality of life as perceived by different people not only relates to their income, but also their gender, education, family structure, and so on (Becker et al., 2005). Looking ahead, further research could integrate the above elements with the land-use function framework for producing a comprehensive and more detailed in-depth study.

Secondly, the trade offs/synergies of LUF changes may not always be linear, and thus study only analyzed the changes in LUFs from 2000 to 2015. Further studies should be able select more study years according to major national land space strategies, because land-use changes depend on national policies. Thirdly, the literature on the evaluation of multiple land-use functions at the grid scale, in central China is scarce and difficult to verify by way of direct comparison. Surprisingly, so far there is no standard parametrization for the ecological service evaluation, especially at large spatial scales. The interaction of natural factors varies from place to place which leads to coarse results. Fourthly, there is a typical urban-rural dual structure in China, in that the segregation between the urban and rural realms is still observable. However, this divide cannot be so easily distinguished by raster data at a 0.1° × 0.1° grid accuracy. With more available data and improved data accuracy in the future, we can begin to divide the land space into urban and rural spaces, and then explore differences between them in changes to the living, production, and ecological functions.

5 Conclusions

Ideally, a land-use plan should match the social carrying capacity of natural areas and scientifically delineate its agricultural, urban, and ecological spaces. Although the land is capable of multiple functions, differing land-use patterns and intensities of use will lead to different dominant functions. Yet agricultural production, living, and ecological functions, and their changes are interrelated. How to achieve the simultaneous goals of sustainably developing the land, scientifically identifying the types of land-use functions, and clarifying the characteristics of LUF changes and their spatial correlation is of paramount significance for distinguishing the key problems in current land-use policies and for guiding future land-use planning.

This paper combined well-established methods to analyze the distributional changes in land use functions and their interrelationships based on agricultural function (APF), living function (LVF), and ecological function (ESF). From this, several key findings emerged. 1) In central China, from 2000 to 2015, more land expanded under APF in Hubei Province and Hunan Province than in Jiangxi Province and Anhui Province; actually Jiangxi Province underwent a decrease in APF but an increase in ESF. The LVF increased mostly in the capital cities. 2) Those places featuring better sustainable land planning (such as Dongting Lake Area urban agglomeration) also experienced the coordinated development of production, living, and environmental functions. 3) The degradation of APF and ESF was inevitable as cities there expanded, as exemplified by the clusters for Wuhan City, Changsha City, Nanchang City, and Hefei City, but this was accompanied by an augmented LVF. 4) In general, changes in APF from 2000 to 2015 in central China were significant and positively correlated with LVF changes. By contrast, the ESF changes were negatively but non-significantly correlated with APF changes. Accordingly, our findings suggest the land management of central China in future should focus more on the trade-offs and synergistic effects of land-use function, especially the latter arising for LVF vis-à-vis APF and ESF.

Looking ahead, with more and better quality data becomes available in the future, research must try to optimize the evaluation indexes and evaluation methods for each land-use function. In addition, future studies could explore in-depth the driving mechanisms of land use transformation in the study area, and how using different scales and land-use classification systems would affect the evaluation results. These questions are currently a hot topic in the field of land-use transformation research. Finally, the time scale of inquiry ought to be broadened in the future studies, with research striving to also take the development stages of the economy and society into consideration.

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