

Impacts of Urbanization at City Cluster Scale on Ecosystem Services Along an Urban-Rural Gradient: A Case Study of Central Yunnan City Cluster, China

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Abstract

Urban agglomeration will be the main mode of future urbanization in China, greatly influencing social & economic development and ecosystem protection at the whole city cluster scale. It is important to analyze the impacts of large-scale, scattered land use and cover change (LUCC) consisting of one-pole-multi-point urbanization in city clusters on regional ecosystem services (ESs), so as to increase ecological security and maintain ESs levels. Using the urban-rural gradient analysis method (UGAM), this study examined driver-response mechanisms of large-scale, scattered agglomeration urbanization on ESs along an urban-rural gradient and at regional scale. This was done by simulating and analyzing tempo-spatial variations in ESs characteristics along concentric ring gradients in Central Yunnan City Cluster (CYCC) under its present urbanization path. The results showed that rapid urban sprawl is the main driver affecting the integral value of ESs in CYCC and that ESs trade-offs (through LUCC caused by urbanization) between adjacent zones along the urban-rural gradient will particularly exacerbate degradation of integral ESs levels. Hence, CYCC should follow a sustainable, eco-friendly urbanization path and should consider ecological principles and the impact of LUCC on regional ESs along the urban-rural gradient in top-level design and decision-making on urban planning and strategic land use management. Differentiated regional development policies should be formulated for each areas, the urban-rural development pattern and layout optimized, the scale of construction land rationally controlled, and the overall efficiency of land use improved. Ecological buffers should be set up around areas with sharp and obvious changes in land use, to alleviate the negative impact of large-scale, decentralized city cluster urbanization on regional ESs.

Introduction

Ecosystems services (ESs) are usually defined as benefits acquired by humans directly and indirectly from nature, in the form of materials, energy, information system functions, etc. (Costanza et al. 1997; Daily and Matson 2008; MEA. 2005). Its value is embodied in the interaction between human activities and the nature (Costanza et al. 2017; Fu et al. 2015; TEEB. 2010). However, the interaction and relationship between ESs and human well-being are becoming increasingly complicated, with the expansion of the scope of human activities and the complexity of the content, the enhancing ability of humans to transform the nature (Alcamo et al. 2005; Siqueira-Gay et al. 2020; Zu Ermgassen et al. 2019), as was reported that nearly two-thirds of ESs had already degenerated and the tendency was accelerating (de Groot et al. 2012). And also depends on the ecosystems services provision (ESP) demands of stakeholders and the tempo-spatial scale of the problem was discussed (Duraiappah 2011; Raudsepp-Hearne et al. 2010).

Human activities, especially land use and cover change (LUCC), act as the most direct and important drivers of ESs variation, and urbanization inevitably and particularly leads to LUCC and finally results in large-scale and sweeping changes of ESs (Maes et al. 2012; Tolessa et al. 2017). Even more seriously, agglomeration urbanization as a land use method, and its intensity, patterns, and layout at a larger scale and on a deeper level, ultimately result in great loss of vital ESs and biodiversity (Hou et al. 2014; Łowicki

and Walz 2015; Maes et al. 2012). This in turn impairs ecological integrity and ESs provision (Couch and Karecha 2006; Nuisssl and Rink 2005; Schwarz et al. 2011), reduces carbon storage (Tolessa et al. 2017), aggravates soil erosion and nitrogen export (Bai et al. 2018), degrades water quality and availability (Fiquepron et al. 2013), and decreases esthetic and recreational values (Song and Deng 2017).

In recent years, variation in ESs in urban-rural areas has attracted more research attention with the increasing degree of interaction between humans and nature (Gaglio et al. 2017; Haase et al. 2012). Studies have been conducted at different geographic scales, e.g., European urban-rural areas and Leipzig in eastern Germany (Kroll et al. 2012; Radford and James 2013), on different ES functions, e.g., food provisioning, climate regulation, pollination, and recreation (Nowak et al. 2013; Strohbach and Haase 2012), and on ESs transfer and sensitivity (Lautenbach et al. 2011; Schwarz et al. 2011).

The urban-rural gradient analysis method (UGAM) is a useful tool for describing patterns and trends of urbanization, e.g., by comparing socioeconomic dimensions of biota in urban-rural areas and land cover structures (Hahs and McDonnell 2006; McDonnell and Hahs 2008; Zipperer et al. 2000). The method can be applied to analyze ESs changes and trade-offs along an urban-rural gradient, based on assessments of ESs such as food, water, and energy supply (Kroll et al. 2012), and carbon storage pollination, water regulation, and esthetic and recreation services (Radford and James 2013; Strohbach and Haase 2012). Such studies have shown that significant ESs differences exist at the urban-rural gradient scale, but there is no typical model for gradients in different study areas (Larondelle and Haase 2013).

In recent decades, China has undergone large-scale, rapid urbanization that has attracted worldwide attention (Xie et al. 2020; Zhang et al. 2018). China's urbanization has progressed particularly rapidly since the National New Urbanization Plan (2014–2020) was promulgated and implemented. The urbanization rate has reached 60%, but there is still a large gap before it reaches the 80% seen in other developed countries. In coming decades, China's urbanization will enter the urban agglomeration development stage (CDRF and PricewaterhouseCoopers 2021), which will have a huge impact on the global and regional economy, but also profound impacts on the regional ecological security pattern and the ESs level. Nobel economics laureate Joseph Stiglitz claims that two major events, development of high-tech industries in the United States and urbanization in China, will have the greatest impact on the world in the 21st century. A Sustainable urbanization mode is crucial not only for the future of China, but also for the future of the urbanized world (Fang and Yu 2016).

The city cluster is an important urbanization form in China and an effective measure for accelerating the pace of urbanization, optimizing resource allocation, enhancing driving and radiating roles, and promoting the development of each city in the cluster. China's city cluster formation is in a stage of rapid growth, with the number now approaching 30. Most prefecture-level cities have entered the ranks of large cities and have become the backbone of China's city clusters. In the future, urbanization in the form of city clusters will continue to increase.

In 2006, the China's 13th "Five-Year Plan" proposed to take urban agglomeration as the main form of promoting urbanization. The report to the 17th National Congress of the Communist Party of China (CPC)

in 2007 pointed out that city clusters supported by large cities should be formed to foster new poles of economic growth. The Central Yunnan City Cluster (CYCC) is one of the 8 urban agglomerations proposed in the National New Urbanization Plan (2014–2020) and the Outline of the China's 13th “Five-Year Plan”. In 2016, Yunnan province compiled the Central Yunnan City Cluster Planning (2016–2049). On January 14, 2020, the National Development and Reform Commission approved the plan. CYCC is listed as one of the 9 major urban agglomerations to be cultivated and developed in China's 14th “Five-Year Plan” for National Economic and Social Development and outline of 2035 Vision Goals. So far, the central CYCC has officially become one of the 19 national key cultivation urban agglomeration, an important part of the national "two horizontal and three vertical" urbanization strategy pattern, the key area of strategy for large-scale development of western China, and the important growth pole of China's new economic support belt based on the Yangtze River.

With the implementation of “One Belt and One Road”, CYCC has further highlighted its regional advantage of opening to South and Southeast Asia. Its development orientation is to make full use of its geographical advantages, lead Yunnan's modernization, build a new support for ecological civilization construction, promote ethnic unity and progress, build a new pattern of reform and opening up, start a new journey of prosperity and stability in the border area, and build a gateway city cluster open to South and Southeast Asia. Aiming at speed up breakthroughs in building a core area that connects South and Southeast Asia, a comprehensive hub that connects South and Southeast Asia and the Indian Ocean, an important economic growth pole and a powerful engine for modernization in the western China, and an ecological and liveable city cluster on the Plateau. By 2025, the functions of CYCC will be basically improved, and the urban-rural spatial pattern will be greatly optimized, gathering 50% of the province's population and 68% of GDP. By 2035, it will become a powerful engine for the Radiation Center of South Asia and Southeast Asia, gathering 55% of the province's population and more than 70% of GDP.” In a word, CYCC will usher in period of strategic opportunities for rapid economy development and urbanization.

Against this background, it is critical to study the impact of urbanization at city cluster scale on tempo-spatial changes in ESs in CYCC during the past 30 years and to formulate strategies for future high-quality and sustainable development of the region, so as to maintain regional ESs level and ecological security, and build a strong ecological security barrier in Southwest China. However, there is a gap in understanding and identifying driver-response mechanisms between LUC and ESs change, especially at large spatial scales such as agglomeration urbanization areas (Kindu et al. 2016; Xu et al. 2017).

The present study aims at bridging this gap by quantitatively characterizing and spatially explicitly describing, along an urban-rural gradient, ESs arising from urbanization by city cluster formation. The study addressed the following main issues: (1) quantitative and tempo-spatial variations in ESs at city cluster scale and gradient scale under the large-scale, scattered agglomeration urbanization of CYCC in recent decades; (2) impacts and trade-offs of urbanization on tempo-spatial changes and distributions of ESs at gradient scales; and (3) countermeasures for mitigating the impact of development and urbanization at city cluster scale on regional-scale and gradient-scale ESs.

Materials And Methods

Study area

Central Yunnan City Cluster (100°43'-104°49'E, 24°58'-25°09'N) is a typical plateau mountain city located in the center of Yunnan Province in southwest China (Fig. 1). It lies in a region (elevation 122–4282 m asl) with a subtropical plateau monsoon climate zone. CYCC consists of 49 cities, covering an area of 114,600 km², and contains Kunming, Yuxi, Chuxiong, and Qujing Prefecture and seven northern counties in Honghe Prefecture. By the end of 2019, the resident population was 21.37 million and the regional GDP was 1.41 trillion yuan, accounting for 44.1% and 60.7% of the province's totals, respectively. CYCC has always been the economic, political, and cultural center of Yunnan Province. It is a region with large and medium-sized cities, convenient transportation and logistics, a solid industrial foundation, comprehensive economic strength, and relatively well-developed science, education, culture, and health facilities. It plays a vital role in the economic and social development of the whole province (Lin et al. 2019; YNGOV. 2020).

Urban-rural gradient setting

Urban-rural gradient setting is the key step in UGAM, and has been proven to be useful and effective in revealing spatial variations in ecosystem processes, states, and functions (Hou et al. 2015; Vizzari et al. 2015). Two mainstream gradient setting patterns are available, namely transect gradient (TG) and concentric ring gradient (CRG). The TG approach has a series of directional transect gradients crossing the city center and extending outside, linking two ends (Hahs and McDonnell 2006; McDonnell and Hahs 2008; Zhou and Wang 2011). The CRG approach has a series of closed curves distributed from the city center to the suburbs.

In this study, CRG was used to analyze and describe the tempo-spatial variations and distributions of ESS along an urban-rural gradient in CYCC. First, according to the principles of economic geographical space in urban planning, the physical geographical and economic & social characteristics of CYCC, as well as regional and urban development laws and urban planning, taking the outer circle of the four districts and counties (Wuhua, Panlong, Xishan and Guandu) in CYCC, which have the earliest, most concentrated and fastest urbanization development, as the core area (namely the core circle in the paper), the urban and rural scale is divided by the outer circle as the buffer radius.

The reasons and basis for this definition are mainly as follows: First, in terms of the development scale layout of CYCC Planning, there is a spatial pattern of "one main and four auxiliary, channel docking and point-axis linkage". In other words, Kunming as the main center relies on the axis of highway, railway and aviation transportation network, and promotes the joint development of cities and towns at all levels. Second, the implementation Plan of Yunnan Province to Promote Regional Coordinated Development proposes the construction of one-hour economic circle centered on Kunming, which will greatly promote and guide the urbanization development of the surrounding areas of the CYCC centered on Kunming. Third, the "14th Five-year Plan for Coordinated Regional Development of Yunnan" proposed to build "CYCC on the track", aiming at constructing the metropolitan circle within one-hour commuting around the

central city of Kunming. Therefore, the urban-rural scale designed in this study is closely related to the future regional development, urban planning and territorial space control of the CYCC.

Ecosystem services assessment

(1) Representative parameter selection

Due to a mainly mountainous and intermountain terrain, large elevation difference and high evaporation rates, the water resources in CYCC present an extremely uneven spatial distribution, a large inter-annual variation and not uniform within a year, and part of the water environment is seriously polluted (eutrophic pollution caused by nitrogen and phosphorus inputs). In CYCC, the area with the fastest economic and population growth in Yunnan Province, the utilization efficiency of water resources is not high. Water supply has become the bottleneck problem restricting sustainable development of the region and is an issue that the Yunnan Government is determined to address, especially under future climate change.

CYCC has been plagued by moderate and serious soil erosion historically, which mainly distributed in the elevation range 1900–2100 m and the slope range 5-25°. The soil is vulnerable to hydraulic erosion, which intensifies the degree of soil and water loss. In sustainable economic and social development, the status of the ecological environment and the demands of all stakeholders concerned must be considered (Bai et al. 2018; Wang et al. 2021). So water yield, carbon storage, soil retention, and nitrogen export was selected as critical indicators to represent ESs in CYCC, provided that data were available, according to Millennium Ecosystem Assessment and Common International Classification of Ecosystem Services (CICES) (Haines-Young et al. 2012; MEA. 2005).

(2) Ecosystem services evaluation

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, Version 3.7.0, Stanford University, The Nature Conservancy and the World Wide Fund for Nature, Stanford, CA, USA) was used to calculate the ESs in 1995, 2005, 2015 and 2018 in CYCC, which was originally designed to mapping ESs provision at spatial scale and evaluating tradeoffs between them (Redhead et al. 2018; Sharp et al. 2016). Land use data divided into 6 categories (Section 2.4, Table S5), key parameters and biophysical attributes tables calibrated and validated in our previous study (Wang et al. 2021), were inputted to drive the InVEST models. InVEST has the advantage of mapping the distribution of ESs at spatial scale and evaluating trade-offs between different (Redhead et al. 2016) (Supplementary Information 2).

The study also comprehensively assessed the tempo-spatial impact of LUCC on ESs and sought to identify trade-offs between urbanization in the form of city clusters and the synergistic/antagonistic interaction of ESs between adjacent gradient rings. The evaluation procedure is described in Supplementary Information 2 and parameterization of InVEST in Supplementary Information 3. The sources and availability of data are summarized in Table S2 in Supplementary Information, while model settings are listed in Tables S3 and S4. Key parameters and biophysical attributes tables, which we

calibrated and validated in a previous study (Wang et al. 2021), are presented in Supplementary Information 1.

Statistical analysis

The annular buffer areas generated in CYCC (Fig. 1) were used to extract the land use type and ESs values in the corresponding gradient zones. These were then used to elucidate tempo-spatial changes in land use (caused by urbanization) and ESs in different gradient zones. Trade-offs between ESs in different study years and synergistic or antagonistic correlations of ESs between adjacent gradient zones were also analyzed. To ensure objectivity and rigor in establishing the trade-offs, ArcGIS 10.5 was used to generate 40,000 random points within the study area and to extract various ESs values for each random point. The trade-offs between different kinds of ESs in different study years were then analyzed by bivariate correlation in SPSS 26.0, based on the extracted values of random points. Synergistic or antagonistic correlations of ESs between adjacent gradient zones in 2018 were identified by Paired-Samples *t* test in SPSS 26.0, based on the relevant value extracted from the 40,000 random points.

Data preparation

Spatial map datasets and designated biophysical tables were used as input to run the InVEST models (Bai et al. 2019). The DEM and land use data (spatial resolution 30 m, overall accuracy 92.27%) were acquired from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn/>). These data were combined and processed into six land use classes: forest, grass, open water, constructed (built-up), agriculture, and unused (Table S5). Other relevant parametric and spatial data (5 physical geographic factors and 5 economic and social factors) used are shown in Table S2 and S6. All spatial data layers used in this study were re-sampled to 90 m resolution under the reference system WGS 1984 Albers.

Results

Land use gradients

Land use structure and quantity in CYCC changed substantially from 1995 to 2018 (Figs. 2 and 3, Table S1). Among the six land use classes studied, land formerly under grass underwent the largest reduction (743.64 km², or 48.47% of the total reduction in main land use types), followed by agricultural land (490.45 km² or 31.97%) and forest land (300.22 km² or 19.57%). Constructed land exhibited the largest increase (1354.09 km², to double the area in 1995, representing 88.25% of the increase in main land use types), followed by open water (175.18 km² or 11.42%) and unused land (5.03 km² or 3.14%). This shows that expansion of built-up area due to large-scale, scattered agglomeration urbanization is the main driving force for changes of land use pattern and structure in CYCC.

Comparing the different annular rings, from 1995 to 2018 the proportion of forest land showed an obvious increasing trend from 35% in the core cohesion zone to more than 60% in the outermost

concentric ring (ring 8), while there was an obvious downward trend in constructed land area from 22% in the core cohesion zone to less than 0.2% in the outermost ring. In the same period, the proportion of grass land showed an increasing trend, but with apparent and irregular fluctuations, from 20% in the core cohesion zone to 35% in the outermost ring, although the total area decreased strongly from 1995 to 2018. Agricultural land proportion showed a first rise (0–1 ring) and then a continuous decline trend, exceeding 20% for core cohesion zone from 1995 and 2005, while lower than 20% in 2015 and 2018. The proportions of open water and unused land both displayed a general decrease, although with indistinct and irregular fluctuations, along the urban-rural gradient from core to outermost ring from 1995 to 2018.

Ecosystem services gradient

At the entire CYCC scale, there was an increase in water yield (of $4.84 \times 10^8 \text{ m}^3$) from 1995 to 2018, while the other three ESs analyzed all experienced a general downward trend, with carbon storage decreasing by 4.81×10^6 tons, soil retention by 0.27×10^6 tons, and nitrogen export by 5.57×10^5 tons (Table 1).

The average values for the four ESs in CYCC differed along the urban-rural gradient from 1995 to 2018 (Fig. 5). Average carbon storage showed an irregular increasing trend from the core cohesion zone to the outermost concentric ring between 1995 and 2005 and then suddenly declined, while it showed a slight increase in 2015 and 2018. Water yield displayed an irregular W-shaped overall downward trend along the urban-rural gradient with a suddenly increased in the 7th ring, but remained lower in than the 4th ring across the study period. Soil retention showed a continuous increasing trend from core to outermost ring, although the increase between the 1st and 2nd rings was smaller during the study period. Nitrogen export first displayed a temporary increase, and then a continuous irregular decrease trend along the gradient from the core outwards, over the study period.

A noteworthy observation was that the average carbon storage and nitrogen export values showed a sudden surge in the 3rd concentric ring in 1995, 2005, 2015 and 2018, and also a sudden surge in the 5th concentric ring for carbon storage in 2015 and 2018, and a sudden surge in the 5th concentric ring for nitrogen export in all four years.

Table 1

Variation in total ecosystem services (ESs) supply in Central Yunnan City Cluster (CYCC) from 1995 to 2018

ESs	1995	2005	2015	2018	Variation	Rangeability
Carbon storage(10^6t)	891.87	891.74	891.14	887.06	-4.81	-0.54%
Water yield (10^8m)	256.94	257.32	258.78	261.77	4.84	1.88%
Soil retention (10^6t)	6920.48	6920.59	6920.95	6920.22	-0.27	-0.0039%
Nitrogen export (10^5t)	631.17	628.52	623.04	625.61	-5.57	-0.88%

Driving mechanism analysis of ESs changes

As mentioned above, land use change was one of the most important driving factors affecting ESs, and urbanization in particular changed regional land use in a large area and completely. Therefore, we analysed the impact of urbanization on regional ESs from the aspects of physical geography, economic and social factors. Specifically, a total of 11 factors (8 physical geographic factors and 5 economic and social factors) were selected to further study the influence and driving mechanism of CYCC urbanization process on regional ESs. 40,000 random points generated as section 2.2 were used to extract the intensity values of various ESs and the attribute values of the spatial layers of potential drivers made above (Table S6 in Supplementary Information), binary Logistic regression SPSS 26.0 (SPSS Inc., Chicago, IL, USA) was used in to analyze the correlation between the 4 representative ESs and 10 potential drivers factors one by one (Fig. 6).

For carbon storage change, the influential factors with stronger correlation in turn are: Distance to nearest town, NDVI and Night light index. Carbon storage was negative with distance to nearest town and night light index, positive with DIVI. The distance to towns and night light index is closely related to human activities. The demand for construction land is large in places close to towns (where night light index is always higher), and vast grassland, cropland and forests are converted into construction land, this resulted in decline of carbon storage. This is consistent with the previous analysis results, the carbon storage carbon storage decreasing by 4.81×10^6 tons during the study period (Table 1).

For water yield change, the influential factors with stronger correlation in turn are: distance to nearest town, distance to nearest road and slope. Water yield was negative with distance to nearest town and distance to nearest road, positive with slope. Areas close to towns and cities are highly disturbed by human activities. For example, the impervious surface of the ground is relatively high, resulting in increased water production in such areas. This is consistent with the previous analysis results; the water yield increased 4.84×10^8 m³ during the study period (Table 1).

For soil retention, the influential factors with stronger correlation in turn are: the distance to nearest town, NDVI and population density. The soil retention was positively correlated with the above former two factors, negative with population density. Because areas far from cities and towns are less vulnerable to human interaction (such areas tend to have high NDVI), they are more conducive to soil conservation. And the opposite is true in densely populated areas. With increasing human interaction in the CYCC, regional soil retention by 0.27×10^6 tons during the study period (Table 1).

For nitrogen export, the influential factors with stronger correlation in turn are: the distance to nearest road, the distance to nearest town and Population density. NDVI and population density. The nitrogen export was positively correlated with the above former two factors, negative with population density. This is because there are more frequent human activities around roads, towns and densely populated areas. For example, farmland is usually distributed around them, so nitrogen output near roads and towns is more serious due to agricultural non-point sources and surface runoff erosion.

In addition, the cumulative correlation coefficient was introduced in this study, that is, the correlation coefficient of the impact of the 10 driving factors on the 4 ESs was summed after the absolute value to judge the correlation between the above driving factors and ESs change. As shown in Fig. 6, the influential factors with stronger correlation in turn are: distance to nearest town, distance to nearest road and NDVI. It further indicates that the urban-rural development pattern and layout change in the process of CYCC urbanization is the main driving force of regional ESs change.

Trade-offs between ESs

Correlation between the ESs were investigated using Pearson correlation test ($df = 39998$). The results showed that, at the entire CYCC, scale carbon storage had an extremely highly significant negative correlation with water yield and a highly significant negative correlation with nitrogen export ($p < 0.01$), and a significant positive correlation with soil retention ($p < 0.01$) in 1995 and 2018 (Table 2). Water yield displayed a highly significant positive correlation with soil retention and nitrogen export across the study period. Soil retention showed a significant negative correlation with nitrogen export across the study period. This suggests that large-scale, scattered urbanization at city cluster scale in CYCC, with marked impacts on land use change, eventually lowers the regional ESs supply. Moreover, the correlations between ESs appear to persist for a long time under large-scale, scattered urbanization at city cluster scale.

Statistically significant ESs trade-offs were also found between adjacent rings along the gradient in CYCC (Paired samples t test; $df = 1143$, $P < 0.01$) (Fig. 7). Thus when one ESs tended to increase or decrease, the corresponding ESs in adjacent concentric circles followed the same trend. This was especially evident for carbon storage between concentric rings 0&1, 1&2, 2&3, 3&4, and 7&8; for water yield between rings 0&1, 1&2, 2&3, 3&4, 5&6, and 6&7; for soil retention between rings 1&2 and 6&7; and for nitrogen export between rings 0&1, 3&4, 5&6, and 6&7.

Table 2
Trade-offs among ecosystem services (ESs) in Central Yunnan City Cluster (CYCC) from 1995 to 2018.

Year	ESs	Carbon storage	Water yield	Soil retention
1995	Water yield	-0.712**		
	Soil retention	0.084**	-0.109**	
	Nitrogen export	-0.419**	0.377**	-0.026**
2005	Water yield	-0.712**		
	Soil retention	0.084**	-0.109**	
	Nitrogen export	-0.418**	0.376**	-0.026**
2015	Water yield	-0.711**		
	Soil retention	0.083**	-0.110**	
	Nitrogen export	-0.415**	0.368**	-0.025**
2018	Water yield	-0.704**		
	Soil retention	0.086**	-0.113**	
	Nitrogen export	-0.413**	0.360**	-0.027**
Note: $n = 40,000$ in the whole CYCC. ** $p < 0.01$.				

Discussion

Impact of urbanization on ESs

Rapid sprawl of built-up area was found to be the factor exerting the largest and most immediate impact on integral ESs in CYCC. The constructed land area doubled over the 20-year period from 1995 to 2015, in parallel with an acceleration in large-scale, scattered urbanization, mostly at the expense of grass, forest, and agricultural land. There was also a statistically significant ESs trade-off between adjacent rings along the urban-rural gradient. Overall, the observed LUCC depleted the supply of regional ESs in CYCC, while the specific LUCC caused by large-scale, scattered agglomerations urbanization particularly exacerbated depletion of the integral ESs level in CYCC.

The main and direct reason for the rapid increase in constructed land is that CYCC is the most economically developed area, with the fastest urbanization process and the fastest population growth, in Yunnan Province. CYCC accounts for 29% of the province's territory area (and two-thirds of its flat land) and 44% of the province's population. CYCC also has the densest transportation infrastructure in the province. CYCC is one of 19 national city clusters in China and accelerating the development of central CYCC has been established as an important measure to deepen cooperation between China and South

and Southeast Asia. CYCC is conducive to promoting the leapfrog development of border ethnic areas and plateau and mountainous areas, and is also the most important starting point to improve the level and quality of urbanization.

Natural forest and grassland are much richer in biomass and biodiversity than artificial land use forms, especially constructed land, but are of little or no productivity value or economic benefit. Urban sprawl and transportation infrastructure construction on forest and grassland areas could generate much higher short-term productivity and economic profits, in turn encouraging local governments to accelerate urbanization and further development of transportation infrastructure. The decrease in grass and forest land since 1995 has led to a decrease in the integral ESs level in CYCC. In parallel, international and domestic governments have been trying to increase ESs provision (especially food provision) and satisfy the increasing demands of the human population, which requires governments at all levels to increase or protect forest, grass, and agricultural land. For example, in China, Cropland Protection Red Line, covering 0.12 billion hectares, is a national long-term policy protecting cropland and maintaining national food security (Tan et al. 2017). Thus while accelerating regional urbanization may be of great significance for regional economic and social development, attention should still be paid to maintaining the structure and services provided by ecosystems.

Implications for ESs optimization and management

With the approval of Central Yunnan City Cluster Planning (2016–2049) in 2020, CYCC entered the stage of organization and implementation. It is intended to be a demonstration zone for ethnic unity and progress, a vanguard for ecological progress, and a radiating center for China towards South and Southeast Asia. It is planned that by 2049, the total population will reach 36 million, with 28.8 million urban residents, the urbanization rate will reach 80%, and economic output will reach 10 trillion yuan. Investment in fixed assets in industrial parks is expected to reach 9 billion yuan/km², and the output intensity of industrial land will reach 13.5 billion yuan/km². Over 6,000 kilometers of expressways, 12,000 kilometers of national and provincial highways, 7,000 kilometers of railways in operation are planned, with 80% of cities at and above county level covered by the railway network. Obviously, this future large-scale and high-intensity agglomeration urbanization in the CYCC region will inevitably lead to significant LUCC and have a profound impact on regional ESs.

The area and range of regional construction land will thus increase further, as will the intensity of urban development, resulting in unprecedented impacts on the regional and surrounding ESs level. A difficult problem for governments at all levels is to maintain the regional ecosystem structure and level of ESs despite accelerating large-scale, scattered agglomeration urbanization in CYCC. A sustainable urbanization path could to some extent alleviate this problem. Local government should consider the influence and ecological effects of LUCC caused by large-scale, scattered agglomeration urbanization on regional ESs.

Firstly, ESs should be incorporated into the top-level design of CYCC's future construction and development decisions (Wolff et al. 2015, Wong et al. 2015), and serve as the premise and basis for the formulation of regional development strategies and goals, urban planning, land use planning and management, and other policies. The ecological security pattern based on ESs should be established at the whole CYCC scale. Secondly, the future urban planning, land use planning and management of CYCC should be formulated from the overall level of CYCC region. CYCC should adopt a series of differentiated regional space control policies, narrow the development gap of urban agglomeration, tap the potential of land development; Pay attention to the spatial correlation of land use efficiency in different regions, gradually eliminate administrative barriers, enhance the spatial spillover effect of efficient use regions, and improve the land use efficiency of neighbouring regions. Thirdly, the urbanization process of CYCC in the future should fully consider the optimization of urban pattern and construction land layout to reduce the impact on regional ESs; Strictly control the scale of construction land, improve the intensive use degree of construction land, and continue to deepen the improvement of rural residential areas and urban-rural construction land increase and decrease linking target. New construction land and residential areas should avoid areas with high and sensitive ESs value; Urban expansion and infrastructure construction should preserve ecological corridors between ESs plates. In addition, ecological isolation strips (EIS) should be set up in high-density urbanized area, a 100 m wide EIS (if properly set up) is reported to be effective in reducing around 10% of soil export and 5% of nitrogen export, compared with areas without buffer strips (Gao et al. 2017).

Innovation and limitations

The innovative value of this study lies in presentation of empirical evidence that large-scale, scattered agglomeration urbanization exerts noticeable impacts on land use change in city clusters like CYCC, resulting in declining regional ESs supply. The main driving mechanism of urbanization on regional ESs at urban agglomeration scale is obtained, that is, the change of urban pattern caused by urbanization and the large-scale increase of construction land caused by urbanization. Building on these observations, corresponding countermeasures can be identified. Thus the study provides important theoretical guidance and a technical basis for ecological protection, urban planning, strategic land use management, and territorial space control in CYCC.

The study also has inherent limitations by introducing uncertainties, due to the complexity of the ecosystem itself, researchers' personal preferences, the model and methodology used, etc. (Hou et al. 2013; Scolozzi et al. 2012). First, spatial scale selection and land use data errors unavoidably affect the accuracy of ESs simulation and assessment (Dong et al. 2015; Yanai et al. 2010). Second, the ESs gradient analysis was mainly based on mean ESs changes and land use characteristics and information between each adjacent concentric ring along the gradient, while insufficient consideration was given to directional differences of them (Hahs and McDonnell 2006; Zhu and Carreiro 2004). Thus, multiple gradient partition methods should be comprehensively applied to study the ESs gradients in future research. Third, ESs provision (ESP) should match human demand, so as to achieve sustainable

development for both humans and natural ecosystems (Boesing et al. 2020; Burkhard et al. 2012; Zhang et al. 2017).

Conclusions

This study demonstrated the complexity of tempo-spatial variations in ESs along an urban-rural gradient under the large-scale, scattered agglomeration urbanization taking place in CYCC in recent decades. The findings add to existing awareness and understanding of both land use and ESs changes, and driver-response relationships between the two, in an increasingly human-dominated and accelerating urbanizing city cluster scale, and along the urban-rural gradient. The study showed that the patterns of ESs supplied by different land use types and structures diverge along the urban-rural gradient, which calls for sophisticated consideration and balancing between land uses and their impacts on ESs. The study also revealed synergies and trade-offs of ESs at gradient scale, knowledge which could effectively reduce uncertainty in decision making on land use and urbanization.

Suggestions for future urbanization in CYCC can be made as follows: First, CYCC should follow a sustainable urbanization path, strategic land use planning and management, urban planning, and regional transportation infrastructure planning for CYCC must take into account the impact on regional ESs and seek to minimize the impact; Second, urban and land use layout planning from the perspective of the whole region, and also must be made along the urban-rural gradient continuum, based on incorporating ecological principles into the decision-making process for utilizing and maintaining ESs level and resources sustainably. Third, differentiated regional development policies should be formulated based on ESs endowment. CYCC should continue to optimize the urban-rural development pattern and layout, rationally control the scale of construction and improve the overall efficiency of land use. EIS should be established in high-density urbanized areas and along transportation infrastructure in CYCC, to mitigate the impact of LUCC on regional ESs.

Declarations

Ethical Approval: Not applicable

Consent to Participate: Not applicable.

Consent to Publish: Not applicable.

Authors Contributions:

All authors contributed to the study conception and design. 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. Guimei Guo: Investigation, Validation. Zhangqian

Yang: Conceptualization, Validation, Visualization. Zongbao Yang: Visualization, Validation. Wei Yang: Investigation, Validation.

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Competing Interests

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.

Availability of data and materials

The DEM and land use data (spatial resolution 30 m, overall accuracy 92.27%) were acquired from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn/>). Other relevant parametric and spatial data (5 physical geographic factors and 5 economic and social factors) used are shown in the table below. And Table S2 and S6 were also included in the “*Supplementary Information*” submitted before

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Figures

Figure 1

(Left) Location of Central Yunnan City Cluster (CYCC) in south-west China and (right) gradient of concentric rings from core (0) to outermost ring (8) established for CYCC in this study.

Figure 2

Spatial distribution of land use cover change (LUCC) in Central Yunnan City Cluster (CYCC) in (left) 1995 and (right) 2018.

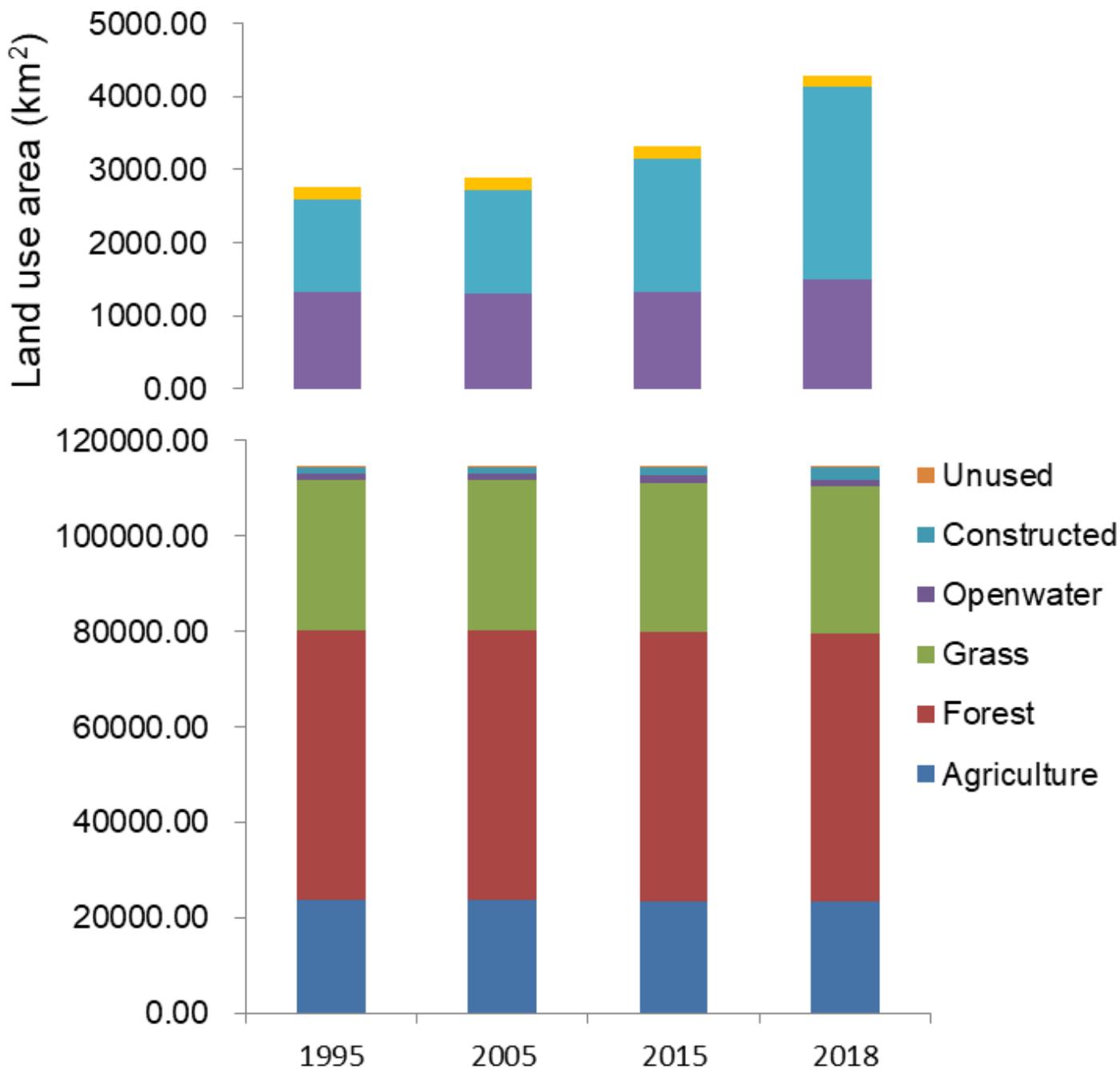


Figure 3

Land use cover change (LUCC) in Central Yunnan City Cluster (CYCC) from 1995 to 2018. The upper bar graph shows specific changes in the area of constructed land, open water, and unused land, while the lower bar graph shows the overall change in regional land use.

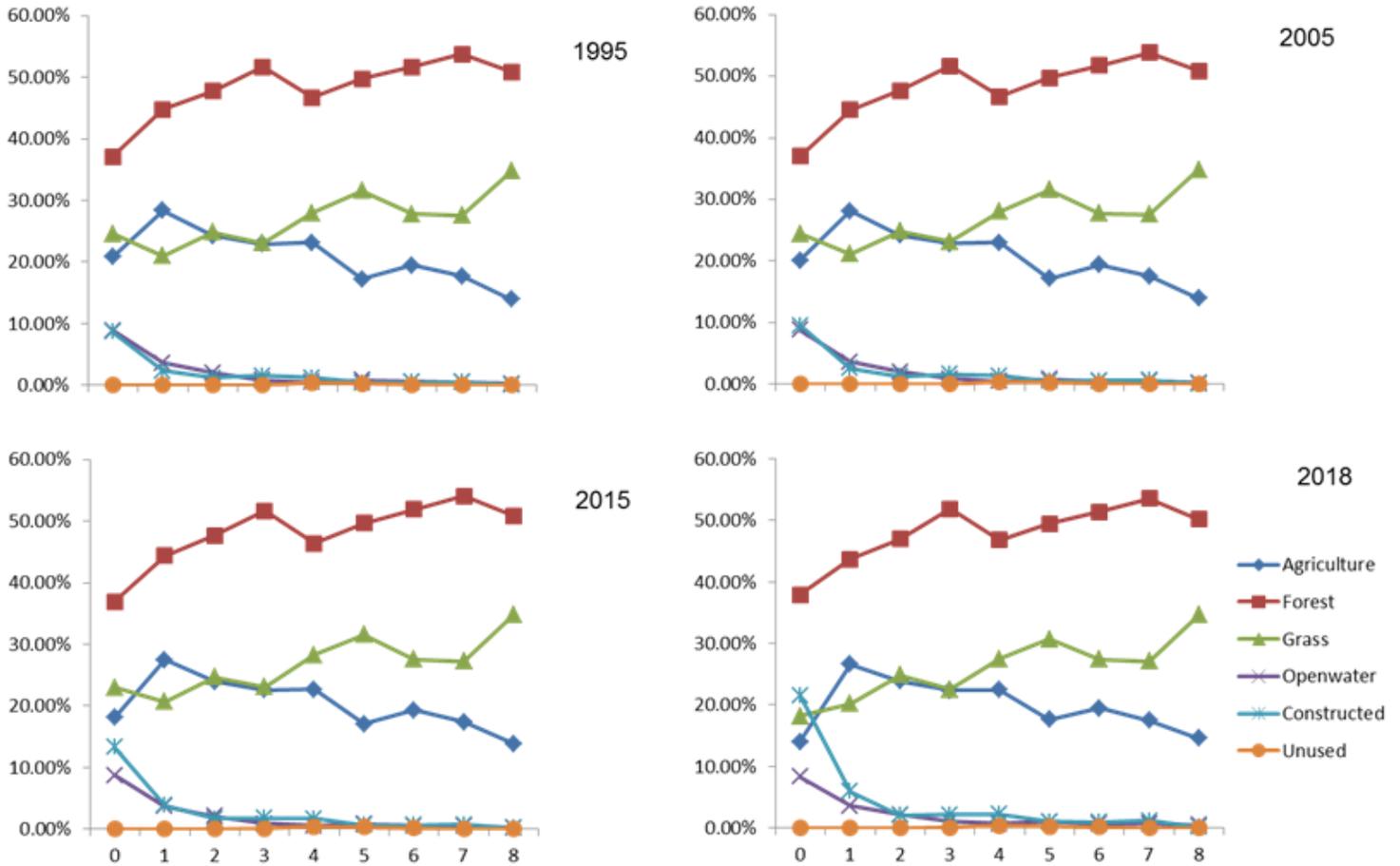


Figure 4

Land use class proportions (y-axis) along the urban-rural gradient from core (0) to outmost ring (8) (x-axis) in Central Yunnan City Cluster (CYCC) in 1995, 2005, 2015, and 2018.

Figure 5

Average value of different ecosystem services (ESs) along the urban-rural gradient from core (0) to outermost ring (8) in Central Yunnan City Cluster (CYCC) in the four years studied.

Figure 6

Impacts and driving factors of CYCC ecosystem services in 1995 and 2018.

Figure 7

Significant differences ($P < 0.01$ in paired-samples t test) in ecosystem service (ESs) between adjacent rings from core (0) to outermost ring (8) in Central Yunnan City Cluster (CYCC) in 2018.

Supplementary Files

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