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Impacts of rapid urbanization on ecosystem services under different scenarios – A case study in Dianchi Lake Basin, China

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ABSTRACT

Dianchi Lake Basin (DLB) is a typical and representative type of urbanization model based on the plateau lake ecosystem, with scarce land resources, deficient water resources, and a fragile ecological environment, in parallel with large-scale and rapid urbanization. To increase ecological security and maintain ecosystem services (ESs), it is essential to analyze the paths and processes for implementing sustainable urbanization. Using combined CLUE-S-Markov-InVEST modeling, the study simulated ESs changes and distribution in DLB under a natural increase scenario (NIS), an urban plan scenario (UPS), and an ecological protection scenario (EPS). EPS proved to be the best-optimized urbanization path and land use pattern that can meet land use demand for urbanization, but also maintain (or even improve) regional ESs levels. The major driving mechanisms underlying urbanization effects on ESs were found to be selection of urbanization path, scale control and layout of construction land, demarcation and implementation of ecological red line and ecological protection areas. The results indicate that DLB should follow the EPS urbanization path, an ecological red line should be reasonably delineated and observed, and ecological isolation strips should be established at appropriate locations. Additionally, the scale of construction land should be strictly controlled, constructed land should be used more intensively, and the utilization efficiency of construction land should be improved.

1. Introduction

Ecosystem services (ESs) supply dual attributes, for the economy and human society. Their value depends on people's recognition and utilization of ESs, defined as the well-being humans derive from nature (Costanza et al., 2017; Costanza et al., 1997; TEEB, 2010). The ESs concept has been widely used across disciplines to identify and tackle the frontier issue of interactions between humans and the environment, by comprehensively considering natural and eco-social sciences. However, the human benefits deriving from ESs cannot be summarized simply as synergies or tradeoffs, due to differences in ESs types, demands for human benefits, and scale of analysis (Duraiappah, 2011; Haines-Young and Potschin, 2010; MA, 2005; Raudsepp-Hearne et al., 2010).

Human activities are one of the most important key drivers of changes in ESs supply (MA, 2005; Nelson et al., 2005; Zhang and Xie, 2019). In particular, the land use and land cover change (LUCC) induced by human activities influences ESs and regional environments (Pocewicz et al., 2008), by decreasing ESs provision in series of ways (Gao and Bryan, 2017). These include reducing biodiversity (Maes et al., 2012), carbon storage (Tolessa et al., 2017), recreational and esthetic values (Song and Deng, 2017), aggravating soil erosion and nitrogen export (Bai et al., 2018; Choubin et al. 2017; Tolessa et al., 2017), and degrading water quantity and quality (Fiquepron et al., 2013; Mashayekhi et al. 2010). Therefore LUCC is widely regarded as the key factor altering the function and structure of ecosystems, and the greatest and most direct driving force in ESs change and distribution over recent history (Huang et al., 2019; Xu et al., 2017a; Xu et al., 2017b).

Urbanization, while being an inevitable trend and expanding activity

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worldwide (Xie et al., 2020; Zhang, 2018), particularly drives land use change on a large scale and always involves radical land cover change, even when carefully planned. It ultimately results in huge and irreversible impacts on ESs (Durina and Patanakano, 2013; Satterthwaite et al., 2010), as seen recently in rapidly developing countries like China (Wei and Ye, 2014). Even worse, some urban planning and development policies do not consider ecosystem carrying capacity, environmental capacity, and the impacts of urbanization on ESs (through land use change). An eco-friendly pattern of urbanization urgently needs to be promoted and applied worldwide, so as to maintain ecological balance and ESs provision (Bai et al., 2018; Mendoza-González et al., 2012). To achieve this, the pressure-drive-response mechanism of urbanization on ESs variation and distribution needs to be further clarified.

Rather than simply attributing changes in regional ESs to the increasing human activities or climate change (Shirmohammadi et al. 2020a; Tolessa et al., 2017; Kindu et al., 2016), the difficult task of identifying the driving mechanism of urbanization effects on regional ESs must be addressed (Bai et al., 2019). Identification of drive-response relationships is complicated, but critical, in decision making on urban planning, land use management, and ecosystem protection (Bai et al., 2018; Huang et al., 2019). It involves identifying the main driving force and factors in the existing regional urbanization process (past 20 years) and impacts on regional ESs, the inertia influence of these factors on future urbanization and ESs, and intelligent selection of optimized future urbanization path, in the hope of minimizing urbanization damage to regional ESs. Knowledge in this area is needed in order to help balance the contradiction between rapid development and ecosystem protection during the process of rapid urbanization. Scenario analysis could be useful for quantitative assessment of changes of ESs and mapping the spatial distribution of ESs. Based e.g., on comparison of simulated ESs maps for different urbanization scenarios, a reasonable urbanization path could be selected and land use allocation optimized.

In the present study, we considered the case of DLB, a plateau lake basin area in China where the lake is the main aquatic ecosystem, with scarce land resources, deficient water resources, and a fragile ecological environment. Meanwhile DLB is the liveliest region in Kunming and even in Yunnan Province, and a concentrated area of urban and rural construction and development. Rapid urbanization will continue in coming decades, inevitably exerting huge impacts on regional ESs. In parallel, Yunnan is aiming to become a demonstration area of national unity and progress, a vanguard of ecological civilization construction, and a radiation center facing South and Southeast Asia. Kunming is aiming to become an international central city and to improve its services and functions as a provincial capital (KMGOV, 2020b). DLB is earmarked as the core area for transforming Kunming into an international center (KMGOV, 2016). Owing to its regional advantages and regional development strategies, urbanization of DLB will accelerated in the next 20 years and demand for construction land will also increase substantially. This will inevitably lead to great changes in regional land use pattern and path, and thus have profound impacts on regional ESs, so the urbanization path and land use pattern selected for DLB will play a decisive role in regional ecosystem security and ESs maintenance.

Based on data charting the tempo-spatial variation in LUCC in DLB from 1995 to 2015, we used the CLUE-S model in combination with the Markov model to predict and map land use change by 2035 arising from urbanization under three future scenarios (natural increase, urban plan, ecological protection). Specific objectives of the work were to: (1) simulate changes and distribution of land use in 2035 under three urbanization scenarios, based on tracking of land use change trends and studying relevant regional natural geographical factors and economic and social development factors; (2) calculate, evaluate and compare ESs changes in the three scenarios; and (3) evaluate the impacts of the three scenarios on ESs in DLB.

2. Materials and method

2.1. 2.1. Research area

Dianchi Lake Basin (24°29′-25°28′N, 102°29′-103°01′E), located on the Yunnan-Guizhou Plateau in central Yunnan Province, belongs to the Jinsha River system and lies within the subtropical plateau monsoon climate zone. It occupies an area of 2920 km^2 and is located at around 1890 m elevation (Fig. 1). Mean annual temperature in the basin is 15 °C and mean annual precipitation is 1000 mm. Dianchi Lake (China 's sixth largest freshwater lake), is the 'mother lake' and foundation of urban development in the nearby city of Kunming (Pan and Gao, 2010; Peng, 2016). From 1995 to 2019, gross domestic product (GDP) increased by around 20-fold, from 32.97 billion yuan to 647.59 billion yuan, the urban population increased by 1.7-fold, from 2.36 million to 4.05 million, and the built-up area (cities and towns) increased by 1.6-fold, or by 229 km^2 (Statistics Bureau of Kunming, 2019).

The area around the lake is the fastest-developing part of Yunnan, and the core and most concentrated urbanization zone in Kunming. In coming decades, urbanization in DLB is projected to continue on a huge scale, which will inevitably impact regional LUCC and ESs to a strong degree. During recent urbanization, there has been a relative lag in establishment of urban drainage systems and sewage treatment facilities, and new urban and agricultural non-point sources of contaminants have emerged, so the pollution load in Dianchi Lake has increased sharply and water quality has declined rapidly since the 1990 s (Huang et al., 2017). The lake is now suffering heavy eutrophication, with Cyanobacteria blooms erupting frequently.

2.2. Scenarios setting

Setting scenarios is the key step and core problem in scenarios simulation analysis (Shirmohammadi et al. 2020b). We set our scenarios by comprehensively considering the tempo-spatial distribution characteristics of ecosystems and ESs, stages of regional economic and social development, and existing processes (1995–2015) and potential future trend in urbanization. Based on our previous research, in the existing urbanization process (past 20 years) of DLB, the most influential mechanism for regional ESs has been the substantial increase of construction land (increased by 50.77% in 20 years), mainly at the expense of the agricultural land (now 12.4% of that in 1995) and grassland (now 6.6% of that in 1995) (Wang et al., 2021). In addition, DLB is the only center in Yunnan province, with the largest population and economic density, and is the core area for regional development and rapid urbanization in future decades. The accompanying demand for construction land will cause significant change to regional land use layout and pattern, which in turn will inevitably have huge impacts on regional ESs. Thus we created land use maps for DLB in 2035 under three future scenarios (see Table 1):

(1)Natural growth scenario (NIS): Urbanization following existing trends (1995–2015), where land use demands and distribution were considered immune from natural geography and policy factors. Demand for six types of land use in 2035 was predicted by the Markov model based on actual LUCC in 2015 and a transfer probability matrix derived from the actual conversion tendency (from 1995 to 2015) (see Supplementary Information). Only the minimum permanent prime agricultural land (368.84 km^2) was maintained in this scenario.

(2)Urban plan scenario (UPS): Urbanization under the current urban planning system and a strict policy of agricultural land protection. Based on the premise of stronger protection of agriculture land, construction land was increased to 795.24 km^2 according to the Kunming development plan, which was 50.26 km^2 less than in NIS, where the original state was maintained within the limits of permanent prime agricultural land. Other land use types were simulated according to the parameter setting and operation mechanism of the model.

(3)Ecological protection scenario (EPS): Urbanization under

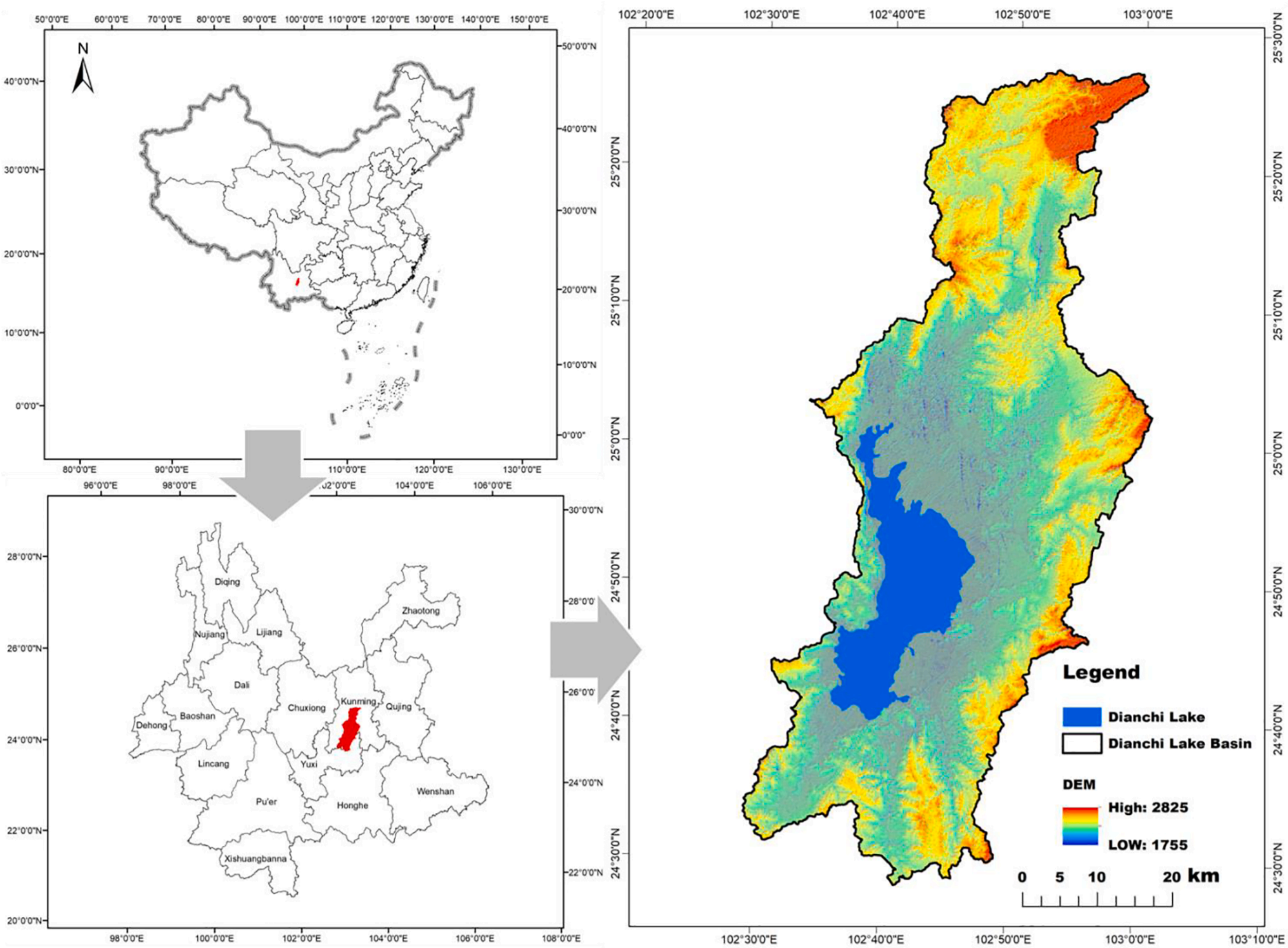

Fig. 1. Location of Dianchi Lake Basin (DLB) in Yunnan province, southern China.

strengthened ecological protection, based on the urban planning system. The scale of construction land in the Kunming development plans was retained, but assuming compliance with ecological red line areas (ERAs) and establishment of ecological isolation strips (EISs) as shown in Fig. S2. Land use patterns within these ecological areas and strips were assumed to be maintained at the level in 2015, which is of great importance to maintaining regional ESs and ecological security, i.e., forest, shrubland, grassland, ecological preservation areas, and open water. LUCC outside these restricted areas was simulated according to the parameter setting and operation mechanism of the model.

2.3. Land utilization simulation

2.3.1. Markov model

The Markov model was used to predict "memory-less" conversion of land use in certain areas, based on the mathematical technique and the hypothesis that land use quantities and layout in certain areas and on certain occasions are relatively stable (Wang and He, 2011). The principle is described by the simplified formula:

$$X(n) = X(n-1)Pij$$

where *Pij* is the transition probability matrix corresponding to each condition, *i, j* are land use classes, and *X(n)* and *X(n-1)* are system status at time *n* and *n*-1, respectively. Then:

$$\sum_{j=0}^{n} Pij = 1(i,j = 0,1,2,\cdots,n)(\text{thetotalvalueforeachrowis1})$$

where $0 \le Pij \le 1$ ($i, j = 0, 1, 2, \ldots, n$) (between 0 and 1, non-negative)

It has been shown that incorporating the Markov model makes the CLUE-S model perform better (Hu et al., 2013; Zheng et al., 2015). We adopted this approach to optimize the simulated results for LUCC in DLB under the three future scenarios and to predict the land use demand for the CLUE-S model based on following three assumptions: (i) no major adjustment in policy; (ii) urbanization proceeds along the existing trend; and (iii) ecosystem areas possess the dual attributes of being independent and accumulative.

2.3.2. CLUE-S model

The CLUE-S model is a powerful tool for simulating land use change and conducting scenario analyses under different ecosystem and spatial scales (Veldkamp and Verburg, 2004; Verburg, 2002), such as urban agglomerations (Zucca et al., 2010), hills (Zhu et al., 2010), watersheds (Luo et al., 2010), and reservoirs (Molina-Navarro et al., 2014). It was originally developed for spatially explicit simulation of LUCC based on empirical analysis of location suitability combined with analysis of interactions and competition among the tempo-spatial dynamics of land use systems (Molina-Navarro et al., 2014; Muller and Middleton, 1994; El Yacoubi and El Jai, 2002).

The advantage of the CLUE-S model lies in comprehensive consideration of physical geographical factors (e.g., elevation, vegetation, and water) and economic-social factors (e.g., GDP, population, and policies), and the clear illustration it provides of the hierarchical organization of land use change, spatial connectivity, and stability among locations. It

Table 1
Summary of the future urbanization scenarios setting.

Urbanization scenarios	Description	Growth of construction land	Protection of farmland	Implementation of urban planning
Natural growth (NIS)	The growth rate and pattern of each land use type follows the existing trend from 1995 to 2015.	Unrestricted, free growth.	Maintain only the minimum permanent prime farmland. (368.84 km2)	No consideration
Urban plan (UPS)	Urbanization and strict agricultural land protection policy under the current urban planning system	Moderate growth, meeting the needs of urban development	Farmland has been further protected.	Consider only the most basic urban planning
Ecological protection (EPS)	On the basis of urban planning, ecological protection should be further strengthened	Moderate growth, meeting the needs of urban development	Farmland has been further protected.	Optimized urban planning through enhanced ecological protection

has been widely used to simulate tempo-spatial land use change, especially at small regional scale (Jiang et al., 2016).

2.3.2.1. Logistic regression analysis (LRA). The land use conversion probability for each raster (30 m × 30 m) was calculated by binary stepwise logistic regression (Zhou et al., 2011). Eleven driving factors, comprising six physical geography factors (elevation, slope, aspect, distance to the nearest river, distance to the nearest lake, normalized difference vegetation index (NDVI) and five socioeconomic factors (GDP density, population density, night light index, distance to the nearest main road, distance to the nearest town center), were selected, based on relevance, suitability and availability of data (Liang et al., 2011). The process and results of logistic regression analysis are described in Supplementary Information 4.

2.3.2.2. Spatio-temporal scale selection (STS). Image entropy increases with increasing spatial resolution (although it also provides more information), which could reduce the certainty and accuracy of simulations (Huang et al., 2009). In this study, we adjusted spatial scale (spatial resolution) by setting raster cell size as high as possible based on the assurance of simulation accuracy. We tested resolution increasing stepwise (100 m/step) from 900 m (the default resolution of CLUE-S) and found 100 m generated the best simulation results. The temporal scale was set at 20 years, due to the availability of land use maps for 1995 and 2015, which were used to repeatedly simulate land use in 2015 in CLUE-S and to verify the accuracy until satisfactory. The accuracy of simulation is described in Supplementary Information 5.

2.3.2.3. Land use conversion rules (LCR). Land use conversion rules (LCR) denote the permission to change to different types of land uses, in the form of a land use transfer matrix. Transfer among any two types was accepted under the NIS, and was adjusted based on the actual status of urbanization (Table S5).

2.3.2.4. Elasticity for land use conversion (ELAS). Elasticity for land use conversion (ELAS) is used to present the ease or difficulty of one land use conversion to another (Liang et al., 2011). It value ranges from 0 to 1, where the closer the value comes to 1, the more difficult it is for a certain land use to convert to another, and the easier it is to do the opposite (Table S6).

2.3.2.5. Land use policies and restrictions (LUPR). Land use policies and restrictions (LUPR) in form of regional development strategy, land use policy, protected area setting, etc. also had an important influence on the results and precision of simulation. Here, LUPR was configured according to General Plan of Land Use of Kunming City (2006–2020) and Master Plan of Kunming City (2011–2020) (KMGOV, 2011; KMGOV, 2016), where ERAs and EISs were the main restrictions (Fig. S2).

2.3.2.6. Land use demand (LUD) prediction. Land use demand (LUD) in the future scenarios was predicted using the Markov model, based on land use status in 1995 and 2015, Kunming Dianchi Lake Protection Planning Outline (2018–2035) (KMGOV, 2020a), etc. (Tables S7-S9). Parameters used as input to Clue-S are shown in Table S10.

2.4. Ecosystem services evaluation

We used four representative indicators (carbon storage, water yield, soil retention, nitrogen export) to represent ESs in DLB as long as the data were available (Chitsaz & Malekian 2016; Wang et al., 2021) (see Supplementary Information 1). The InVEST model is useful in mapping ESs provision at spatial scale and in evaluating trade-offs between ESs (Redhead et al., 2018). We used the water yield model imbedded in InVEST to estimate water production per pixel of the study landscape under the different scenarios, usually simplified to precipitation minus evapotranspiration due to data accessibility. We used the carbon storage model to calculate the carbon quantity captured and stored in the landscape in the different scenarios, based on LUCC maps and parameterized stocks in carbon pools (from a biophysical attributes table). We used the nitrogen export model in InVEST to calculate transmission and attenuation of nutrient mass while flowing through the landscape, according to the principle of mass conservation. We used the soil retention model to estimate generation and delivery of overland sediment to streams (Sharp et al., 2016).

The model settings and relevant input parameters used are listed in Tables S11 and S12 in Supplementary Information 3. Simulation results from land use mapping in Section 2.3 and key parameters and biophysical attributes in tables (calibrated and validated in Supplementary Information 3) were used as input to drive the models. The InVEST model was used in estimating ESs based on LUCC, usually adapted to evaluate the tempo-spatial impacts of urban land use changes on ESs and to identify tradeoffs between urbanization and ESs provision (under the different scenarios.

2.5. Statistical analysis

Tradeoffs in ESs under the different urbanization scenarios were analyzed. To ensure objectivity and rigor in identifying tradeoffs, ArcGIS 10.5 was used to generate 1000 random points within the research area and to extract various ESs values at each random point. Tradeoffs between different kinds of ESs in 2035 were then analyzed by bivariate correlation in SPSS 26.0, based on the extraction value of 1000 random points. The correlation of a particular ES between the three scenarios was inspected by paired-samples *t* test in SPSS 26.0, based on the relevant value extracted from 1000 random points.

2.6. Data collection and processing

2.6.1. Data description

Land use layer and DEM data (30 m spatial resolution, 92.27% overall accuracy) were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn/). The six land use types considered (forest, shrub, agriculture, grass, open water, and constructed) and corresponding classification criteria are listed in Table S1. Other relevant data needed are listed in Table S2, including source of each dataset and introduction of models. All layers used were adjusted to uniform coordinate systems and resolution (WGS 1984 Albers, 30 m).

The LUCC in DLB during 2016–2035 was simulated using the CLUE-S model under scenarios NIS, UPS, and EPS. To trace the drivers and response relationships among LUCC and urbanization, the 11 selected influencing factors (six physical geographical factors, five socioeconomic factors) were considered (Table S3). The result indicated that all 11 selected factors performed quite well in simulating LUCC in DLB during the study period. Spatial map datasets (Table S2), such as LUCC in 2035 simulated by the CLUE-S model and designated biophysical tables (Table S12), were used as input to the InVEST model (Bai et al., 2019). Calibration and validation of parameters in biophysical tables is described in Supplementary Information 3.

2.6.2. Data processing

Rasters of elevation, slope, and aspect were generated from the DEM using ArcGIS 10.5. Those manifesting socioeconomic factors (GDP density, population density, night light index, distance to the nearest highway, distance to the nearest town) were calculated using ArcGIS 10.5. All layers used were adjusted to uniform coordinate systems and resolution (WGS 1984 Albers, 30 m) (Table S3).

3. Results

3.1. Land use simulation

Under NIS, the scale of construction land increased rapidly from 412.94 km^2 to 845.03 km^2, mainly at the expense of agricultural land, grassland and shrubland. Although the area of permanent prime agricultural land was maintained, overall agricultural land area was reduced from 634.24 km^2 to 368.81 km^2 (a 41.6% reduction). The area of grassland decreased from 531.83 km^2 to 420.47 km^2 (20.9% decrease) and that of shrubland from 488.08 km^2 to 432.81 km^2 (11.4% decrease). Open water area in the basin decreased by 4.94 km^2 (Table 2, Fig. 2, Fig. S3).

Under UPS, construction land area increased at a moderate rate from 412.94 km^2 to 793.81 km^2, an increase of 92.2%. Compared with NIS, protection of agricultural land was strengthened in this scenario, and the reduction in agricultural land was 51.23 km^2 less than that in NIS. The changes in forest, shrubland, and grassland area were similar to those in NIS (Table 2).

Under EPS, systematic ecological protection ideas and measures were assumed. Construction land area increased to 793.77 km^2, meeting the demand of future urbanization and construction land proposed in urban planning. Forest land and open water area increased by 0.12% and 0.52%, respectively, compared with UPS, while agricultural land, shrubland and grassland area basically remained unchanged (Table 2).

Table 2
Land use/land cover, as km^2 and percentage, in the natural increase scenario (NIS), urban plan scenario (UPS), and ecological protection scenario (EPS).

Land type		Scenario NIS	UPS	EPS
Forest	Area (km^2)	520.93	520.67	521.28
	Percentage	17.82%	17.82%	17.84%
Shrubland	Area (km^2)	432.31	430.71	432.33
	Percentage	14.79%	14.74%	14.79%
Grassland	Area (km^2)	420.47	423.27	421.09
	Percentage	14.39%	14.48%	14.41%
Open water	Area (km^2)	334.96	334.00	335.77
	Percentage	11.46%	11.43%	11.49%
Agricultural land	Area (km^2)	368.81	420.04	418.27
	Percentage	12.62%	14.37%	14.31%
Construction land	Area (km^2)	845.03	793.81	793.77
	Percentage	28.91%	27.16%	27.16%

3.2. Ecosystem services evaluation

The four indicators (carbon storage, water yield, soil retention, nitrogen export) used to represent ESs in DLB are shown in Fig. 3, while Table 3 shows ESs function quantity under the three scenarios. Overall, soil retention and water yield increased from 2015 to 2035, while carbon storage and nitrogen export decreased (Table 3, Fig. 3). In NIS, water yield increased from 0.78×10^9 m^3 in 2015 to 0.94×10^9 m^3 in 2035, while soil retention increased from 31.125×10^6 to 60.248×10^6 t during the same period. Carbon storage declined from 13.23×10^6 t in 2015 to 12.78×10^6 t in 2035, and nitrogen export declined from 1974.85 t to 1404.35 t across the study period.

Compared with NIS, in UPS carbon storage increased by 0.4%, water yield decreased by 1.5%, soil retention increased by 1.7%, and nitrogen export decreased by 1.4%. Compared with UPS, in EPS carbon storage increased by 4.7%, water yield decreased by 2.4%, soil retention increased by 1.7%, and nitrogen export decreased by 6.8%.

Under UPS, economical utilization of land and effective control of construction land sprawl saved land for construction purposes to a large extent, reducing the loss of agricultural land, grassland, and shrubland. Among the ESs assessed, the rate of carbon storage and water yield reduction was slower than in NIS, soil conservation was slightly enhanced, and regional nitrogen export was slightly decreased, indicating that regional ESs were enhanced to a certain extent under UPS.

Under EPS, protection areas with high ecological value and sensitive ESs were included, e.g., stronger protections of land cover and surface vegetation habitat within ERAs and EISs (Fig. S2), assuming that the vegetation coverage remained the same as in 2015. The simulation results showed that ESs generally increased under EPS compared with UPS.

Overall, the most dramatic improvements and reductions in ESs occurred in EPS and there were some significant increases, such as more than 300% improvement in water yield and more than 200% improvement in carbon storage and nitrogen export (Fig. 4). However, the significantly increased degree of environmental protection within ERAs and EISs induced reductions (estimated 40%-60%) in the same ESs on the south bank of Dianchi Lake. Thus according to the simulation results, the local-scale overall tradeoff manifested as strengthened protection in ERAs and EISs and increased development in southern areas.

3.3. Tradeoffs between ESs

There were some tradeoffs and synergies in ESs provision shifts under different scenarios ($df = 998$) (Table 4). Carbon storage showed a highly significant negative correlation with water yield, a significant negative correlation with nitrogen export ($p < 0.01$), and a significant positive correlation with soil retention ($p < 0.01$) in all three scenarios. Water yield displayed a significant negative correlation with soil retention in all three scenarios ($p < 0.01$), a significant positive correlation with nitrogen export in EPS ($p < 0.05$), and a non-significant correlation with nitrogen export in NIS and UPS (p greater than 0.05). Soil retention displayed a significant negative correlation with nitrogen export in NIS and UPS ($p < 0.01$), and a significant negative correlation with nitrogen export in EPS ($p < 0.05$).

A strong positive correlation was found among the four key ESs in all three scenarios (Pearson correlation; $df = 998$, $p < 0.01$), i.e., when one ES tended to increase from NIS to EPS, the other three ESs showed the same trend (Fig. 5, Table 5). It has been estimated that future ESs provision under EPS will give fewer ESs tradeoffs during urbanization than any other policy for land use (Bai et al., 2019). We found that EPS could maintain more ESs provision than NIS and UPS (paired samples *t* test; $df = 998$, $p < 0.01$). There was a statistically significant difference in ESs tradeoffs between EPS and UPS (paired samples *t* test; $df = 998$, $p < 0.01$). If DLB continues to implement the conventional urbanization path and land use policies, the basin will ultimately have (at a conservative estimate): 0.59 million tons less carbon storage, 22.43 million m^3

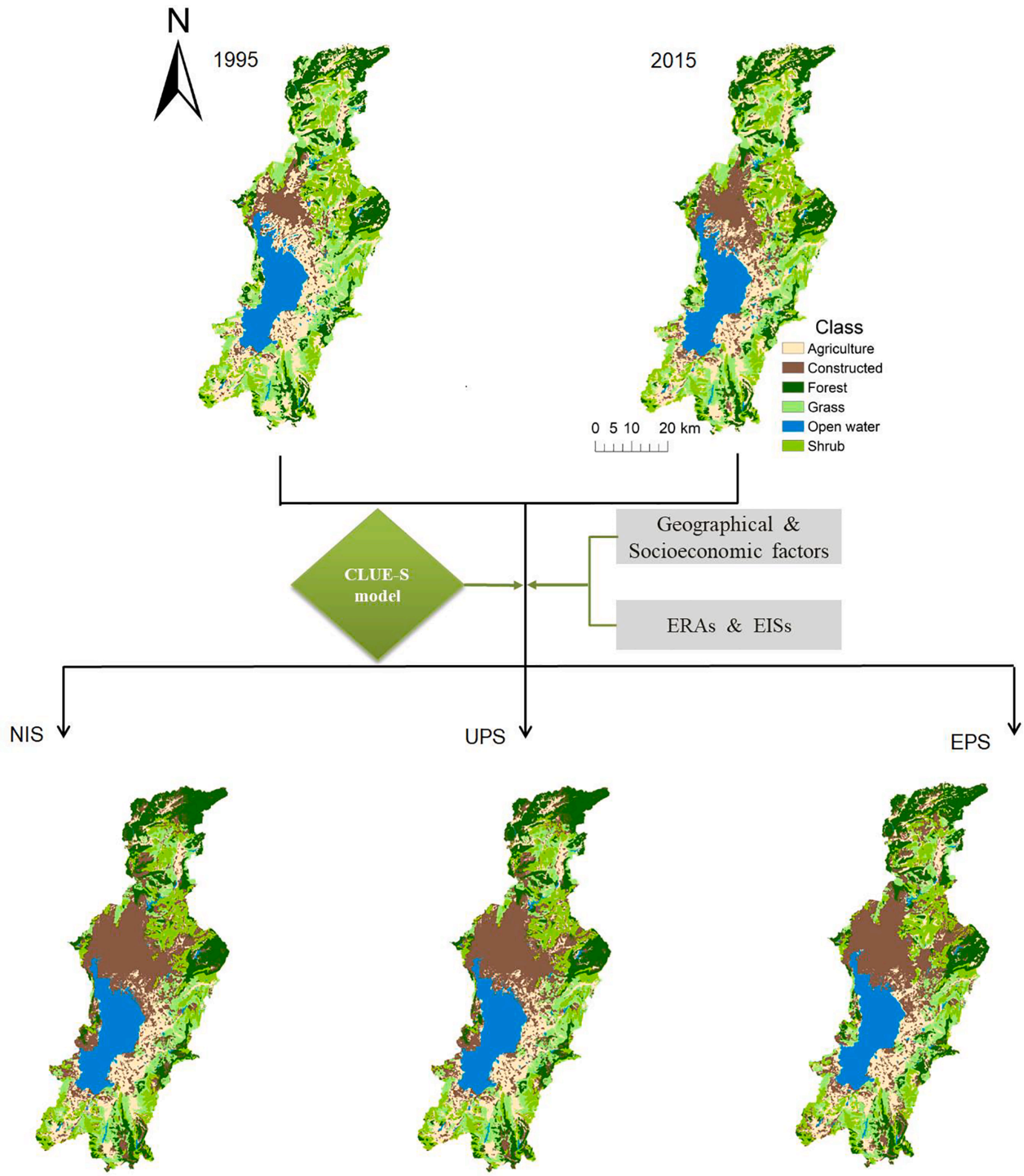

Fig. 2. Land use/land cover simulation maps for (left to right): the natural increase scenario (NIS), the urban plan scenario (UPS), and the ecological protection scenario (EPS).

less water yield, 1.02 million tons less soil erosion control, and 0.09 million kg less nutrient removal (Table 3). Compared with NIS, EPS was estimated to give: 0.66 million tons more carbon sequestration, 36.11 million m^3 less water yield, 2.05 million tons less soil erosion control, and 0.11 million kg less nutrient export.

4. Discussion

4.1. Impacts of urbanization on ecosystem services

Over the past 20 years, DLB has undergone rapid urbanization and in future years urbanization and population agglomeration will accelerate further. However, the resulting relationship between humans and nature, which is mainly about promotion or restriction, is extremely complicated. Our simulation results showed that the urbanization pathway selected can play an important role in maintaining regional ESs. If DLB follows the EPS urbanization mode, regional ESs will be maintained at a relatively optimal level, while there will be fewer ESs tradeoffs than with any other policy (especially land use policy). Compared with NIS and UPS, in terms of ESs provision in the DLB region, EPS could maintain more carbon storage (0.66 and 0.59 million tons more than in NIS and UPS, respectively), achieve more soil erosion control (2.05 and 1.02 million tons more than in NIS and UPS, respectively), and immobilize more nitrogen (0.11 and 0.09 million kg more than in NIS and UPS, respectively). All of these have positive ecological effects, which is conducive to maintaining regional ecosystem security and improving ecosystem service function. It is thus of great importance to choose a reasonable and sustainable urbanization path and land use planning approach.

In the future rapid urbanization process and economic and social

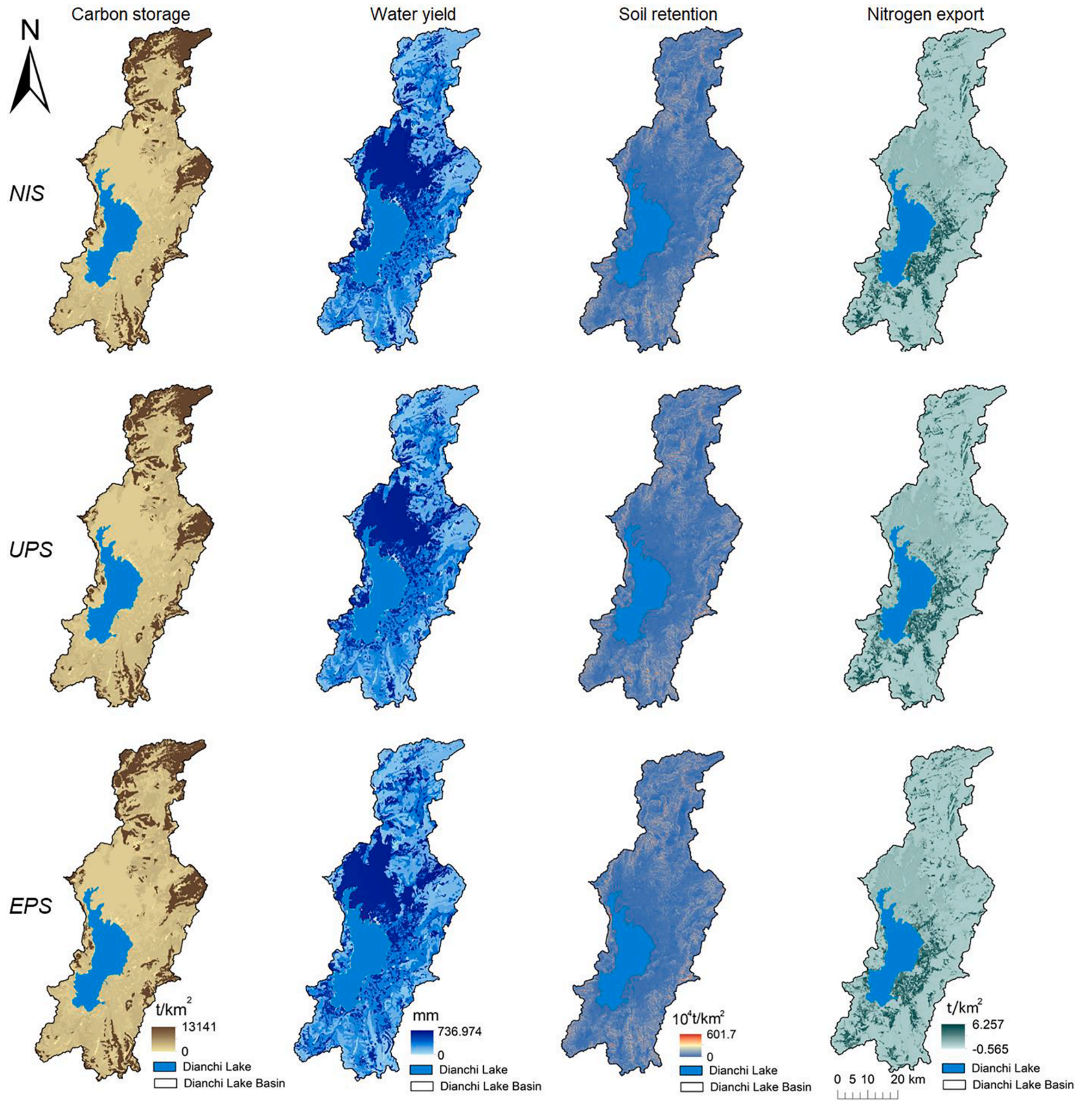

Fig. 3. Spatial distribution of (left to right) the four key ecosystem services (ESs) carbon storage, water yield, soil retention, and nitrogen export in Dianchi Lake Basin in 2035, under the natural increase scenario (NIS, upper diagrams), urban plan scenario (UPS, middle diagrams), and ecological protection scenario (EPS, lower diagrams).

Table 3
Function quantity of four key ecosystem services (ESs) in the natural increase scenario (NIS), urban plan scenario (UPS), and ecological protection scenario (EPS), and percentage change in UPS and EPS compared with NIS.

	Carbon storage	Water yield	Soil retention	Nitrogen export				
	ESs/10^6 t	%-change	ESs/10^6 m^3	%-change	ESs/10^6 t	%-change	ESs/t	%-change
NIS	12.78		940.62		60.25		1,404.35	
UPS	12.83	0.42%	926.95	−1.45%	61.27	1.70%	1,385.17	−1.37%
EPS	13.44	4.74%	904.51	−2.42%	62.30	1.68%	1,291.24	−6.78%

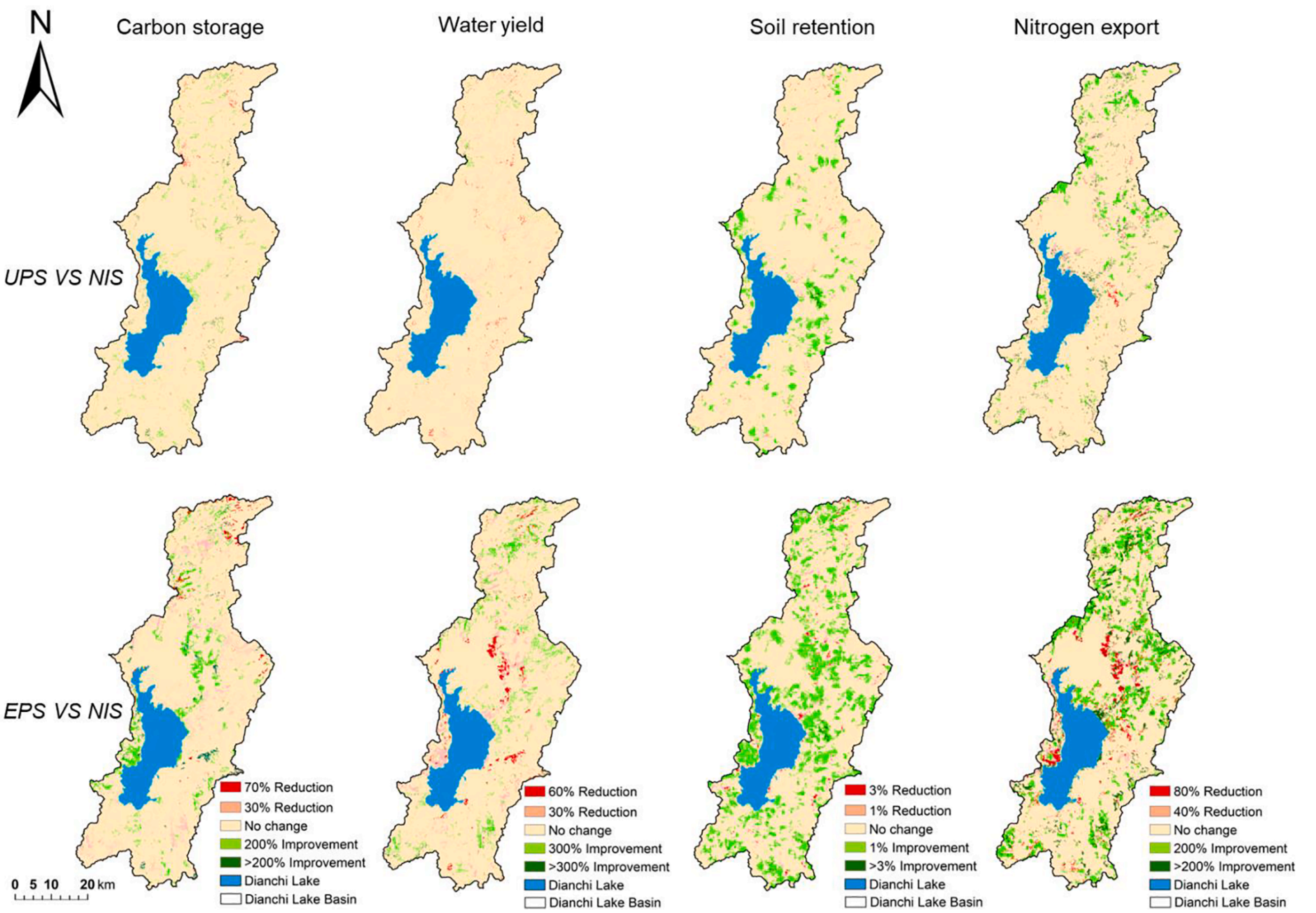

Fig. 4. Spatial changes in (left to right) the four key ecosystem services (ESs) carbon storage, water yield, soil retention, and nitrogen export in Dianchi Lake Basin (DLB) in 2035, comparing the urban plan and natural increase scenarios (UPS vs NIS) and the ecological protection and natural increase scenarios (EPS vs NIS).

Table 4
Correlations among the four key ecosystem services in the natural increase scenario (NIS), urban plan scenario (UPS), and ecological protection scenario (EPS).

Scenarios	Block samples n = 1000	Ecosystem services Carbon storage	Water yield	Soil retention
NIS	Water yield	−0.657**		
	Soil retention	0.203**	−0.192**	
	Nitrogen export	−0.189**	0.06	−0.094**
UPS	Water yield	−0.651**		
	Soil retention	0.201**	−0.184**	
	Nitrogen export	−0.191**	0.05	−0.098**
EPS	Water yield	−0.659**		
	Soil retention	0.185**	−0.179**	
	Nitrogen export	−0.195**	0.070*	-0.078*

Note: **denotes highly significant correlation at $p < 0.01$
*denotes significant correlation at $p < 0.05$.

development of DLB, the large increase in construction land will inevitably lead to changes in regional land use layout and path. In addition, DLB is long and narrow from north to south, with sloping sides. Some mountain areas have a steep slope and thin soil layer, while the flat land around Dianchi Lake has been receiving erosion material from upstream for a long time and the soil layer is thicker. The region's land resources are extremely scarce and its ecosystems are fragile. This is coupled with low level and intensity of land use productivity, non-rational structure and layout of land use, severe soil erosion, relatively low concentration of agricultural land, and difficulties in development and utilization of land. All of these factors ultimately lead to an increasing imbalance between supply and demand for land resources. This will have unavoidable negative impacts on regional ESS, if DLB take the traditional urbanization path. Thus the urbanization path and land use pattern selected for DLB will play a decisive role in regional ecosystem security and ESs maintenance.

4.2. Implications for ESs optimization and management

The development plan for DLB emphasizes protection of ecological environments, strict prevention of land overuse, and control of connectivity between ecological patches, so as to maintain regional ecological security and ESs levels. In NIS, DLB followed the past urbanization trajectory and land use trend by converting agricultural land and grassland to constructed land, causing great loss of ESs. In UPS, with stronger protection of agri-ecosystems, loss of agricultural land was reduced by 50.26 km^2 compared with NIS. In EPS, most forest, shrub, agriculture and grass land could not be arbitrarily appropriated (especially within ERAs and EISs), and therefore the development of constructed land was limited (but still met the needs of urban planning and development). The relationship between regional urbanization, economic and social development, ecological and environmental protection and ESs maintenance was thus optimized and balanced in EPS. Our simulation and maps provide the necessary data support for decision makers to develop a future vision of urbanization and land use based on optimized ecosystem security and ESs levels. This has the following implications:

Frist, government departments and officials in DLB should pursue a sustainable urbanization path (such as the EPS in this study) in top-level design of regional development, so as to minimize the negative impacts

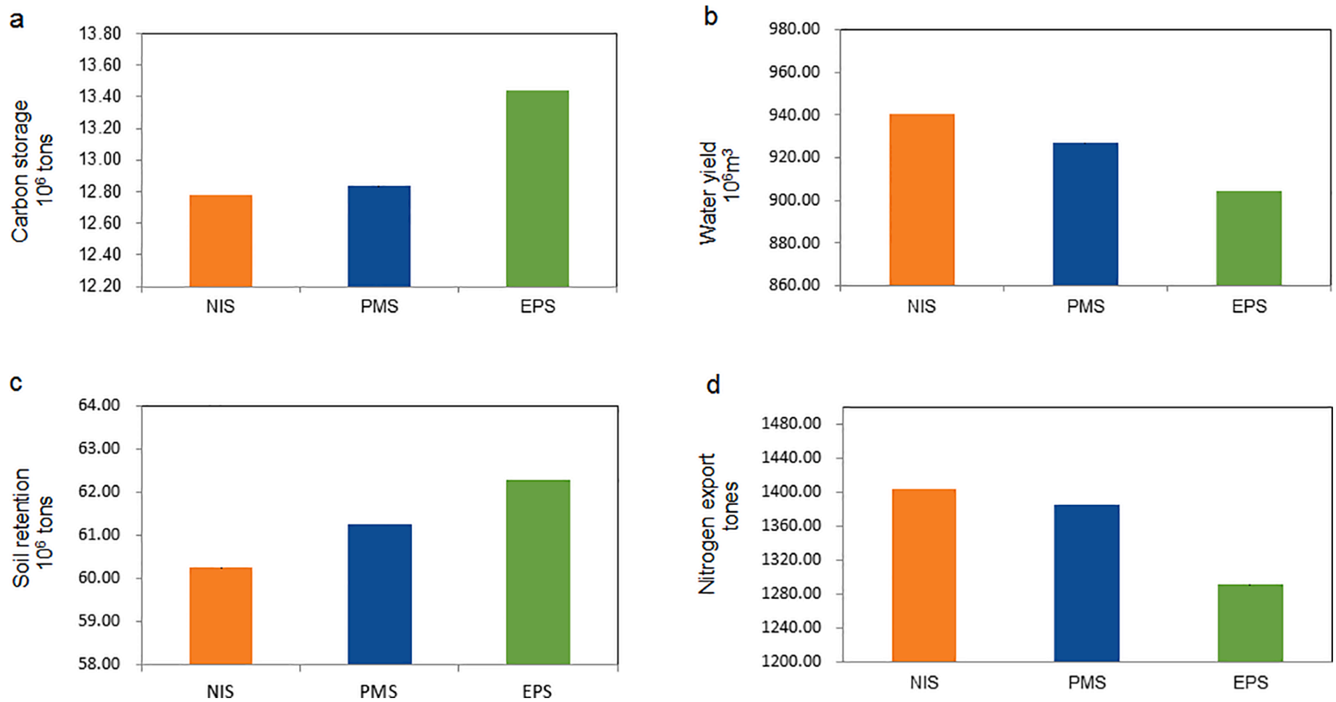

Fig. 5. Ecosystem service values in the natural increase scenario (NIS), urban plan scenario (UPS), and ecological protection scenario (EPS) in 2035. A) Carbon storage, b) water yield, c) soil retention, and d) nitrogen export.

Table 5
Results of paired-samples *t* test for the four key ecosystem services (ESs) comparing the natural increase scenario (NIS), urban plan scenario (UPS), and ecological protection scenario (EPS) in 2035.

ESs	Pairing	95% confidence interval		*t*	Degrees of freedom	Sig. (double tail)
		Lower limit	Upper limit			
Carbon storage	NIS-UPS	−0.043	0.136	1.019	999	0.031
	UPS-EPS	−0.133	0.115	−0.143	999	0.089
	EPS-NIS	−0.101	0.176	0.531	999	0.06
Water yield	NIS-UPS	−1.098	9.586	1.56	999	0.012
	UPS-EPS	−11.453	13.558	0.165	999	0.087
	EPS-NIS	−7.236	17.829	0.83	999	0.041
Soil retention	NIS-UPS	−3.698	3.251	−0.126	999	0.09
	UPS-EPS	−0.005	0.051	1.587	999	0.011
	EPS-NIS	−3.666	3.265	−0.114	999	0.091
Nitrogen export	NIS-UPS	−0.061	0.003	−1.78	999	0.008
	UPS-EPS	0.000	0.099	1.967	999	0.005
	EPS-NIS	−0.025	0.066	0.875	999	0.038

on the layout and pattern of regional land use in future, based on strictly controlling the scale of construction land and improving its utilization efficiency.

Second, ecosystem factors should be fully integrated into the decision-making of urbanization process. In particular, ecological red line areas should be reasonably delineated and strictly adhere to, and the ecological isolation strips should be established at appropriate locations.

Third, considering the tradeoffs among the four key ESs in DLB, the EPS path could help DLB experience fewer ESs tradeoffs during future urbanization than any other policy for land use and maintain more ESs provision than NIS and UPS. Under EPS, carbon storage and soil retention trended to increase and nitrogen export trended to decrease, which would be beneficial in protecting water quality of Dianchi Lake. However, the water yield of DLB would decrease, which may not be conducive to the ecological water supply of Dianchi Lake. Therefore, in the future urbanization process and in planning and management of land use of DLB, the relationship between enhancement of carbon storage and soil retention and maintenance of regional ecological water demand should be fully considered and weighed. In other words, improving carbon storage and soil retention in regional ecosystem, on the premise of maintaining regional ecological water demand, would improve the overall ESS level of the region.

5. Innovation and limitations

The main innovative in the present study was establishment of the CLUE-S-Markov-InVEST integrated methodology. The CLUE-S and Markov models were combined to overcome their respective disadvantages in demand prediction and spatial allocation, and to exploit the advantage of the CLUE-S model in simulating land use change and conducting scenario analyses under different ecosystem and spatial scales, while also integrate the simulation capacity of InVEST models with socio-economic data. Spatial ecological protection factors, i.e., ERAs and EISs, were creatively included in setting the scenarios. Thus, the accuracy of simulation was greatly enhanced and the 2035 simulation maps better reflected the actual situation. The results confirmed that the combined CLUE-S-Markov-InVEST approach better simulated the temporal and spatial ESs in the DLB under different urbanization process and models. Hence, the study provides important theoretical guidance and a technical basis for ecological protection, urban planning, strategic land use management, and territorial space control in DLB.

The study had some limitations, however, e.g., in applying a linear model to simulate LUCC and evaluate ESs (Hou et al., 2013). The urbanization (land use pattern) scenarios are not definite solutions, but rather represent the possibilities and the underlying trend of changes. The main purpose of the simulations in this study was to visualize the trends and states of land use change under different urbanization paths, and their impacts and trade-offs on regional ESS, so as to provide reference information for urbanization path selection and land policy formulation and improvement. A particular limitation of the study was insufficient consideration of the effects of administrative policies in different periods on land use change, mainly due to the lack of mature methods to transform these policies into quantitative spatial parameters. Administrative policies have already had significant impacts on the formation and evolution of land use patterns, so determination of appropriate spatial constraint schemes based on regional land policies is a critical requirement for land use simulation using CLUE-S or other models. Spatial changes in ESs provision also influence the quantity and distribution of ESs beneficiaries.

Therefore, the following issues need to be addressed in future research: (i) Evaluation of ESs provision and human welfare improvements; (ii) identification of mechanisms and measures for balancing ESs demand and ESs provision; (iii) optimization and management of ERAS, EISs, and other policies to achieve ESs obligations and objectives in DLB; and (iv) formulation of measures for strict control of construction land scale, increasing the intensity of use of construction land, and improving the efficiency of use of construction land.

6. Conclusions

In analyzing the effects of urbanization on ESs, we combined the spatial allocation advantage of CLUE-S and the demand prediction advantage of the Markov model and considered natural geography, socioeconomic, and even policy factors (such as ecological red line policy or other restriction policies), while fully weighing realistic and rigid land demands in future urbanization when setting scenarios. The integrated CLUE-S-Markov-InVEST method accurately simulated ESs change and distribution in three urbanization scenarios (NIS, CPS, EPS). The results showed that the process and path of urbanization have significant impacts on regional land use change, and thus affect the tempo-spatial change and distribution of regional ESs. EPS was shown to be a sustainable urbanization path and land use pattern that can help to offset ESs loss, preserve regional ecological security, and maintain ESs in DLB.

During the process of future urbanization, ecological red line areas (ERAs) should be reasonably delineated and adhered to, and ecological isolation strips (EISs) should be established in appropriate locations. The scale of construction land should be strictly controlled, constructed land should be used more intensively, and its utilization efficiency should be improved. Under EPS, DLB would undergo fewer ESs tradeoffs than any other policy for land use. Based on the adequate guarantee of regional ecological water demand, the overall regional ESs level of DLB could be improved by enhancing the carbon storage and soil retention function. These findings provide sound indications for urbanization path selection, urban planning, and land resources management for DLB and beyond.

CRediT authorship contribution statement

Ruibo Wang: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Validation. **Yang Bai:** Conceptualization, Methodology, Resources, Project administration, Funding acquisition, Supervision. **Juha M. Alatalo:** Writing - review & editing, Validation. **Zhangqian Yang:** Conceptualization, Validation, Visualization. **Zongbao Yang:** Visualization, Validation. **Wei Yang:** Investigation, Validation. **Guimei Guo:** Investigation, Validation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108102.

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