Exploring the impact of integrated spatial function zones on land use dynamics and ecosystem services tradeoffs based on a future land use simulation (FLUS) model

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ABSTRACT

Spatial function zones (SFZs) provide an effective means to determine the function of spatial zone and to optimize land use layout. China has initiated a series of spatial planning policies to delineate SFZs, which influence not only land use configuration but also the structure and function of ecosystems as well as the services ecosystem provides. Taking Wuhan city, China as an example, this study explored the impact of integrated spatial function zones (ISFZs) on four selected ecosystem services (i.e., crop production, CP; water yield, WY; carbon storage, CS; and erosion prevention, EP) and their synergies and tradeoffs. Specifically, by incorporating different spatial functional zones into the land use simulation model, we simulated land use under both business as usual (BAU) and integrated spatial function zones (ISFZs) scenarios. Then, we assessed and compared the ESs and their correlations under the two scenarios. The results showed that compared to the BAU scenario, in the ISFZs scenario, quantities of farmland and forests would be increased by 410.99 km^2 and 28.49 km^2, while construction land would be decreased by 342.45 km^2; average CP, CS and EP would be improved by 0.05, 2.23 t/ha, and 7.3 t/ha, while average WY would be reduced by 6.4 mm; synergies between most pairs of ESs would be slightly promoted. It is concluded that ISFZs are beneficial to sustainable improvement and balanced development of multiple ESs. This study provides theoretical and technical references for the formulation of spatial regulation policy and ecosystem-based management.

1. Introduction

Ecosystem services (ESs) are goods or services provided by nature for human welfare and wellbeing (Costanza et al., 2014). Ecosystems provide a multitude of ESs ranging from provisioning (e.g. grain and timber), regulating (e.g. air purification and water regulation) and cultural services (e.g. tourism and historical values) that benefit human survival and welfare through ecological process and function (Costanza et al., 2014; MEA et al., 2005). Multiple ESs do not vary independently but are correlated with each other due to complex natural and human factors underpinning them, manifesting as tradeoffs or synergies (Jia et al., 2014). When people attempt to improve or maximize the benefit of one ecosystem service, they will simultaneously change other ESs intentionally (Feng et al., 2017; Zhang et al., 2015b). Although scholars have recognized the importance of ESs correlation and have conducted

extensive research on the quantitative identification of ESs correlation, it remains a challenge to implement ESs correlation analysis during land use planning. However, ignoring the ESs correlation would impede the improvement of ecological benefits and even bring about certain ecosystem degeneration in land use practices (Geneletti, 2013; Divinsky et al., 2017).

Land use/land cover (LULC) change, induced by the acceleration of economic development, industrial evolution and urbanization, has been a predominant driver of ESs change (Estoque and Murayama, 2012; Zank et al., 2016; Yu et al., 2023; Zhang et al., 2021). LULC alters the composition, structure and function of ecosystems, thus changing the ability of ecosystems to provide services. Studies revealed that the extensive replacement of human dominated landscapes (i.e., urban and towns) with natural landscapes (i.e., vegetated lands, wetlands, and water bodies) would impede ESs provisioning and ecosystem

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sustainability (Xie and Ng, 2013; Arowolo and Deng, 2018). The total value of global ES is reported to be reduced by an estimated USD 20 trillion/yr over the period 1997–2011 due to changes in LULC (Costanza et al., 2014). Huang et al. (2020) found that from 2000 to 2015, urban land expansion encroached an area of 59,170 km^2 cropland (almost 45.9% of the expanded urban land), leading to a decrease of 58.71 TgC of cropland NPP at a global scale. Wu et al. (2013) revealed that socioeconomic development and accompanying LULC change might be an essential reason for the overall 24.04% decline in total ESs value in Hangzhou metropolitan area in China.

In response to the ecological crisis brought about by large-scale natural resource exploitation and land use transformation, many countries have delineated spatial function zones (SFZs) to guide land development, construction activities and ecological conservation. Formulating SFZs entails delineating the spatial distribution of high-value ecological and social areas (e.g. conservation areas of fragile species and ecosystems, areas of high-quality agricultural land, and sites of cultural treasures), as well as the distribution of processes that threaten their persistence (e.g., road construction and industrial siting) (Lawler et al., 2015). On this basis, ecological conservation areas could be determined where intensive construction activities (e.g., urban land development and road construction) are usually excluded. In practice, Poland takes legal measures, e.g., the act on the protection of agricultural land and forests, to guide land conversion (Kurowska et al., 2020). In Australia, a legal plan for natural resource management (NRM) has been initiated since the 1980 s as a community movement to address environmental issues such as climate change (Adams et al., 2017). In China, administrative departments of natural resources at all administrative levels formulate territory spatial plans (TSP) which delineate SFZs aiming at guiding (e.g., prohibit or restrict) the direction of land development and construction activities, or delineate conservation areas (Li et al., 2020). These plans have delimited three major categories of SFZs: production zone, living zone and ecological zone, of which major functions are agricultural production, human settlement and ecological conservation, respectively (Zhang et al., 2015b). In practice, SFZs make use of management tools like land use licenses, use change approval, and other land use conversion supervisions, to achieve their goals to guide land development and ecological conservation.

Current research on the SFZs mainly focuses on the institutional evolution (Tremblay-Racicot and Mercier, 2014; Hilber and Robert-Nicoud, 2013), zoning delineation technique (Peng et al., 2018), economic effect like effect on land price and industrial development (Han et al., 2020; Monkkonen, 2013), ecological effect and other aspects. In the era of ecological civilization, scholars are paying increasing attention to the effect of SFZs on land use change and ecological environment. Existing research has attempted to explore the effects of different SFZs on land use change and soil erosion (Han et al., 2013) or carbon metabolism (Hersperger et al., 2018; Li et al., 2020). In the planning system of China over the past two decades, SFZs have originated from various sources of spatial plans, including urban plan, land use plan, major function zoning, ecological function zoning and other land use governance plan (Wen and Zhang, 2015). Different government departments develop and implement these spatial plans with different planning goals or objectives. Integrating these SFZs into an integrated framework and examining their combined effects on land use and ecological environment would provide knowledge for land use planning and ecosystem-based management. However, there is little academic research on such attempt. Moreover, most previous studies have mainly explored the impact of SFZs on a single ecological service, with little research on the impact of SFZs on integrated ESs value and ESs correlations.

Wuhan city is the largest city in central China, located on the reach of the Yangtze River Plain and the eastern part of the Jianghan Plain. It is abundant in natural resources, especially water resources, with 1/4 territory land covered by lakes, and is known as the "City of Hundreds of Lakes". However, rapid urban construction and population concentration have led to the occupation, fragmentation and pollution of a large

number of natural habitats, which is a serious threat to Wuhan's ecological stability and sustainability. Against this background, Wuhan government has initiated a series of spatial governance measures to mitigate human interference with natural ecosystems, such as the delineation of urban growth boundary (UGB) to control unordered urban expansion and the delineation of ecological redline (ERL) to identify conservation areas. However, there is still a lack of empirical discussion on the impacts of these spatial function zones on land use andecosystem services. In this study, we address the following issues: (1) to conduct multi-scenario land use simulation with different SFZs incorporated; (2) to assess ecosystem services and their correlations under different land use scenarios; and (3) to reveal the impact of SFZs on ecosystem services and their correlations to inform urban planning and decision making.

2. Study area and data sources

2.1. Study area

Wuhan is located between 29°58′ – 31°22′ N and 113°41′ – 115°05′ E, covering 8569.15 km^2 (Fig. 1). The topography is characterized by a flat plain in the middle, surrounded by a hilly landform, with altitude ranging from −138 m to 834 m. Wuhan's land use is dominated by farmland, water and forests, covering 2577.04 km^2, 2440.45 km^2 and 1399.68 km^2, accounting for 30.07%, 28.48% and 16.33% of the total area respectively. As a typical rapid urbanization city, the population urbanization rate of Wuhan reached 80.29% in 2018.

2.2. Data sources

Natural condition datasets, socio-economic development datasets, LULC data and spatial function zones were combined to implement this research. Digital elevation model (DEM) data was retrieved from the Geospatial Data Cloud (https://www.giscloud.cn/). It was utilized to process topographic information such as slope and altitude. Time-series meteorological datasets of temperature and precipitation for the period 2005 to 2015 were downloaded from the National Meteorological Science Data Center (https://data.cma.cn/). These datasets were preprocessed by interpolating the original point shapefile data into raster at 100 × 100 m^2 resolution by time synthesis analysis. Soil datasets, composed of data on soil organic carbon and soil texture, were provided by the Big Data Center of Sciences in Cold and Arid Regions (https://westdc.westgis.ac.cn/). LULC datasets in 2005 and 2015, with a resolution of 30 m, were obtained from the Wuhan Planning and Design Institute. Spatial function zone datasets, including ecological redlines, basic farmland protection zones and urban development plans, were also obtained from the Wuhan Planning and Design Institute.

3. Methods

3.1. Flowchart of the method

In this study, we explored the impact of integrated spatial function zones (ISFZs) on land use change and ESs correlations based on FLUS model. First, we introduced FLUS model, a combined CA-Markov model with Markov chain to predict urban land demand and CA to project urban spatial layout, to conduct multi-scenario land use simulations. Second, we selected and assessed four types of ESs and then utilized a Spearman rank correlation to identify ESs tradeoffs. Finally, we conducted a multi-scenario land use simulation by varying the way of ISFZs impacting land use simulation and then compared ESs and their tradeoffs among the multi scenarios. The flowchart of the method was presented in Fig. 2.
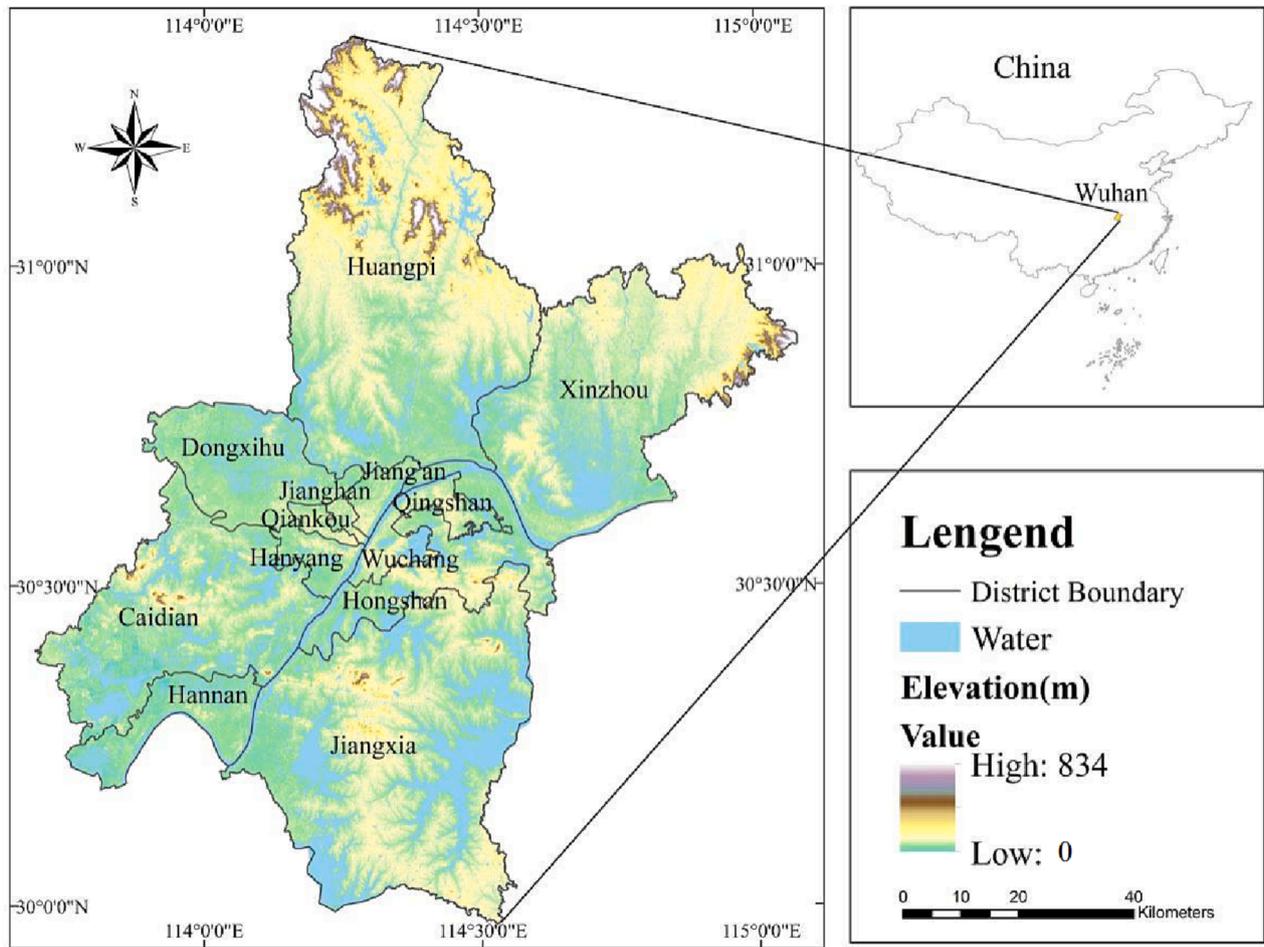
Fig. 1. Study area.

3.2. Multi-scenario land use simulation based on future land use simulation (FLUS) model

This study utilizes the future land use simulation (FLUS) model that couples the Markov chain and cellular automata (CA) to predict land use change in Wuhan. The Markov module is utilized to predict land use demand to exert a "top-down" effect, and the CA module is used to address the spatial configuration of land use in a "bottom-up" way (Liu et al., 2017). The two modules are tightly integrated by adjusting the spatial allocation of LULC types according to their quantities during iterations and updates. This approach ensures adequate feedback between the two complementary modules and high accuracy in long-term land use simulation.

3.2.1. Land use demand prediction through Markov chain

Markov chain is used here to simulate land use quantity following previous studies (Arsanjani et al., 2013; Fathizad et al., 2015; Zhang et al., 2020). It describes a stochastic and non-aftereffect process that land use state at time $t + n$ is only related to the state at time t but not the states before time t. Predicting land use quantity through the Markov chain follows two main procedures: (1) generating a transition probability matrix according to the past two-term land use state data; and (2) calculating the future land use demand based on the conversion probability matrix and the current land use quantity. This process can be expressed as follows:

$$Q_{(t+k)} = P_{ij}{}^k \times Q_t = \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{bmatrix}^k \times [q_1, q_2, \cdots q_n]_t \quad (1)$$

Where $Q_{(t+k)}$ and Q_t denote matrices of land use quantity at time $t + k$ and t, respectively. P_{ij} denotes matrix of conversion probability from land use type i to land use j, $0 \leq P_{ij} \leq 1$ and $\sum_{i=1}^{n} P_{ij} = 1$. Markov process and the subsequent CA model in 2.3.2 were implemented in GeoSOS-FLUS V2.4 software.

3.2.2. Land use pattern simulation based on FLUS model

FLUS model is developed following the principle of CA but has improvements over the conventional CA for it embedding two components (Liu et al., 2017): (1) an artificial neural network (ANN), a module to simulate the probabilities of occurrences for all LULC types at a certain location; and (2) an elaborate self-adaptive inertia and competition mechanism, which reflects the trend of land use conversion on a cell during iteration and competitions between various LULC types.

ANN has the advantage of dealing with the complex and non-linear relationship between land use patterns and the influential underlying factors (Lin et al., 2011). Typically, an ANN model is composed of three layers input, hidden and output layers. The neurons in the input layer are various natural and human factors like slope, elevation, population density and locational factors, and neurons in the output layer are LULC types. The hidden layer is determined according to the number of driving factors and expert experience. After model establishment, ANN is trained through a supervised learning process, during which it first calculates the error between simulated and actual outputs and then adjusts model parameters to minimize the error. The trained ANN is then utilized to produce the conversion probabilities to all LULC types.

The elaborate self-adaptive inertia is a coefficient automatically adjusting the trend of a cell to inherit its current land type based on the
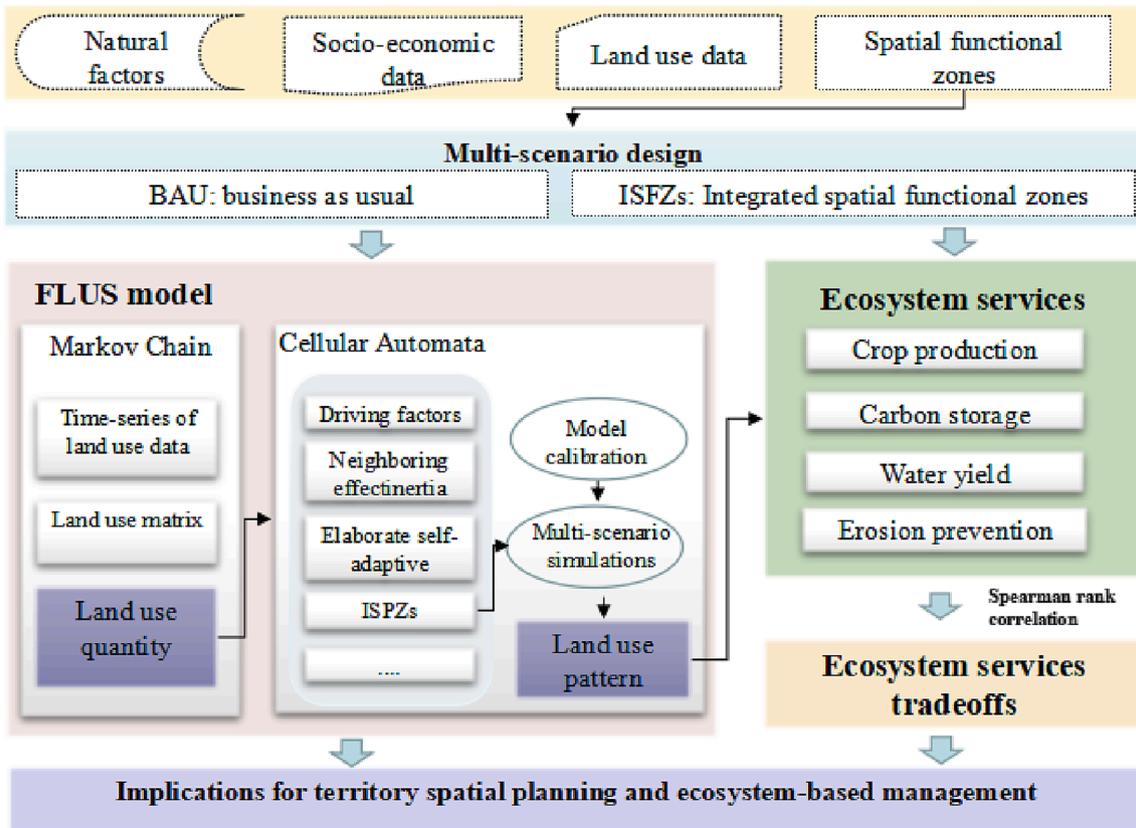
Fig. 2. Flowchart of the method.

difference between the simulated and the targeted land use quantities. The integration of elaborate self-adaptive inertia improves the accuracy of the model in simulating the complex and random LULC change in the real world. This coefficient can be expressed as:

$$I_k^t = \begin{cases} I_k^{t-1} & if \left|D_k^{t-1}\right| \le \left|D_k^{t-2}\right| \\ I_k^{t-1} \times \dfrac{D_k^{t-2}}{D_k^{t-1}} & if D_k^{t-1} < D_k^{t-2} < 0 \\ I_k^{t-1} \times \dfrac{D_k^{t-1}}{D_k^{t-2}} & if 0 < D_k^{t-2} < D_k^{t-1} \end{cases} \quad (2)$$

Where I_k^t denotes the self-adaptive inertia coefficient for LULC type k on a grid at time t. D_k^{t-1} and D_k^{t-2} are respectively the differences between the targeted and simulated land use quantities at time $t-1$ and time $t-2$.

The total probability of all LULC types on a certain cell can be calculated by integrating the probability produced by ANN and Inertia coefficient, as well as the neighboring effect, constraint factor and conversion cost as follows:

$$TP_{p,k}^t = P_{p,k}^t \times N_{p,k}^t \times I_k^t \times (1 - c_{c,k}) \times R_p \quad (3)$$

Where $TP_{p,k}^t$ is the total probability of the cell p converting from its current LULC type to the target type k at the tth iteration. $N_{p,k}^t$ is the neighboring effect of LULC type k, which was defined as 5×5 kernel type in this study. I_k^t is the inertia coefficient for LULC type k at the tth iteration. $c_{c,k}$ is the conversion cost from the current LULC type c to the target LULC type k; in this case, we set all $c_{c,k}$ values as 0 to indicate that all LULC types are freely converted with each other. R_p is the restrictive factor for land use conversion on the grid p, with value 1 representing that the conversion is allowed and value 0 representing that conversion is prohibited.

The FLUS model adopts a roulette selection mechanism to decide the future LULC type on a cell. In this mechanism, a higher total probability score means a higher opportunity for a specific land use type, but it does not mean that a lower probability has no opportunity. A land use type with a lower probability will still has a chance of being allocated. The random of this mechanism ensures FLUS deals with the contingency and uncertainty of LULC change and the simulation of leapfrog LULC conversion (Liu et al., 2017).

3.2.3. Model running and calibration

In this study, the simulation accuracy of FLUS was examined based on the land use data in 2015. Specifically, land use quantities in 2015 were predicted through Markov process based on the land use conversion during 2005–2015. Taking the simulated land use quantities as an input component, the CA module of FLUS model was run to project land use pattern in 2015. The overall accuracy, Kappa coefficient and FoM coefficient of the simulation are 0.801, 0.824 and 0.4874 respectively, which indicate a high accuracy of FLUS model in land use simulation and a good applicability in this experiment.

3.3. Quantification of ecosystem services and their correlations

Four types of ecosystem services, including crop production (CP), water yield (WY), carbon storage (CS) and erosion prevention (EP) were selected to indicate the ecological effect of land use change. These ESs were selected based on their sensitivity to the urbanization process and their availability to be quantified based on the existing data.

3.3.1. Crop production

Crop production (CP) manifests an ecosystem's ability to produce food (e.g., wheat, rice and rape), which is essential for food security and human livelihood (Jansson and Polasky, 2010). Many studies have spatialized CP by downscaling statistical CP data to each farmland patch according to the patch's vegetation condition, like VCI or NDVI (Zhang

et al., 2018; Peng et al., 2019). Owing to the lack of potential data on statistical CP and vegetation condition in the future, we flip to adopt the farmland quality as a proxy to spatialize the potential CP referring to previous studies (Yuan et al., 2018; Zhao et al., 2019). In this research, farmland quality is assessed through a multiple criteria evaluation method that aggregates factors from typography, soil, irrigation condition and traffic conditions. Given that the physical and chemical characteristics of the soil, like soil texture, organic composition and nutrients, are the most important determinants of crop production, we assigned related factors a higher weight of 0.2 whereas a lower weight of 0.1 to other factors. The formula could be expressed as:

$$GP_i = 0.1Ele_i + 0.1Slp_i + 0.2Tex_i + 0.2Org_i + 0.2Nutri_i \\ + 0.1Dis\_river_i + 0.1Dis\_road_i \tag{4}$$

Where GP_i represents the potential crop production of the ith farmland patch. Ele_i denotes elevation, Slp_i signifies slope factor, Tex_i is soil texture that indicates the combination of mineral particles with different sizes and diameters in soil. Org_i represents content of organic carbon in soil. $Nutri_i$ is total content of nutrients in soil, including nitrogen (N), phosphorus (P) and potassium (Pot). Dis_river_i is distance to rivers, which indicates the irrigation convenience of a farmland patch. Dis_road_i is distance to roads, which represents the transportation facilitation to crop plantation. Please see more details on scoring rule of factors in Table A1.

3.3.2. Water yield

Water yield (WY) is the water retained by an ecosystem during a period, which plays an important role in the water regulation of a region. In this study, WY is estimated by the water balance equation, which determines the water yield of a plot according to precipitation and transpiration (Jia et al., 2014).

$$WY = PPT - ET \pm S \approx PPT - ET \tag{5}$$

$$ET = \frac{P\left(1 + \omega\frac{PET}{P}\right)}{1 + \omega\frac{PET}{P} + \left(\frac{PET}{P}\right)^{-1}} \tag{6}$$

Where WY denotes water retained by a cell (mm). PPT denotes annual precipitation (mm), which is estimated by a time synthesis method averaging the precipitation in Wuhan during 2008 ∼ 2018. ET is the evapo-transpiration (Sun et al., 2011). S is the change of water yield, which can be ignored in large space and time scales. PET is the potential evapo-transpiration, which could be estimated based on Thornthwaite's empirical regression with temperature and latitude (Thornthwaite, 1948). ω is the underlying surface influence coefficient, which depends on the LULU type following the achievements of Feng et al. (2017) and Wu et al. (2018b) (see details in Table A2).

3.3.3. Carbon storage

Carbon storage (CS) manifests the amount of organic carbon stored and sequestrated by green vegetation and soil from atmosphere to biosphere during a certain period (Field et al., 1998), which represents the biological production capacity of an ecosystem (Potter et al., 1993). This study utilizes the InVEST model to evaluate the CS stored in four types of carbon sinks: (1) aboveground biomass (carbon in all living plants above the ground); (2) belowground biomass (carbon in the living root system of plant); (3) soil organic matter (carbon in organic and mineral soils), and (4) dead organic matter (carbon in litter and standing dead tree), which could be expressed as follows (Tallis and Ricketts, 2010):

$$C_{total} = C_{above} + C_{below} + C_{total} + C_{soil} + C_{dead} \tag{7}$$

In this study, we assess carbon densities of four pools according to their correspondence to different land use types referring to previous research (Zhang et al., 2017; Li et al., 2020) (Table A3).

3.3.4. Erosion prevention

Erosion prevention (EP) represents the ability of an ecosystem to reduce soil erosion and intercept sediment from the upstream caused by natural factors and human activities (Xu et al., 2017). We utilize the revised universal soil loss equation (RUSLE) to assess soil conservation capacity following the equation (Wischmeier, 1978):

$$A = R \times K \times L \times S \times (1 - C \times P) \tag{8}$$

Where A denotes the annual amount of soil erosion per unit area (t/ hm^2), R is rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$). K is soil erodibility factor, representing the soil-loss rate per R-factor in a standard plot (t ha h ha^{-1} MJ^{-1} mm^{-1}). The values of R-factor and K-factor in Wuhan are extracted from Zhang's research (Zhang et al., 2018). L and S are slope length and slope deepness factors (dimensionless), respectively. C is crop management factor (dimensionless), which is a LULC-related value acquired from previous research (Dabral et al., 2008; Zare et al., 2017; Zerihun et al., 2018) (Table A4); P is the erosion prevention supporting practices factor (dimensionless), which is set to 1.00 here for the lack of data on the spatial distribution of soil conservation measures in the study area.

3.3.5. Ecosystem services correlations

Identifying tradeoffs and synergies among ESs is vital for improving ecological management practices and informing decision-making (Carreno et al., 2012). Since the four selected ESs are non-normally distributed as suggested by the Kolmogorov Smirnov test, we utilize Spearman rank correlation here to identify correlations among ESs following the study of Lyu et al. (2019). Generally, a significant (p < 0.05) negative Spearman coefficient means a trade-off effect, whereas a significant positive value means a synergy. In this step, 1000 points that are randomly generated over the study area are utilized to extract sample data.

3.4. Analysis on the effect of ISFZs on land use change and ecosystem services tradeoffs

In this section, we conduct a two-step process to explore the effect of integrated spatial function zones (ISFZs) on ESs and their tradeoffs: 1) conducting multi-scenario land use simulations by varying the way of ISFZs to impact land use conversion; 2) assessing ESs and their tradeoffs based on simulation results and comparing ESs and their tradeoffs among the multi scenarios. We design two scenarios, including Business as usual (BAU) and ISFZs constraint scenarios in the first step. BAU is a baseline or default scenario in which LULC types would be converted with each other following the historical trend but not interfered with by any spatial function zone. Land use quantity obtained from the Markov process is processed as the potential quantity, and the land use pattern is determined only considering the relative combined probabilities of LULC types as described in 3.2.2. The ISFZs constraint scenarios are designed to simulate land use transformation under the effect of ISFZs constraint to make rational use of land resource, optimize territory land space, and promote land use efficiency.

In the current spatial planning system of Wuhan, the ISFZs consist of three primary classes and six secondary classes of spatial zones. Farmland protection zone (FPZ) (Class I) consists of two classes basic farmland protection (BFPZ) and general farmland protection (GFPZ). Ecological redline (ERL) (Class II) is composed of ecological baseline (EBL) and ecological development line (EDL); Urban development zone (UDZ) (Class III) contains permitted development zones (PDZ) and conditional development zones (CDZ). The impact of SFZs on land use conversion can be interpreted based on the restrictive levels of SFZs and the correspondence between SFZs and land use types (see more details in Table 1). For the rigid constraint zones (i.e., BFPZ and EBL), we set them as restrictive areas where any land use conversion is prohibited. For the plastic constraint zones (i.e., GFPZ, EDL, PDZ, and CDZ), we improve the

Table 1
Spatial function zones and their effects on land use/land cover types.

Spatial function zones (Class I)	Spatial function zones (Class II)	Land use/land cover types	Restrictive levels
Farmland protection zone	BFPZ	Farmland	Rigid
	GFPZ	Farmland	Plastic
Ecological redline	EBL	Forests, Grassland, Water	Rigid
	EDL	Forests, Grassland, Water	Plastic
Urban development zone	PDZ	Construction land	Plastic
	CDZ	Construction land	Plastic

Note: BFP denotes basic farmland protection; GFP denotes general farmland protection; EBL denotes ecological baseline; EDL denotes ecological development line; PDZ denotes permitted development zones; CDZ denotes conditional development zones.

probability-of-occurrences of the land use types in correspondence to a specific SFZ to affect land use conversion so as to optimize land use configuration. Specifically, we improve the probability-of-occurrences of farmland located in GFPZ, forests, grassland and water in EDL, and urban land in CDZ by a certain percentage (Abbreviated as p) and urban land in PDZ by $2p$. In this experiment, we manually set p as 20% to maintain a sound probability-of-occurrences after several trials in the experiment of the ISFZs constraint scenario.

4. Results

4.1. Land use change scenarios

The predicted land use patterns under BAU and ISFZs constraint scenarios in 2035 are shown in Fig. 3. We can observe that in future construction land expansion and its induced farmland loss is a predominant feature of land use conversion of the study area. This phenomenon is most striking around the existing urban areas and roads. In addition to farmland, forests and water bodies would be vulnerable to being lost during construction land expansion. From the perspective of scenario comparison, the ISFZs scenario would generate a more compact pattern of construction land than the BAU scenario, featured by a clustered distribution of new construction land in urban surroundings while a parse distribution in remote rural areas in Xinzhou, Huangpi and Caidian districts.

Fig. 4 and Fig. 5 present the predicted land use quantities under BAU
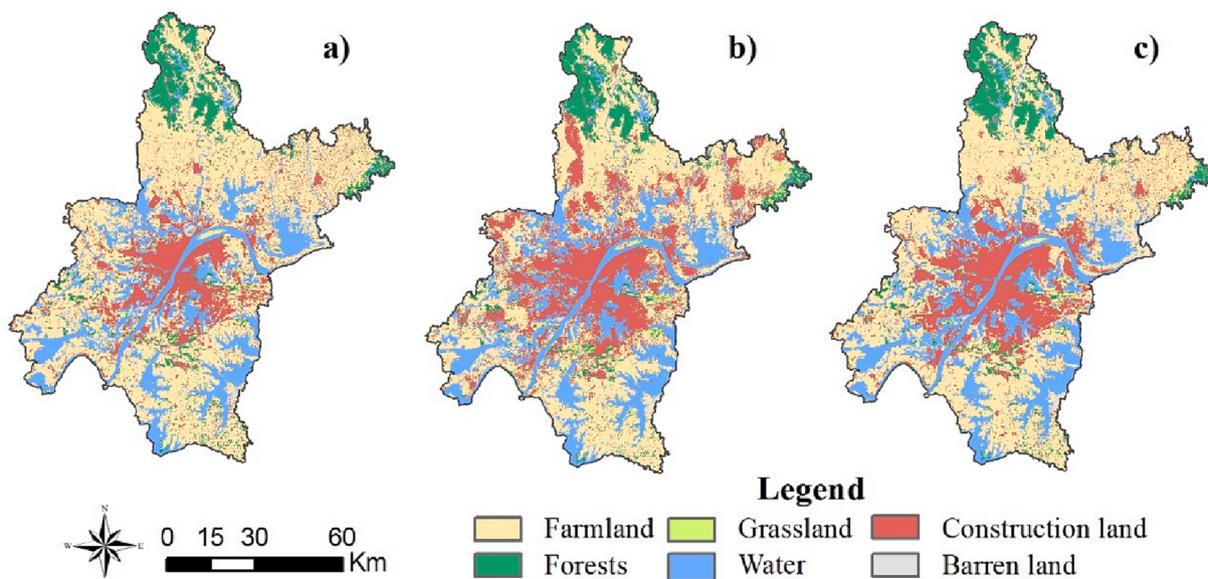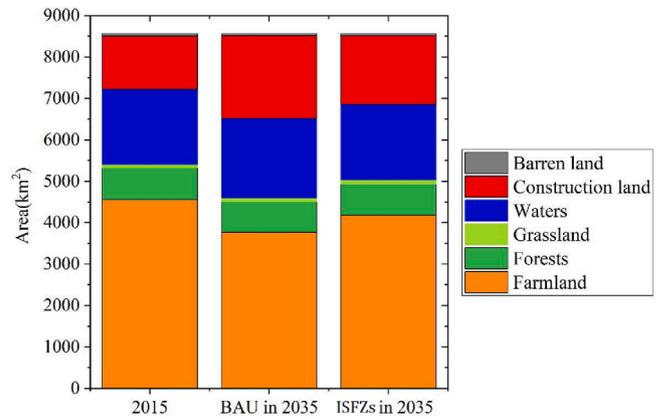
Fig. 4. Land use compositions of the study area in 2035 (BAU: business as usual; ISFZs: integrated spatial functional zones).

and ISFZs constraint scenarios in 2035 and quantitative conversions among various LULC types during 2015–2035. Overall, construction land, grass land and waters would expand, while farmland, forests and barren land would shrink during 2015–2035. Compared to the BAU scenario, the ISFZs would generate more farmland, green forests and barren land, while less construction land, waters and grassland. Areas of farmland and forests would be increased by 410.99 km^2 and 28.49 km^2 respectively and construction land would be reduced by 342.45 km^2 in the ISFZs scenario. From land use conversion perspective, conversions of other LULC types to construction land would be the most remarkable conversion in the future, which is coincident with the historical trend during 2005–2015. Farmland, waters and forests would be the major sources of construction land growth. Moreover, conversions of farmland and forests to construction land would be greatly constrained when there is an integrated spatial regulation indicated by 369.24 km^2 less farmland and 16.31 km^2 fewer forests transformation in the ISFZs scenario. However, the conversion from construction land to other LULC types, especially farmland would be promoted, indicated by 43.01 km^2 more conversions from construction land to farmland in the ISFZs. The finding may indicate a favorable efficiency in the construction land consolidation and rehabilitation along with the spatial regulation policy. It should be noted that conversion from farmland to forests would also be active, especially in the ISFZs scenario indicated by 5.26 km^2 more farmland conversion to forests.
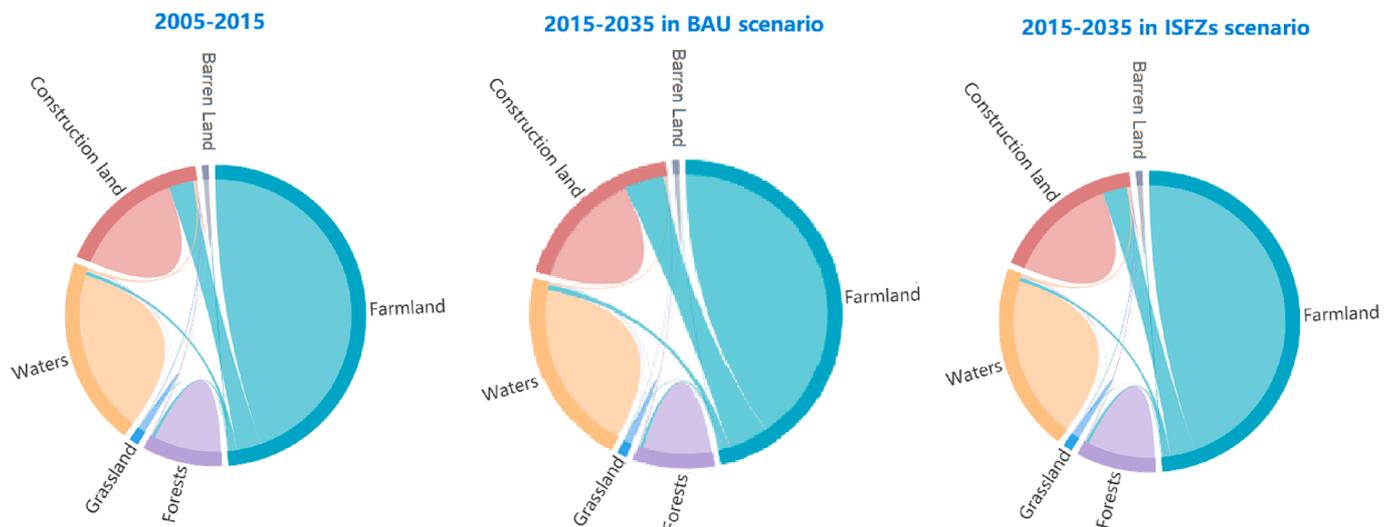
Fig. 3. Land use scenarios: a) 2015; b) BAU (Business as usual) in 2035; c) ISFZs (Integrated spatial function zones) in 2035.

Fig. 5. Land use conversion during 2015 ~ 2035 in different scenarios (BAU: business as usual; ISFZs: integrated spatial function zones).

4.2. Ecosystem services estimation

Fig. 6 shows spatial distributions of ESs under the two spatial regulation scenarios in the study area. We can see that all ESs are spatially heterogeneously distributed. WY shows a gradually declining trend from the southwest to the northeast, while the other three ESs display a distinctive "urban–rural" difference. Spatial regulation would not vary the overall pattern of ESs, but it would impact the pattern of ESs in local space. Compared to the BAU scenario, the ISFZs scenario would generate a more globally aggregated and a less locally differentiative pattern of all ESs.

In terms of individual ecosystem service, the highest values of CP occur around water bodies in the flat plain, especially in the northern Huangpi District and southern Caidian District, while the lowest values occur in the mountainous areas in the northeastern Huangpi District.

Compared to the BAU, the higher values of CP are distributed in the flat agricultural areas, especially in the fringe of concentrated and aggregated farmland. The WY shows the highest values in the southwestern areas of Caidian and the lowest values in the northeastern areas of Huangpi and Xinzhou. Less mosaic of different-grade values of WY (e.g., high and relatively high values) is detected in the ISFZs, resulting in a more aggregated spatial pattern. The spatial pattern of CS is consistent with the LULC types' distribution, with the highest values in the northern and southern mountainous areas, middle values in the plain areas of urban surroundings, and the lowest values in water bodies. The ISFZs present a more aggregation pattern of CS compared to the BAU, characterized by relatively low infiltration in relatively high values. EP presents a decreasing trend from the region's center to its outersphere. Different from the BAU, the distribution of low EP values in the ISFZs would be greatly reduced in the flat plain of rural areas.
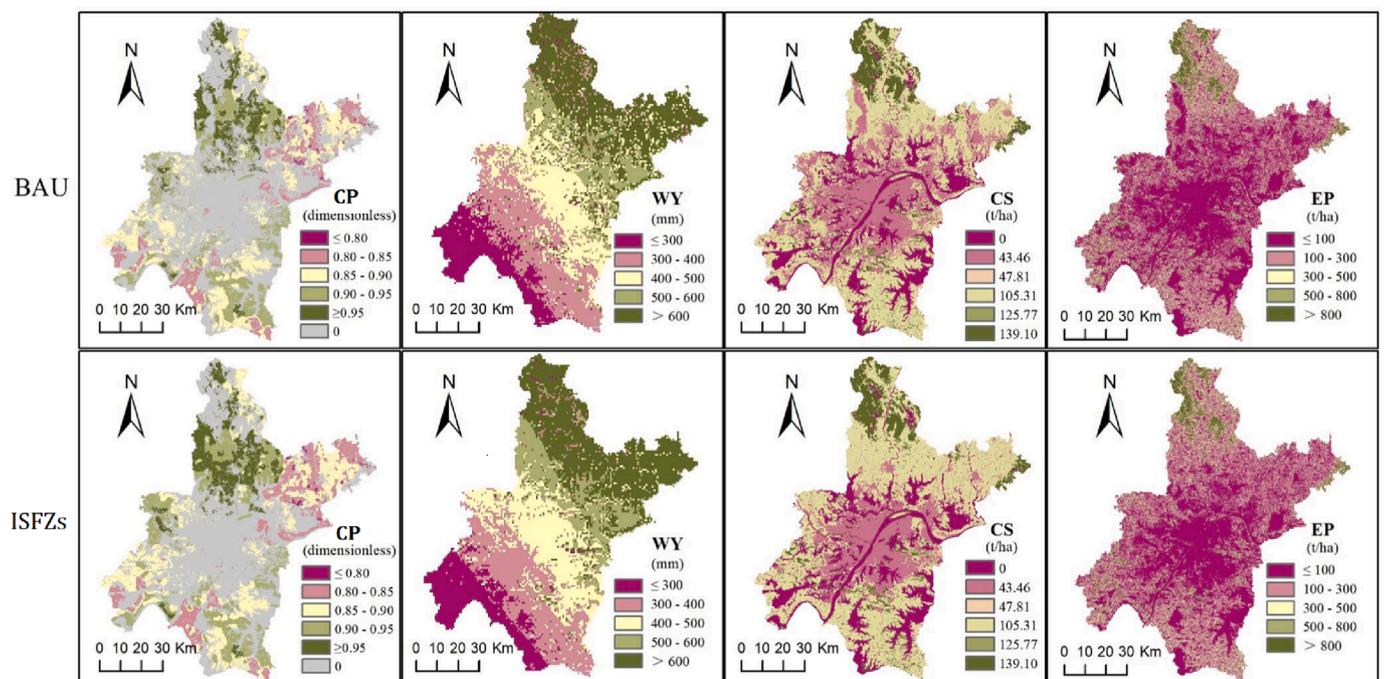

Fig. 6. Spatial pattern of ecosystem services in 2035 at two scenarios (BAU: business as usual; ISFZs: integrated spatial functional zones. CP: crop production; WY: water yield; CS: carbon storage; EP: erosion prevention).

We statistic value distributions of four ESs to facilitate a quantitative comparison of ESs between the two scenarios (Fig. 7). Overall, ISFZs would generate higher average values of ESs (except WY) than those of the BAU, which indicates its superiority in conserving high-value ecosystem services in future. The average of CP, CS and EP would be increased by 0.05, 2.23 t/ha, and 7.3 t/ha respectively, while the average of WY would be reduced by 6.4 mm in the ISFZs scenario. In detail, values of CP are ranged between 0 and 1 regardless of the scenario, and average CP values of all land patches are 0.86 and 0.91 in the BAU and ISFZs scenarios. Values of WY would change from 0 to 1546.2 and from 0 to 1450.7 with average values of 472.8 mm and 466.4 mm in the two scenarios. CS values would be ranged between 43.46 and 139.10 in both scenarios and average CS values would be 68.92 and 71.15 respectively. EP values would be in the range of $0 \sim 1323.45$ m and in the range of $0 \sim 1410.83$ m with average values of 186.02 and 193.32 respectively.

4.3. Correlations among ecosystem services

Correlations among four ecosystem services under the two regulation scenarios in 2035 in Fig. 8. The size of the sector represents the intensity of correlations, and the diagonal line indicates the significance level at P < 0.05. We can see that most pairs of ESs are positively correlated and most synergies would be slightly promoted in the ISFZs scenario compared to the BAU scenario.

Under the BAU, most pairs of ESs (except WY-EP) are positively correlated, indicated by a significant positive Spearman coefficient, revealing a synergy effect between these ESs pairs. Among all ESs pairs, the synergy between CP and CS is the strongest, with a Spearman coefficient of 0.574, followed by those between CS and EP (Spearman = 0.455) and between CP and EP (Spearman = 0.455), and that between WY and CS is the weakest with a Spearman value as 0.164. Please note that CP as a provisioning service would be positively correlated with other regulating ESs (e.g., CS and EP), which verified the functions of farmland in providing the indirect regulating ecological functions and services.

Under the ISFZs scenario, except the pair WY-EP, ESs pairs are positively correlated. Moreover, except the pair CP-WY, the positive correlations of other pairs are significant at P < 0.05. The values of

correlation and their relative ranks of them in the ISFZs are rather similar to those in the BAU, e.g., the correlation between CP and CS is the strongest while that between WY and CS is the weakest. Different from the BAU, ISFZs would obtain a tradeoff rather than a synergy effect between CP and WY; it would also obtain stronger synergies between CP and EP, between WY and CS, and between CS and EP, as well as weaker synergies between CP and WY and between CP and CS.

5. Discussion

5.1. Interpretation of the effect of integrated spatial function zones (ISFZs) on ecosystem services correlations

Exploring the socio-physical factors and ecological processes that contribute to ecosystem services correlations will benefit the establishment and improvement of ecosystem-based management practices (Carreno et al., 2012; Zheng et al., 2014). Before analysing the mechanisms of ESs correlations, it is necessary to identify the factors that influence the provision of ESs. For the ESs investigated in this study, in addition to LULC change, CP is influenced by elevation gradient, soil properties, irrigation conditions and tillage convenience; WY is affected by precipitation and potential evapotranspiration; CS is mainly impacted by vegetation coverage; EP largely depends on topography, soil property, vegetation coverage and management practice. Of all the drivers, meteorological condition and topography feature would remain relatively unchanged during a short period of time. In contrast, other factors, i.e., land use change and vegetation coverage, are vulnerable to be varied under human influence, which is the major focus of ecological management (Fagerholm et al., 2016; Feng et al., 2020). Changes in these factors would first influence the individual ES and subsequently vary the correlations among the multiple ESs through a complex mechanism (Feng et al., 2017).

According to Bennett et al. (2009), there are two types of mechanisms causing the ESs correlation: common drivers and interactions among ecosystem services. Common drivers refer to factors that contribute to the provision of multiple ecosystem services, like climatic factors and vegetation coverage (Bennett et al., 2009). Whereas, those factors that may impact a single ES can be recognized as independent factors (Feng et al., 2020). Land use change as a common human
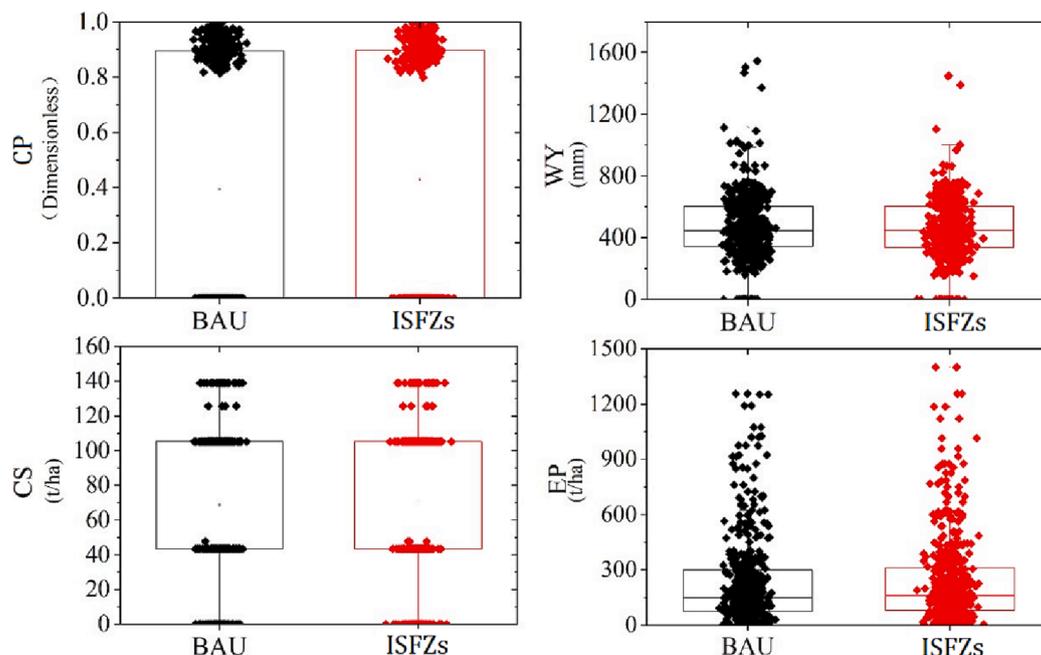

Fig. 7. Value distributions of ecosystem services in 2035 under the two scenarios (BAU: business as usual; ISFZs: integrated spatial functional zones. CP: crop production; WY: water yield; CS: carbon storage; EP: erosion prevention).

Fig. 8. Correlations among ecosystem services under the BAU (left) and ISFZs (right) scenarios at 2035 (BAU: business as usual; ISFZs: integrated spatial functional zones. CP: crop production; WY: water yield; CS: carbon storage; EP: erosion prevention).
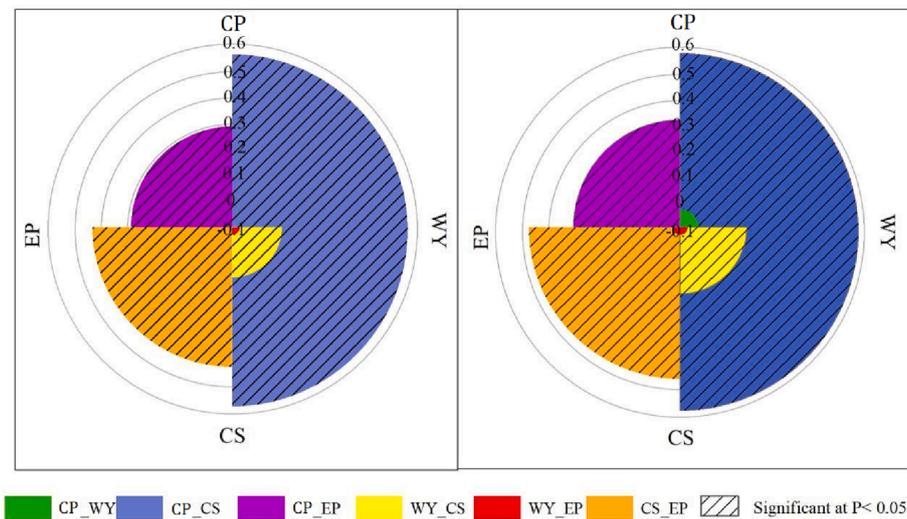
intervention is recognized to be one of the most common drivers of ESs interactions (Berry et al., 2020). Xu et al. (2017) proposed two types of land use change mechanisms: land use conflict and land use consistency. The former refers to a LULC type used for the provision of one ES that would no longer be used for another, which usually gives rise to a tradeoff effect. The latter signifies that a LULC type would benefit the provision of two or more services simultaneously, leading to a synergy. However, given the mosaic characteristic of landscape as a composition of various LULC types in the real situation, the major LULC type that compromises the landscape would be the determinant of the land use conflict/consistency mechanism (Zhang et al., 2020).

Our study revealed a significant impact of the ISFZs on ecosystem services correlation which could be mainly interpreted by a LULC transmission mechanism. As revealed by the modeling results, ISFZs would increase farmland, green forests and barren land while decreasing construction land, waters and grassland in future (Fig. 3). As a response, average values of most ESs would be improved (Fig. 6) and interactions among ESs are slightly varied (Fig. 7). Taking the correlation between CS and EP as an example, ISFZs would promote the growth of green forests and thus promote synergy between the services of CS and EP for the high capacity of green vegetation in both sequestrating carbon dioxide from the atmosphere and preventing soil water loss and soil erosion. However, the effect of ISFZs on the ESs correlation is not only dependent on LULC change but is also influenced by the aforementioned common socio-biophysical factors (i.e., non-LULC factors), like terrain and vegetation. For instance, we found ISFZs scenario would conserve more farmland, and enhance both services of CP and CS, and consequently promote synergy between CP and CS. Suppose only the LULC transmission mechanism (i.e., a land use conflict mechanism in this case) is considered, it would easily be inferred that farmland growth would intensify the tradeoff between CP and CS since farmland has a high capacity to provide CP service, but the low capacity to supply CS (Feng et al., 2020), which have been revealed by extensive previous studies (Foley et al., 2005; Jopke et al., 2015; Liu et al., 2019). However, due to the specific socio-physical conditions of the increased intensive farmland around urban areas, i.e., high vegetation coverage, flat elevation and convenient transportation condition, the correlation between CP and CS would shift from a tradeoff to a synergy effect in this case. Under this context, farmland growth would cause an improvement in synergy between CP and CS.

5.2. Implications for territory spatial planning and ecosystem-based management

SFZs are extracted from the TSPs, which aim to guide the direction of regional development as well as regulate the mode, intensity and spatial pattern of land use (Li et al., 2020). To interpret the effective function of the SFZs in guiding land use conversion, two key issues should be addressed: one is to develop an effective land use simulation model to depict land use evolution; the other is to develop a sound mechanism which incorporates the function of the SFZs into land use simulation to optimize land use pattern. To address the first issue, we coupled the Markov and FLUS models to implement the land use simulation process, which has been validated and authenticated by the results in section 3.1 and extensive previous studies (Zhang et al., 2020; Lin et al., 2020). As for the second issue, we utilized ISFZs to guide land use conversion in an ex-ante intervention way, i.e., promoting or constraining land use conversions on a land patch under the impact of a regulation rule, following the studies of Li et al. (2012) and Yin et al. (2018). This is different from the post-evaluation mechanism that usually implements land use simulation in the first step and then evaluates the resulted in land use strategy from the perspective of its impact on socio-economic development and ecological conservation (Ishaya et al., 2008; Sun et al., 2018; Zank et al., 2016). In comparison, the ante-intervention mechanism allows direct regulation of spatial policy on land use conversion, thus presenting a clearer logic flow and generating a better-understood result. Following the logic above-mentioned, we conducted an experiment in Wuhan and found that ISFZs are beneficial to conserve agricultural and ecological land, to control the increase of construction land and to promote urban compact growth. Moreover, it helps to improve urban land management and regulation in urban surrounding areas, and constrain the loss of farmland green vegetation encroached by urban growth. The proposed method can be applied to inform the formulation, implementation and evaluation of TSP. For example, in the planning formulation stage, the potential impact of SFZs on land use patterns can be evaluated, on which basis, by comparing the potential land use pattern with the targeted one, more reasonable SFZs can be delineated. Moreover, by varying the way SFZs affect land use change, more reasonable land use conversion policies can be formulated.

SFZs would undoubtedly impact natural ecosystems and regional sustainable development. Currently, little research has examined the effect of spatial planning or spatial regulation on urban land use change and the induced ecological processes and functions, like greenhouse gas emissions and carbon metabolism (Leibowicz, 2017; Li et al., 2020).

They usually analyze the impact of spatial regulation on a single ecological process or function but ignore their joint impact on multiple domains of ecological services, which may lead to a biased conclusion. To overcome this drawback, this study put the multiple spatial function zoning policies into an integrated framework to analyze their joint effect on the multiple ESs (i.e., CP, WY, CS and EP) and their correlations. As a prerequisite, this study utilizes methods that couple LULC data and environmental factors in assessing the selected ESs indicators, which not only facilitate the analysis of the LULC transmission mechanism but also overcome the efficiency of simple LULC-based assessment approaches that overlook the environmental background affecting ESs (Aspinall and Staiano, 2019). Our results showed that ISFZs would promote most ESs and generate a more aggregated pattern for all ESs. Moreover, it would enhance the synergy effect among most pairs of ESs. We furthermore revealed that a LULC transmission mechanism would significantly affect ESs correlations, but common drivers would also play a role. For example, the conservation of high-quality farmland conservation would promote synergy between production services and regulation services. In this regard, this study is beneficial to ecological conservation and rehabilitation as well as the coordinated development between urban systems and ecosystems.

5.3. Drawbacks and prospects

There are some limitations in this study that may need to be improved. First, when assessing the ESs consequence of a particular land use policy, it is very important to choose appropriate and comprehensive indicators of ESs. Due to the limited space, we select only four ESs indicators from the providing and regulating domains, which may overlook other ESs that play a vital role in the eco-social system, such as recreation services in natural ecosystems. Moreover, in assessing ESs, we adopted simulated data on background conditions like vegetation and precipitation obtained from the time-synthesis method as an alternative to real values, which may lead to a biased or even deviated result. Future studies could develop time-series models like exponential extrapolation, gray forecast model and other intelligent techniques such as wavelet transform to better estimate these background data as well as ESs values.

6. Conclusion

This study investigates the impact of spatial regulations on ESs and their correlations through multi-scenario land use simulations. In this case, the FLUS model proved to be effective for land use conversion simulations, with overall accuracy, Kappa coefficient and FoM coefficient of 0.797, 0.762 and 0.4874 respectively. Two scenarios with different spatial regulation policies incorporated as BAU and ISFZs scenarios were designed under which land use simulations were respectively conducted. Scenario comparison revealed that the ISFZs scenario would generate a more compact pattern of construction land than the BAU scenario. It would also generate more farmland, green forests and barren land, while less construction land, waters and grassland. The change in land use quantity and pattern would lead to the variation of ESs featured by higher average values of ESs (except WY) and a more aggregated global pattern for all ESs in the ISFZs than those in the BAU. The ESs correlations would also vary in the two scenarios, indicating synergies between most ESs pairs would be slightly promoted in the ISFZs that the BAU. We further infer that spatial regulation affects the correlation of ESs primarily through the LULC transmission mechanism, but is also influenced by common socio-biophysical factors such as terrain and vegetation. This study informs the exploration of spatial policies for land use change and ecology and also advocates the need for terrestrial spatial planning and ecosystem-based management in ESs improvement, as well as the coordinated development of urban systems and ecosystems.

CRediT authorship contribution statement

Yan Zhang: Conceptualization, Methodology, Funding acquisition, Writing – original draft. **Peiheng Yu:** Visualization, Writing – review & editing. **Yasi Tian:** Investigation, Supervision, Project administration. **Huiting Chen:** Software, Visualization. **Yiyun Chen:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110246.

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