

# Impacts of traffic accessibility on ecosystem services: An integrated spatial approach

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**Abstract:** The continuous degradation of ecosystem services is an important challenge faced by the world. Improvements in transportation infrastructure have had substantial impacts on economic development and ecosystem services. Exploring the influence of traffic accessibility on ecosystem services can delay or stop their deterioration; however, studies on its impact are lacking. This study addresses this gap by analysing the impact of traffic accessibility on ecosystem services using an integrated spatial regression approach based on an evaluation of the ecosystem services value (ESV) and traffic accessibility in the Middle Reaches of the Yangtze River Urban Agglomeration (MRYRUA) in China. The results indicated that the ESV in the MRYRUA continuously decreased during the study period, and the average ESV in plain areas, areas surrounding the core cities, and areas along the main traffic routes was significantly lower than that in areas along the Yangtze River and the surrounding mountainous areas. Traffic accessibility continued to increase during the study period, and the high-value areas centred on Wuhan, Changsha, Nanchang, and Yichang were radially distributed. The global bivariate spatial autocorrelation coefficient between the average ESV and traffic accessibility was negative. The average ESV and traffic accessibility exhibited significant spatial dependence and spatial heterogeneity. Spatial regression also proved that there was a negative association between the average ESV and traffic accessibility, and scale effects were evident. The findings of this study have important policy implications for future ecological protection and transportation planning.

**Keywords:** ecosystem services value; traffic accessibility; spatial regression; Middle Reaches of the Yangtze River Urban Agglomeration; China

## 1 Introduction

Improvements in transportation infrastructures have greatly promoted economic development and urbanisation, but have resulted in a series of severe ecological problems (Karlson

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*et al.*, 2014; Mo *et al.*, 2017). Exploring the impact of traffic accessibility on the ecosystem is of great significance for traffic planning and the development of ecological protection policies. Traffic accessibility accelerated the intraregional and interregional flow of materials, energy, and information, which has greatly impacted the supply and demand of ecosystem services (Forman and Alexander, 1998; Chen *et al.*, 2020a). Few studies, however, have explored the spatial interaction between traffic accessibility and ecosystem services and our limited understanding of its impacts constrains ecosystem conservation (Liu *et al.*, 2008; Mo *et al.*, 2017). In this context, it is necessary to explore the spatial relationship between traffic accessibility and ecosystem services (Forman and Alexander, 1998).

An ‘ecosystem’ refers to an organic community composed of mutually dependent and restricting organisms and the environment (Tansley, 1935). An ecosystem provides products and services needed to sustain life through its structure, functions, and operational processes (MEA, 2005). The proposed concept of ecosystem services in a well-connected natural ecosystem within the human system lays a theoretical foundation for understanding the interactions between human activities and the ecosystem (Carroll and Wilson, 1970; Westman, 1977; Ehrlich and Ehrlich, 1981). Previous studies conducted extensive research on ecosystem services; for example, Costanza *et al.* (1997) proposed an ecosystem services classification system and economic value evaluation method. This provided new perspectives and methods for the assessment of and increased interest in ecosystem services. Since then, ecosystem services have been studied globally (Costanza *et al.*, 1997). Xie *et al.* (2008) revised the proposed classification system and the equivalent table of ecosystem services in China based on the expert knowledge of more than 700 ecologists. Specifically, 17 types of ecosystem services classified by Costanza *et al.* (1997) were revised to include four primary categories (supplying, regulating, supporting, and cultural services) and nine secondary categories (food production, raw materials, gas regulation, climate regulation, hydrology regulation, waste treatment, soil conservation, biodiversity maintenance, and aesthetic landscape provision). This created a new approach for the valuation of ecosystem services and related research in China (Xie *et al.*, 2008).

The continuous deterioration of ecosystem functions has attracted considerable attention and led to increased research efforts to explore the factors causing a sharp decline in ecosystem services and identify the influencing mechanisms. Human activities are the primary factor that led to a sharp decline in ecosystem services value (ESV) and caused ecological problems (Vitousek *et al.*, 1997; Mahmoud and Gan, 2018; Wang *et al.*, 2018; Zhang *et al.*, 2020). Traffic accessibility is important for human activity; however, traffic networks may lead to the deterioration of the ecosystem by expanding the scope of human activities, promoting the flow of elements, and enhancing the regional socioeconomic development, directly or indirectly (Zeng *et al.*, 2018; Park *et al.*, 2019; Zhao *et al.*, 2019). Human activities caused the evolution of regional ecosystem services, and traffic networks can reshape the spatial distribution pattern of human activities (Hansen, 1959; Vitousek *et al.*, 1997; Mahmoud and Gan, 2018; Chen *et al.*, 2019; Liu *et al.*, 2019). Although the improvement of traffic networks can promote regional economic development, it inevitably leads to the consumption of ecosystem services and several unintended ecological effects (e.g., landscape fragmentation, urban heat island, and air pollution) (Spellerberg, 1998; Liu *et al.*, 2008; Park *et al.*, 2019). Scientific research on the impact of traffic accessibility on ecosystem services provides a solid foundation for ecological protection and the formulation of differentiated

ecological management policies (Han *et al.*, 2018; Qi *et al.*, 2020; Zhang *et al.*, 2020).

As the carrier of economic development, a traffic network can link production and consumption, balance regional supply and demand, and play a role in attracting, producing, and agglomerating industries, capital, and the population (Chi, 2010; Jiao *et al.*, 2017; Zheng and Cao, 2021). Traffic networks are among the most important factors affecting industrial layout due to the necessity to reduce transportation costs (Jiao *et al.*, 2017). The perfection of a traffic network can improve the regional economic radiation capacity and bring a competitive advantage to regional economic development (Cui *et al.*, 2018). The economic scale and aggregation effect create conditions for this comparative advantage, and the traffic network can provide comparative benefits for product output (Debrezion *et al.*, 2011). Therefore, improvements in traffic networks can greatly promote economic development. Previous studies have shown that construction land tends to expand along major traffic roads, and this expansion takes up a large quantity of ecological land, thereby leading to the decline of ecosystem functions (Ho and Wong, 2007; Cervero and Kang, 2011; Aljoufie *et al.*, 2013; Tan *et al.*, 2014; Zeng *et al.*, 2018; Chen *et al.*, 2020a). To a certain extent, the level of traffic accessibility reflects the level and intensity of human activities. Therefore, researching the spatial relationship between traffic accessibility and ecosystem services can further reveal the interaction between humans and natural systems and provide references for the scientific formulation of ecological protection policies.

Urban agglomeration is the highest form of spatial organization in the mature stage of urban development, and urban agglomerations have gradually become the main form of new-type urbanisation and an important carrier of China's modernisation. Exploring the spatial relationship between traffic accessibility and ecosystem services in urban agglomerations provides a scientific reference for ecological protection and transportation planning. Existing studies have carried out research concerning ecosystem services and traffic accessibility (Liu *et al.*, 2008; Guo *et al.*, 2014; Hu *et al.*, 2016; Mo *et al.*, 2017); however, few studies have comprehensively considered the spatial dependence and spatial heterogeneity of the impact of traffic accessibility on ecosystem services, especially in the rapid urbanisation of urban agglomerations. In this study, an integrated spatial approach, including global and local spatial regression models, was used to explore the interactions between traffic accessibility and ecosystem services. Bivariate spatial autocorrelation analysis can well identify the spatial agglomeration characteristics between traffic accessibility and ecosystem services, while the global spatial autocorrelation model can well manage the spatial dependence between traffic accessibility and ecosystem services, and the local spatial autocorrelation model can well manage the spatial heterogeneity effects (Chi and Ho, 2018; Chen *et al.*, 2019).

In addition, the spatial interaction between traffic accessibility and ecosystem services has significant scale effects that have been insufficiently considered in previous studies, limiting the effective formulation and implementation of ecological protection and land use policies. Existing studies are mostly based on statistical data of administrative units, which tend to conceal spatial heterogeneity characteristics within ecosystems and spatial differences of socioeconomic data distribution and traffic accessibility (Chen *et al.*, 2020c). In this study, 5-km and 10-km grid scales were employed to identify the scale effect of the impact of traffic accessibility on ecosystem services. It has been shown that 5-km and 10-km grid scales maximise the retention of relevant details compared to larger pixel sizes, while at the same

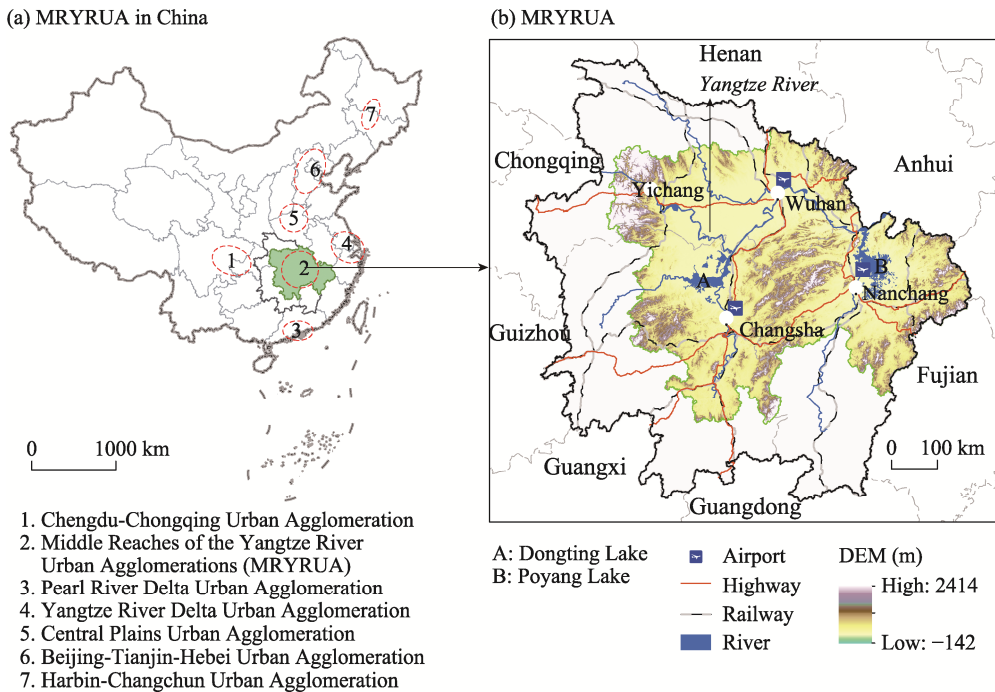
time avoiding noise of landscape patterns of smaller pixel sizes (Su *et al.*, 2011, 2012; Tan *et al.*, 2014).

This study takes the Middle Reaches of the Yangtze River Urban Agglomeration (MRYRUA) as a case. The MRYRUA has many modern ports, regional hub airports, trunk railways, and highways, forming a dense three-dimensional traffic network. The construction of a comprehensive transportation hub has led to progress in the MRYRUA which has an important strategic position in the national comprehensive traffic network. Thus, it is an exemplary site for exploring the spatial relationship between traffic accessibility and ecosystem services based on a comprehensive consideration of spatial dependence and spatial heterogeneity. Identifying the impact mechanism of traffic accessibility on ecosystem services is of immense importance for promoting regional sustainability. To reveal the relationship between them, this study primarily focused on the following three aspects: (1) measuring the spatiotemporal pattern of the ecosystem services value (ESV) at 5-km and 10-km grid scales in the MRYRUA from 2000 to 2020, (2) examining the spatiotemporal pattern of traffic accessibility at 5-km and 10-km grid scales in the MRYRUA from 2000 to 2020, and (3) investigating the spatial interaction of traffic accessibility and ecosystem services using an integrated spatial regression approach. This article is organised as follows. First, the study area and the data used for the empirical research and models adopted in this study are briefly introduced. Subsequently, the spatiotemporal variations of ecosystem services and traffic accessibility in the MRYRUA in 2000, 2010, and 2020 are analysed and the spatiotemporal variations between ecosystem services and traffic accessibility are determined using spatial regression analysis. Then, the spatial relationship between ecosystem services and traffic accessibility, relevant policy enlightenment, and future research directions are discussed.

## 2 Materials and methods

### 2.1 Study area

The MRYRUA, the first approved large cross-regional urban agglomeration of the State Council, is located in the hinterland of China, consisting of the Wuhan, Yichang–Jingzhou–Jingmen, Changsha–Zhuzhou–Xiangtan, and Poyang Lake urban agglomerations. In 2018, the MRYRUA contributed 9.8% of the total national gross domestic product (GDP) with its land area accounting for 3.4% of the country's total and 9% of the population. It runs through eastern and western China and connects the north and south. Transit-oriented urban development is evident in the MRYRUA. Several major modes of transport, including densely interwoven land transport, international airports, and water transport (e.g., the Yangtze River and its tributaries) have enabled the MRYRUA to cover a large geographical area with varying ecosystems. The traffic distribution between different cities is remarkable because it reflects the scope and intensity of human activities, thereby affecting regional ecosystem services by disturbing natural systems to varying degrees. Substantial divergence in ecosystem services and heterogeneous traffic accessibility coexist, making the MRYRUA a suitable area for studying the relationship between traffic accessibility and ecosystem services.



**Figure 1** Location of the study area (Middle Reaches of the Yangtze River Urban Agglomeration) in China

## 2.2 Data sources

The calculation of traffic accessibility in this study is primarily based on Feng *et al.* (2009), comprehensively considering port, airport, and land transportation modes. Land transportation included railways and various types of roads (e.g., highway, national road, provincial road, and county road), data of which were downloaded from the 1.4 million databases of the National Geomatics Centre of China (<http://ngcc.sbsm.gov.cn/>). Airport and port data were collected from Google Earth (<http://www.google.cn/maps>) and the China Port Network (<http://ship.chinaports.com>), respectively. Basic geographic information data such as water systems, administrative boundaries, and city centres were also sourced from the 1.4 million databases of the National Geomatics Centre of China (<http://ngcc.sbsm.gov.cn/>). The Resource and Environment Data Cloud Platform provided 1000-m resolution land use/land cover change data (<http://www.resdc.cn/DataList.aspx>) (Liu *et al.*, 2014; Ning *et al.*, 2018). We downloaded the 100-m resolution population raster data from the WorldPop program ([www.worldpop.org](http://www.worldpop.org)) and the 90-m resolution digital elevation model data were derived from the Geospatial Data Cloud site of the Computer Network Information Centre at the Chinese Academy of Sciences (<http://www.gscloud.cn>).

## 2.3 Assessment of the ecosystem services value

The benefit transfer method has been widely used to assess the ESV globally since it was proposed (Costanza *et al.*, 1997; Costanza *et al.*, 2014). The ESV classification method proposed by Costanza *et al.* (1997) was not suitable for the evaluation of ESV in China, as it may have underestimated or ignored certain categories of ecosystem functions (Costanza *et al.*, 1997; Xie *et al.*, 2008). Xie *et al.* (2008) improved the classification of China's ecosys-

tem functions and the equivalent table based on the knowledge of at least 700 ecologists (Xie *et al.*, 2008). Ecosystem functions were subdivided into nine categories, and the equivalent table was determined based on their relative importance to the economic value of cultivated land food production. The equivalent coefficients of ESV per unit area were defined as 1/7 of the economic value of the average annual grain yield of cultivated land per hectare. Since land-use types and ecosystem categories cannot match one to one exactly, we assigned equivalent coefficients of ESV per unit area of every ecosystem type to the closest land-use type (Chen *et al.*, 2020d; Ye *et al.*, 2018). The equivalent value was 344.927 USD/(ha·a) according to the grain output per unit area and the average grain price in the MRYRUA (Chen *et al.*, 2020b) (Table S1). This value can be expressed through the following equation:

$$ESV = \sum_{j=1}^m \sum_{i=1}^n (LUC_i \times VC_{ij}) \quad (1)$$

where  $LUC_i$  is the  $i$ -th land-use type area,  $VC_{ij}$  is the equivalent value of the  $j$ -th ecosystem function of the  $i$ -th land-use type ( $j = 1, 2, 3 \dots 9$ ), and  $i$  is the number of land-use types in the study area. The average  $ESV$  can be estimated by the  $ESV$  per unit area.

## 2.4 Measurement of traffic accessibility

Traffic accessibility, first proposed by Hansen (1959), refers to the ability to overcome spatial separation. Previous studies have focused on the accessibility of urban internal systems from microscopic perspectives, such as pedestrian accessibility and public transport accessibility (Levinson *et al.*, 2015; Eggermond and Erath, 2016). However, few studies have been conducted on accessibility at the macro level reflecting regional development changes. Since the beginning of the 21st century, China's vigorous infrastructure construction has greatly improved the connectivity between cities and shortened commuting time (Zhu *et al.*, 2018; Jin *et al.*, 2019). Empirical research showed that the denser the transportation trunk lines in a region, the higher the degree of connection in the region, and the higher the supporting capacity of transportation facilities (Cheng *et al.*, 2013; Xie *et al.*, 2019). In addition, in the context of regional opening, the degree of difficulty of commuting between regions was found to play a decisive role in its economic radiation and factor transfer (Feng *et al.*, 2009). Highways, railways, airports, and ports are the main transportation facilities and are important media for regional commuting, and their accessibility to a large extent indicates the convenience of regional communication with the outside. For example, when individuals living in areas A and B want to travel to Beijing via airport (railway or port) C, those in area B which is located farther away from C than A, cannot avoid spending more time, money, and energy than those living in area A. Therefore, individuals in this area have less traffic convenience. Hence, based on the Technical Rules for the Division of Provincial Main Functional Areas (Trial) issued by the China Development and Reform Commission (Zeng *et al.*, 2018) and the study on county traffic accessibility by Feng *et al.* (2009), the regional traffic accessibility was defined as the comprehensive manifestation of traffic density (the degree of security of its transportation facilities) and traffic convenience (the convenience of travelling to external regions). This study assumed an equal importance of internal and external transportation. The specific equation is as follows:

$$TA = \frac{1}{2} \times (MD + BD) \quad (2)$$

where  $TA$  stands for traffic accessibility; and  $MD$  and  $BD$  represent the traffic density and convenience index, respectively.

Specifically, the traffic density can be expressed using the three indicators of road density ( $RM$ ), railway density ( $TM$ ), and navigable river density ( $NRD$ ). The convenience index was calculated from five indicators, including distance to the road ( $RL$ ), distance to railways ( $TL$ ), distance to city centres ( $UL$ ), distance to airports ( $AL$ ), and distance to the wharf ( $WL$ ). The specific equations are as follows:

$$MD = \frac{1}{3} \times (RM + TM + NRD) \quad (3)$$

$$BD = \frac{1}{5} \times (RL + TL + UL + AL + WL) \quad (4)$$

The sub-item index adopted the method of graded assignment, and the specific grade division and threshold value referred to the Provincial Main Functional Area Division Technical Regulation (Trial) scheme (Zeng *et al.*, 2018). The assignment criteria are listed in Table 1.

## 2.5 Spatial regression models

The spatial distribution of aggregation or other spatial anomaly features between ecosystem services and traffic accessibility were measured by global bivariate spatial autocorrelation and local spatial autocorrelation (Anselin and Rey, 2014). Global spatial autocorrelation was used to verify the clustering trend of the spatial distribution of ecosystem services and traffic accessibility across the region. Local bivariate spatial autocorrelation revealed the correlation and spatial heterogeneity between the attribute values of each individual unit and adjacent spatial units. According to the local Moran's  $I$  results, the high-high type represents high average ESV and high traffic accessibility areas, the low-low type indicates low average ESV and low traffic accessibility areas, the high-low type denotes high average ESV and low traffic accessibility areas, and the low-high type denotes low average ESV and high traffic accessibility areas. Spatial autocorrelation analysis demonstrated that there was a significant spatial dependence between ecosystem services and traffic accessibility and neglecting spatial dependency would lead to a limited understanding of the impact of traffic accessibility on ecosystem services (Anselin, 1988a; Anselin, 1988b; Costanza *et al.*, 1997). To clearly explain the complex spatial interaction between ecosystem services and traffic accessibility, we introduced a set of spatial regression models to evaluate the spatial associations. First, the ordinary least squares (OLS) model was used to detect the relationship between ecosystem services and traffic accessibility, regardless of the impact of adjacent areas. Then, two spatial regression models that can be applied to cross-sectional data (namely, the spatial lag model (SLM) and spatial error model (SEM)) were adopted to prove the spatial dependence of ecosystem services on traffic accessibility (Chi and Zhu, 2008; Chi, 2010; Chi and Ho, 2018). Finally, a geographically weighted regression (GWR) model was employed to explore the spatial heterogeneity of the impact of traffic accessibility on ecosystem services. The OLS model and spatial regression models were implemented in GeoDa 095i, and the GWR model was run in ArcGIS 10.3.

**Table 1** Evaluation criteria for each index for traffic accessibility

Type	Sub-type	Level	Standard	Score
Railway	—	1	Owning railway	2
		2	30 km from the railway	1.5
		3	60 km from the railway	1
		4	Others	0
Road	Expressway	1	Owning expressway	1.5
		2	30 km from the expressway	1
		3	30 km from the expressway	0.5
		4	Others	0
	National road	1	Owning national road	0.5
		2	Others	0
	Provincial road	1	Owning provincial road	0.3
		2	Others	0
	County road	1	Owning county road	0.1
		2	Others	0
Shipping transport	Hub ports	1	Owning hub ports	1.5
		2	30 km from the hub ports	1
		3	30 km from the hub ports	0.5
		4	Others	0
	General ports	1	Owning general ports	0.5
		2	Others	0
Airports	International airports	1	Owning international airports	1
		2	30 km from international airports	0.5
		3	Others	0
	General airports	1	Owning general airports	0.5
		2	Others	0
		3	Others	0
Central cities	—	1	100 km from city centres	2
		2	300 km from central cities	1.5
		3	600 km from central cities	1
		4	Others	0
Density of navigable river (m/km <sup>2</sup> )	—	1	>600	2
		2	(200, 600]	1.5
		3	(0, 200]	1
		4	0	0
Railway density (m/km <sup>2</sup> )	—	1	>300	2
		2	(100, 300]	1.5
		3	(0, 100]	1
		4	0	0
Road density (m/km <sup>2</sup> )	—	1	>1500	2
		2	(1000, 1500]	1.5
		3	(0, 1000]	1
		4	0	0



In the spatial regression model, traffic accessibility was set as the explanatory variable, and the average ESV as the explained variable. In addition, elevation and population density were selected as control variables, representing natural and socioeconomic factors, respectively. In a previous study, elevation was shown to have a significant influence on ecosystem services (Chen *et al.*, 2020a). Population density is closely related to regional resources, environment, and economic development, because densely populated areas require more land, water, and biological resources to ensure people's access to food, water, the environment, and infrastructure. Regional economic development, industrialisation, and urbanisation inevitably cause eco-environmental pressure, and people are the main body of socioeconomic activities. Population density can thus be used to reflect the social background index in human-eco-environmental systems (Chi and Ho, 2018).

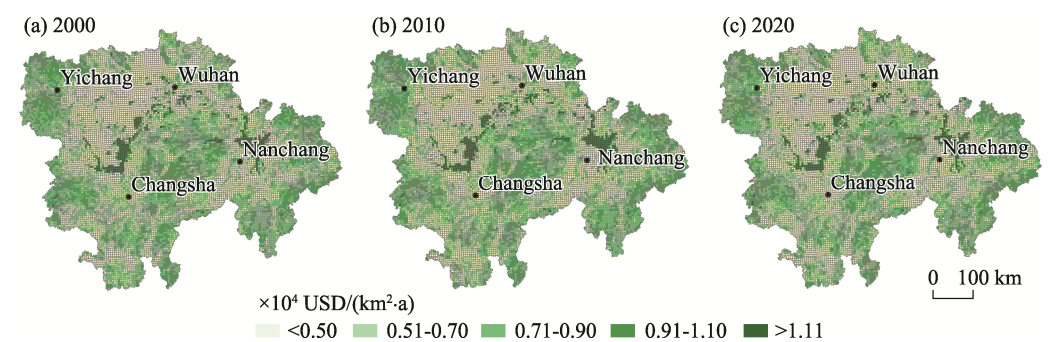
### 3 Results

#### 3.1 ESV in the Middle Reaches of the Yangtze River Urban Agglomerations

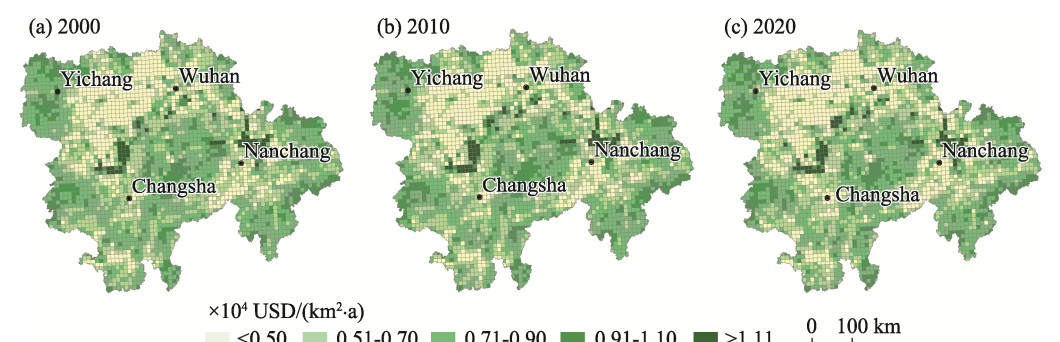
The ESV in 2000, 2010, and 2020 was 2136.866 million, 2135.672 million, and 2093.915 million USD, respectively. A continuously decreasing tendency was found for the ESV in the MRYRUA from 2000 to 2020 (Table S2). The rate of decrease in ESV was  $-0.056\%$  and  $-1.955\%$ , in the periods 2000–2010 and 2010–2020, respectively. The ESV provided by cultivated land, forestland, and grassland experienced a continuous downward trend, while the ESV provided by wetland and unused land increased continuously during the study period. Furthermore, construction land provided increasingly severe negative ESV from 2000 to 2020 in the MRYRUA. The hydrology regulation function accounted for the largest proportion of the ESV function structure in the MRYRUA, followed by the biodiversity maintenance and climate regulation functions, while food production contributed the least to the ESV (Table S3). Additionally, the biodiversity maintenance function was also particularly significant because of the complex topography, numerous water bodies, and wetlands in the MRYRUA. The ESV functions, including food production, raw materials, gas regulation, hydrology regulation, and soil conservation, continuously decreased during the study period. The other four ESV functions, including climate regulation, waste treatment, biodiversity maintenance, and aesthetic landscape, increased during the former decade, and decreased during the latter decade. The other ESV functions, including food production, gas regulation, and hydrology regulation increased, while biodiversity maintenance, climate regulation, and aesthetic landscape provision capacity decreased continuously. The average ESV along the Yangtze River was higher than that in the mountainous areas, while the average ESV in the plains (e.g., Jiangnan Plain, Poyang Lake Plain, and Dongting Lake Plain), and areas along the major traffic routes and around major prefecture-level cities was lower (Figures 2 and 3).

#### 3.2 Traffic accessibility in the Middle Reaches of the Yangtze River Urban Agglomerations

Land transportation links have formed a dense traffic network over the past 20 years, while other types of transportation, such as water transportation, have changed little (Figure 4). In this section, the changes in traffic accessibility in the study area from 2000 to 2020 are assessed. To quantify the characteristics of traffic accessibility, we mapped the spatiotemporal

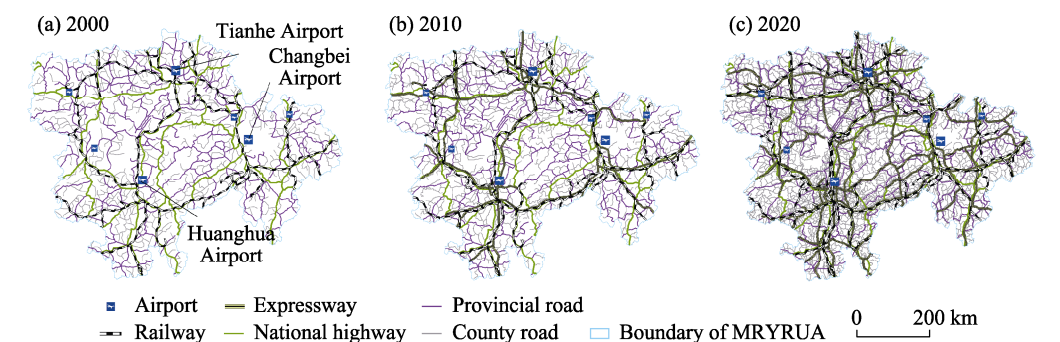


**Figure 2** Spatial distribution of average ESV at the 5-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

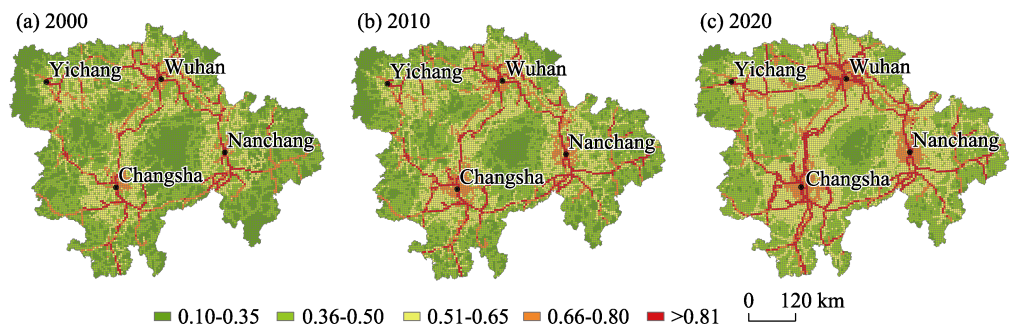


**Figure 3** Spatial distribution of average ESV at the 10-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

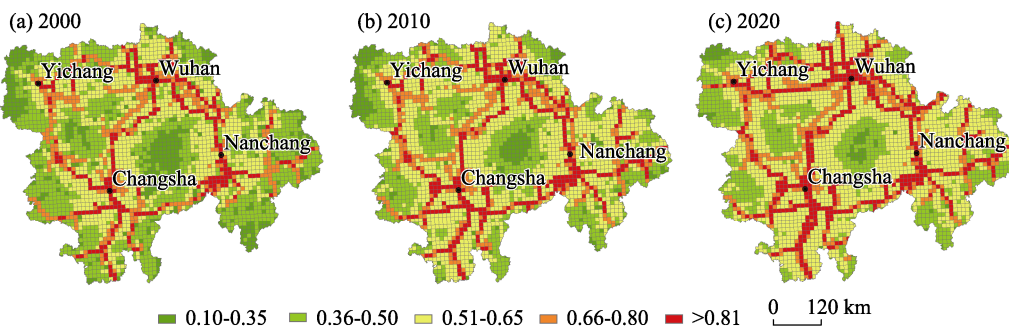
pattern of traffic accessibility in the MRYRUA in 2000, 2010, and 2020 (Figures 5 and 6). Overall, the average traffic accessibility at the 5-km grid scale was 0.450, 0.491, and 0.540 in 2000, 2010, and 2020, respectively, and 0.525, 0.560, and 0.590 at the 10-km grid scale, respectively. We found that the traffic accessibility in the MRYRUA increased significantly during the study period; however, there was still a ‘dead end highway’ phenomenon in 2000. By 2010, the average traffic accessibility in the MRYRUA had increased, but still generally consisted of low and medium accessibility levels. The rapid development of highways and improving their connectivity became an important focus of accessibility improvement in the MRYRUA from 2000 to 2010. Similarly, the improvement in traffic accessibility during



**Figure 4** Spatial distribution of traffic network in the Middle Reaches of the Yangtze River Urban Agglomeration



**Figure 5** Spatial distribution of traffic accessibility at the 5-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration



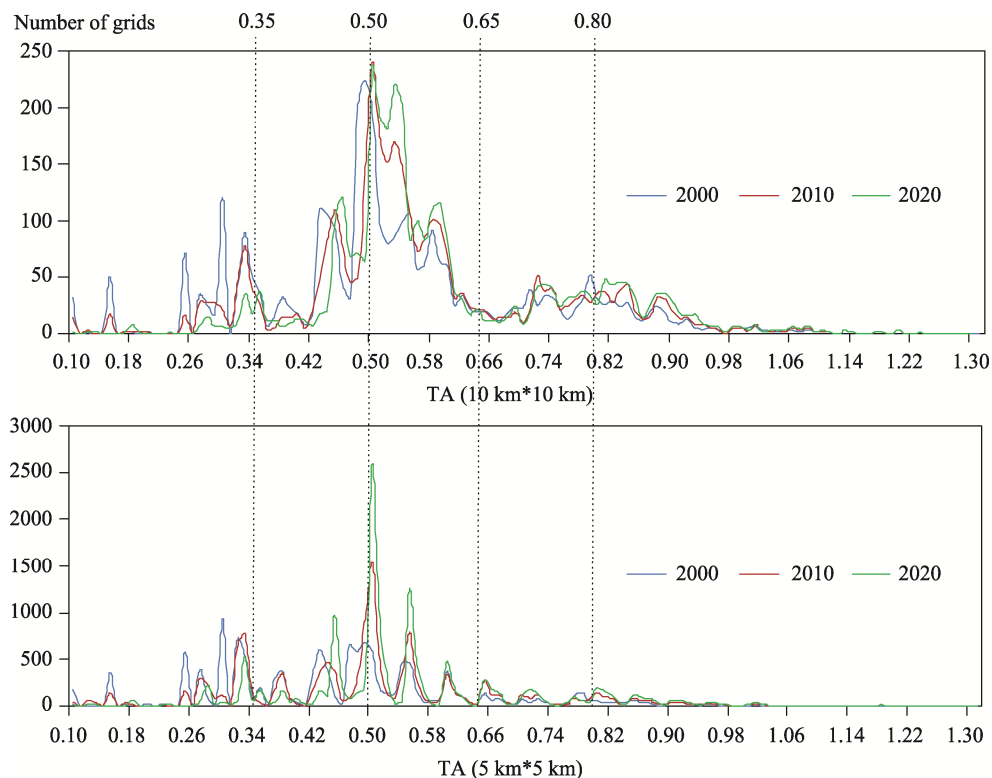
**Figure 6** Spatial distribution of traffic accessibility at the 10-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

2010–2020 also benefited from the continuous improvement of highways and county roads. Figure 4 shows the continuous improvement of the traffic network in the MRYRUA. As shown in Figure 4c, the MRYRUA had a well-connected land transportation network, integrating expressways and national, provincial, and county roads in 2020.

To further analyse the changing trend of traffic accessibility at the 5-km and 10-km grid scales (Figures 6 and 7), the traffic accessibility distribution at different scales is shown in Figure 7. As can be seen, traffic accessibility changed in 2000, 2010, and 2020. In general, we found that the overall level of traffic accessibility of the MRYRUA improved during the study period. As shown in Figure 7, peaks shifted to the right, or low-level peaks decreased, and high-level peaks increased, confirming the previous assumption that traffic accessibility increased progressively with time, especially in low-level areas (Figure 7). This indicates that it is difficult to further improve spatial accessibility in high-level areas, and other methods, such as the time reduction method, need to be considered in future transportation planning.

### 3.3 Spatial autocorrelation analysis between ecosystem services and traffic accessibility

Based on the GeoDa 095i software, the global spatial autocorrelation Moran's  $I$  values between the average ESV and traffic accessibility at different grid scales were measured in 2000, 2010, and 2020. The bivariate global spatial autocorrelation Moran's  $I$  values between the average ESV and traffic accessibility at a 5-km grid scale were  $-0.254$ ,  $-0.256$ , and

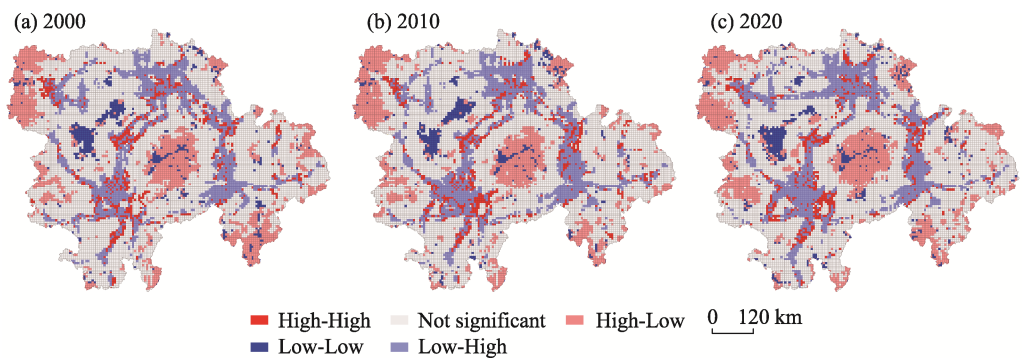


**Figure 7** Statistics of traffic accessibility distribution at different scales in the Middle Reaches of the Yangtze River Urban Agglomeration

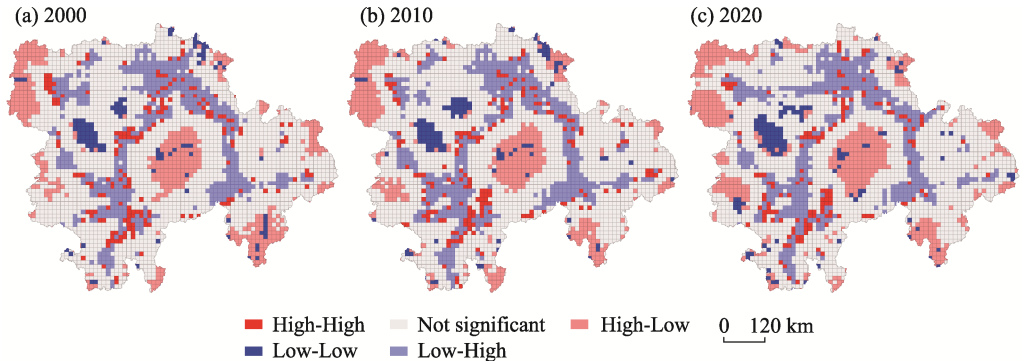
−0.304 in 2000, 2010, and 2020, respectively, while the global spatial autocorrelation Moran’s  $I$  values at a 10-km grid scale were −0.279, −0.270, and −0.299, respectively. We found a significant negative correlation between the average ESV and traffic accessibility levels at both grid scales, indicating that the increase in the traffic accessibility level led to a deterioration of ecosystem services. Additionally, the bivariate global spatial autocorrelation Moran’s  $I$  values exhibited an overall increasing trend, documenting that the negative correlation between the average ESV and traffic accessibility intensified.

Furthermore, we found a clear similarity in the spatial clustering pattern of the bivariate local indicators of spatial association (LISA) maps between average ESV and traffic accessibility in the years 2000, 2010, and 2020 (Figures 8 and 9). The dominant spatial clustering patterns in the MRYRUA were the high-low and low-high types. Specifically, the high-low type was primarily located in the surrounding mountainous areas and the Luoxiao Mountains in the central area, while the low-high type was primarily distributed in the plains, grids around the key prefecture-level cities, and grids along the main traffic routes. The high-high and low-low types also existed in the MRYRUA; the former was sustainable, while the latter was unsustainable. We found that traffic accessibility had a significant negative externality to the ESV during 2000–2020, indicating that traffic development in the MRYRUA caused strong interference for ecosystem services. The existence of spatial spillover effects was due to the material, energy, and information flow among neighbouring regions. Additionally, natural processes (e.g., atmospheric circulation, temperature, and precipitation) and human

activities (e.g., urbanisation, economic development, and population migration) may have also promoted the spatial spillover effects on the ecosystem services.



**Figure 8** Bivariate LISA cluster maps between average ecosystem services value and traffic accessibility at the 5-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration



**Figure 9** Bivariate LISA cluster maps between average ecosystem services value and traffic accessibility at the 10-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

### 3.4 Spatial impact of traffic accessibility on ecosystem services

The results of the OLS regression further revealed that there was a significant spatial dependence between the average ESV and traffic accessibility (Table 2). This spatial relationship cannot be fully and scientifically explained by the OLS model. The results of the SEM and SLM models are listed in Tables 3 and 4. We found that the spatial regression models significantly increased the explanatory ability. The coefficient of determination ( $R^2$ ) values of all the spatial regression models was above 0.60. Negative regression coefficients indicate a negative association between the average ESV and traffic accessibility, significant at the 0.0001 level. Comparing the regression coefficients at different grid scales demonstrated that the regression coefficients of the 5-km grid scale were significantly higher than those of the 10-km grid scale. We further found that population density was negatively associated with the average ESV at both grid scales, while elevation was positively associated with the average ESV at both scales.

The SEM and SLM models accounted for the spatial dependence to a certain extent, but failed to explain the spatial heterogeneity of the impact of traffic accessibility on the average

**Table 2** Regression results of the ordinary least squares (OLS) in the Middle Reaches of the Yangtze River Urban Agglomeration

Variables	5-km grid scale			10-km grid scale		
	2000	2010	2020	2000	2010	2020
TA	-0.146*** (0.010)	-0.159*** (0.010)	-0.261*** (0.011)	-0.141*** (0.016)	-0.135*** (0.017)	-0.201*** (0.017)
Population density	-0.631*** (0.034)	-0.796*** (0.038)	-0.907*** (0.040)	-0.419*** (0.052)	-0.556*** (0.056)	-0.640*** (0.058)
Elevation	0.253*** (0.009)	0.246*** (0.009)	0.246*** (0.009)	0.215*** (0.014)	0.218*** (0.015)	0.225*** (0.014)
Constant	0.406*** (0.004)	0.416*** (0.005)	0.458*** (0.005)	0.424*** (0.008)	0.427*** (0.009)	0.450*** (0.009)
Moran's <i>I</i> (error)	0.595***	0.592***	0.574***	0.558***	0.554***	0.542***
LM (lag)	16202.969***	15949.124***	14942.003***	3400.421***	3336.905***	3166.978***
Robust LM (lag)	52.994***	49.676***	113.351***	10.196**	8.458**	16.859***
LM (error)	16959.133***	16805.582***	15795.762***	3687.966***	3630.687***	3482.858***
Robust LM (error)	809.158***	906.134***	967.110***	297.741***	302.234***	332.738***
LM (lag and error)	17012.127***	16855.258***	15909.113***	3698.1625***	3639.145***	3499.716***
Measures of fit						
Log likelihood	8381.890	8219.170	7834.050	2690.940	2630.150	2583.130
AIC	-16755.800	-16430.300	-15660.100	-5373.880	-5252.300	-5158.250
SC	-16726.000	-16400.500	-15630.300	-5349.480	-5227.900	-5133.850
<i>R</i> -squared	0.167	0.175	0.208	0.205	0.206	0.243
<i>N</i>	12710	12710	12710	3299	3299	3299

Notes: The study uses the Queen's contiguity weight matrix. \*\*\* $p \leq 0.001$ , \*\* $p \leq 0.01$ , \* $p \leq 0.05$ . Standard errors are in parentheses. LM = Lagrange multiplier, AIC = Akaike information criterion, SC = Schwarz criterion.

**Table 3** Regression results of the spatial lag model (SLM) and spatial error model (SEM) at the 5-km grid scale in 2000, 2010, and 2020 in the Middle Reaches of the Yangtze River Urban Agglomeration

Variables	2000		2010		2020	
	SLM	SEM	SLM	SEM	SLM	SEM
TA	-0.043*** (0.006)	-0.059*** (0.008)	-0.054*** (0.008)	-0.077*** (0.009)	-0.075*** (0.008)	-0.097*** (0.010)
Population density	-0.351*** (0.022)	-0.561*** (0.029)	-0.423*** (0.024)	-0.698*** (0.033)	-0.473*** (0.027)	-0.775*** (0.037)
Elevation	0.042*** (0.006)	0.223*** (0.016)	0.038*** (0.006)	0.217*** (0.016)	0.044*** (0.006)	0.248*** (0.017)
Spatial lag term	0.841*** (0.006)		0.838*** (0.006)		0.830*** (0.006)	
Spatial error term		0.858*** (0.006)		0.856*** (0.006)		0.852*** (0.006)
Constant	0.075*** (0.004)	0.379*** (0.006)	0.082*** (0.004)	0.389*** (0.006)	0.094*** (0.004)	0.389*** (0.007)
Measures of fit						
Log likelihood	13220.600	13308.526	12999.600	13097.571	12420.100	12497.926
AIC	-26431.100	-26609.100	-25989.200	-26187.100	-24830.200	-24987.900
SC	-26393.900	-26579.300	-25951.900	-26157.300	-24792.900	-24958.100
<i>R</i> -squared	0.664	0.671	0.663	0.671	0.665	0.673
<i>N</i>	12710	12710	12710	12710	12710	12710

Notes: The study uses the Queen's contiguity weight matrix. \*\*\* $p \leq 0.001$ , \*\* $p \leq 0.01$ , \* $p \leq 0.05$ . Standard errors are in parentheses. LM = Lagrange multiplier, AIC = Akaike information criterion, SC = Schwarz criterion.

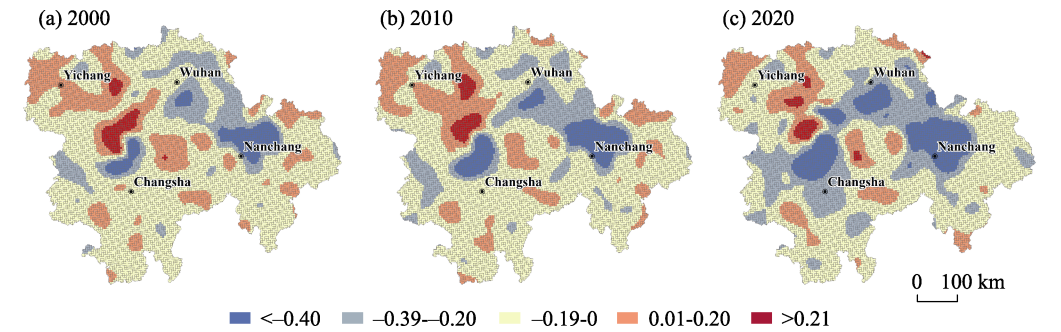


**Table 4** Regression results of the spatial lag model (SLM) and spatial error model (SEM) at the 10-km grid scale in 2000, 2010, and 2020 in the Middle Reaches of the Yangtze River Urban Agglomeration

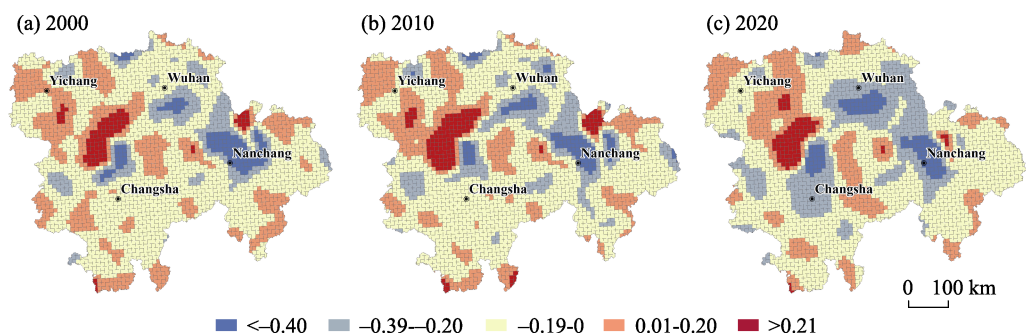
Variables	2000		2010		2020	
	SLM	SEM	SLM	SEM	SLM	SEM
TA	−0.060*** (0.011)	−0.094*** (0.013)	−0.060*** (0.012)	−0.097*** (0.014)	−0.078*** (0.012)	−0.120*** (0.015)
Population density	−0.277*** (0.035)	−0.353*** (0.039)	−0.367*** (0.037)	−0.465*** (0.043)	−0.431*** (0.040)	−0.553*** (0.046)
Elevation	0.037*** (0.010)	0.181*** (0.022)	0.037*** (0.010)	0.183*** (0.023)	0.043*** (0.010)	0.201*** (0.023)
Spatial lag term	0.822*** (0.012)		0.820*** (0.012)		0.814*** (0.012)	
Spatial error term		0.850*** (0.011)		0.848*** (0.012)		0.848*** (0.012)
Constant	0.096*** (0.007)	0.409*** (0.011)	0.099*** (0.008)	0.414*** (0.011)	0.109*** (0.008)	0.414*** (0.012)
<i>Measures of fit</i>						
Log likelihood	3806.200	3850.878	3728.190	3772.807	3654.160	3697.945
AIC	−7602.410	−7693.760	−7446.370	−7537.610	−7298.310	−7387.890
SC	−7571.900	−7669.350	−7415.870	−7513.210	−7267.810	−7363.490
R-squared	0.648	0.663	0.645	0.660	0.655	0.670
N	3299	3299	3299	3299	3299	3299

Notes: The study uses the Queen’s contiguity weight matrix. \*\*\* $p \leq 0.001$ , \*\* $p \leq 0.01$ , \* $p \leq 0.05$ . Standard errors are in parentheses. LM = Lagrange multiplier. AIC = Akaike information criterion. SC = Schwarz criterion.

ESV. The GWR model can provide more local information that is generally hidden in the global regression. Figures 10 and 11 illustrate the regression coefficients of the GWR model, and Figures S1 and S2 present the local  $R^2$  at the 5-km and 10-km grid scales in 2000, 2010, and 2020. We found that the local  $R^2$  in most grids was above 0.3, indicating that the GWR model can explain the relationship between traffic accessibility and the average ESV sufficiently. The impact of traffic accessibility on ecosystem services presented significant spatial heterogeneity. A negative association was found in most of the study area, with only a small proportion of grids exhibiting a positive relationship. The traffic accessibility in the Wuhan,



**Figure 10** Results of geographically weighted regression at the 5-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration



**Figure 11** Results of geographically weighted regression at the 10-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

Changsha–Zhuzhou–Xiangtan, and Poyang Lake urban agglomerations had a stronger negative impact on the ecosystem services. Conversely, a positive association was found in the Yichang–Jingzhou–Jingmen urban agglomeration, and several positively associated areas were found discretely distributed in the MRYRUA.

## 4 Discussion and implications

### 4.1 Spatial relationship between traffic accessibility and ecosystem services

A significant spatial dependence was found between the ecosystem services and traffic accessibility. The global bivariate spatial autocorrelation analysis demonstrated that there was a significant negative correlation between traffic accessibility and the average ESV. The bivariate LISA map between the average ESV and traffic accessibility revealed that the high-low and low-high types were the dominant spatial clustering patterns in the MRYRUA. Furthermore, the GWR model proved that the impact of traffic accessibility on the ecosystem services exhibited significant spatial heterogeneity. In general, there was a significant negative correlation between traffic accessibility and ecosystem services, even though positive relationships were found in some areas. For example, in Tianmen, Qianjiang, Shashi, Yueyang, and the west of Jiujiang, there was an evident positive correlation between traffic accessibility and ecosystem services. This demonstrates that an improvement in traffic accessibility did not necessarily lead to a decline in the average ESV. It is not advisable to completely stop the construction of transportation infrastructure or economic development; instead reasonable planning and management of transportation infrastructure should be carried out to achieve ecological protection and improve ecosystem functions. Identifying the relationship between traffic accessibility and ecosystem services provides an effective reference for formulating scientific management methods of land transformation, urbanisation development, and landscape pattern transformation oriented by transportation development.

In this study, traffic accessibility revealed the extent and intensity of human activities, but did not indicate the reasonable range of human activity intensity. The relationship between traffic accessibility and the average ESV is an important basis for urban landscape planning, the designation of priority areas for ecological protection, and the formulation of ecological compensation strategies. To optimise the urban landscape, it is necessary to determine the degree of disturbance to the ecosystem caused by traffic networks and related socioeconom-



ic development (Cervero, 2013; Ratner and Goetz, 2013). Changes in traffic patterns may cause corresponding changes in regional economic development patterns. Therefore, it is necessary to create reasonable traffic planning layouts and to combine traffic planning with landscape planning.

## 4.2 Policy implications

The spatial regression results revealed that the average ESV in the MRYRUA was not only affected by the regional traffic accessibility level, population size, and elevation factors but also by elements in the neighbouring units. They further confirmed that there were significant spatial spillovers or spatial externalities caused by location-based proximity. For example, the benefits or costs of a neighbourhood can easily affect the individual location (Chi and Marcouiller, 2013; Day and Lewis, 2013). The observed spatial externalities can be explained from the following aspects. First, the traffic network itself was accompanied by material, production factors, and information flow. Second, to ensure the efficient use of resources, not every place has the same quantity of transportation resources, and, therefore, different areas are characterised by different levels of population, material, and economic attraction. Spatially adjacent areas were competitive in socioeconomic development. Therefore, the formulation and implementation of traffic planning and urban landscape planning should not be limited to a single region (Chi and Ho, 2018). Spatial spillovers should be incorporated into ecosystem governance and development decisions.

Presently, China is carrying out green urban construction, focusing on sustainable spatial development. ‘Green development’ and ‘protection priority’ can guarantee healthy regional development in the future. Particularly, attention should be paid to urban agglomerations with high potentials to improve ecosystem services. Additionally, with the development of urban agglomeration strategies and planning, it was inevitable that traffic construction would be carried out to strengthen the interactions between different cities. To a certain extent, the combination of urban landscape planning and transportation planning can prevent or mitigate the damage to the ecosystem caused by transportation and future regional development. The spatial determinants were found to exhibit several local-specific characteristics, given that they varied across space. Therefore, urban planners and managers need to understand the local-specific coefficients or indicators of their areas to investigate the impact of traffic accessibility and ecosystem services in their local settings. The GWR model can provide a set of varying spatial coefficients, from which local coefficients for each grid can be obtained. Varying spatial correlations of traffic accessibility with ecosystem services represents a new supportive framework for enhancing local efforts to regulate ecological development and land-use decision making in the MRYRUA. The results obtained from these models can help discover the impacts of traffic accessibility on ecosystem services at both grid levels, thereby better supporting ecological planners and managers to address ecological issues.

## 4.3 Limitations and future directions

In this study, the spatial accessibility method was used to calculate regional traffic accessibility. Readily available, accurate data was the main advantage of this method, providing an accurate representation of the changes in traffic accessibility. During the study period, traffic

accessibility in the MRYRUA improved significantly, but the increasing spatial association between traffic accessibility and the average ESV suggests that the contribution of time accessibility needs to be considered to further improve the accuracy of this study. Although the assessment of traffic accessibility was not comprehensive, it still provided a useful perspective for understanding the interaction between human activities and ecosystems. The 5-km and 10-km grid scales were employed in this study to identify the scale effect of the impact of traffic accessibility on ecosystem services. However, scale effect is very complex in the social ecological process, and further discussion is needed in the future study. Finally, this study revealed the relationship between traffic accessibility and the average ESV to prevent ecological degradation problems from a subjective regulation level; however, with increasing urbanisation, coordinating the contradiction between ecosystem services and human activities remains the focus of the future research.

## 5 Conclusions

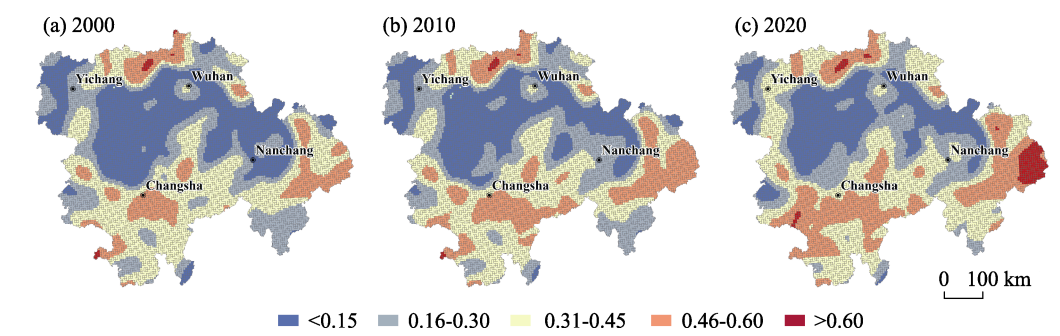
Traffic accessibility weakened the ecosystem services provision capacity of the regional ecosystem by promoting urbanisation, socioeconomic development, and land-use change, directly or indirectly. Understanding the relationship between traffic accessibility and the average ESV is valuable for formulating reasonable ecosystem protection plans. Identifying the spatial features of traffic accessibility and ecosystem services, alongside their spatial relationship, dependence, and heterogeneity, can provide an important reference for creating ecological protection strategies. With a set of spatial regression models, this study analysed the spatial relationship between traffic accessibility and the average ESV based on land use/land cover change and traffic data in the MRYRUA in 2000, 2010, and 2020. During the study period, the ecosystem services provision capacity in the MRYRUA decreased continuously, and the ESV in the plain areas, areas surrounding the core cities, and areas along the main traffic routes were significantly lower than those along the Yangtze River and in the mountainous areas. From 2000 to 2020, the MRYRUA gradually formed a transportation corridor, and the traffic accessibility increased significantly. During the study period, the bivariate spatial autocorrelation between the average ESV and traffic accessibility was negative and significant at the 0.0001 level. Low average ESV and high traffic accessibility, and high average ESV and low traffic accessibility were the primary types of correlation in the MRYRUA. The former was generally distributed in the plain areas, areas surrounding the big cities, and areas along the main traffic roads, while the latter was distributed in the mountainous areas. The results of the spatial regression analysis revealed that there was a significantly negative relationship between the average ESV and traffic accessibility, and the regression coefficients at the 5-km grid scale were significantly higher than those at the 10-km grid scale. Additionally, the regression results demonstrated that the value of the individual ecosystem services was not only affected by the traffic accessibility of the local unit but also by elements in neighbouring units. Finally, the results of the GWR analysis revealed that the impact of traffic accessibility, population size, and elevation on the ESV varied spatially. The findings of this study provided essential implications for traffic planning and regional sustainability.

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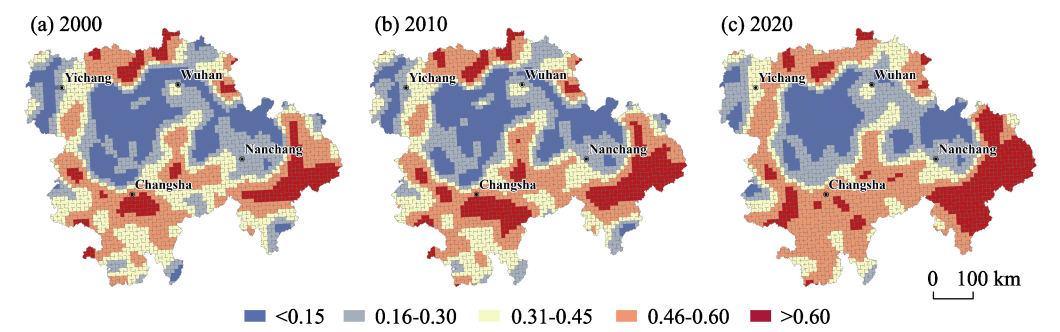
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**Figure S1** Local  $R^2$  of GWR model at the 5-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration



**Figure S2** Local  $R^2$  of GWR model at the 10-km grid scale in the Middle Reaches of the Yangtze River Urban Agglomeration

**Table S1** The equivalent value per unit area of ecosystem services in the Middle Reaches of the Yangtze River Urban Agglomeration [USD/(ha<sup>2</sup>·a)]

Sub-type	Cultivated land	Forestland	Grassland	Water body	Construction land	Unused land	Wetland
Food production	344.927	113.826	148.319	182.811	3.449	6.899	124.174
Raw materials	134.522	1027.883	124.174	120.725	0.000	13.797	82.783
Gas regulation	248.348	1490.086	517.391	175.913	-834.724	20.696	831.275
Climate regulation	334.580	1403.854	538.087	710.550	0.000	44.841	4673.765
Hydrology regulation	265.594	1410.753	524.290	6474.286	-2590.404	24.145	4635.823
Waste treatment	479.449	593.275	455.304	5122.171	-848.521	89.681	4966.953
Soil conservation	507.043	1386.608	772.637	141.420	6.899	58.638	686.405
Biodiversity maintenance	351.826	1555.622	645.014	1183.101	117.275	137.971	1272.782
Aesthetic landscape provision	58.638	717.449	300.087	1531.477	3.449	82.783	1617.709
In total	2724.926	9699.356	4025.302	15642.454	-4142.577	479.449	18891.670

Notes: 100 US dollars could be exchanged for 622.84 yuan in 2015.

**Table S2**    ESV provided by different land use types in the Middle Reaches of the Yangtze River Urban Agglomeration

Years	Cultivated land	Forestland	Grassland	Water body	Wetland	Unused land	Construction land
2000 (×10 <sup>4</sup> USD)	31791.713	145005.741	2850.153	27040.381	10188.576	1.305	−3191.266
2010 (×10 <sup>4</sup> USD)	31293.248	144899.336	2726.990	27506.025	10967.188	1.336	−3826.940
2020 (×10 <sup>4</sup> USD)	30486.233	143298.548	2673.709	27029.617	11663.780	1.757	−5762.117
2000 (%)	14.878	67.859	1.334	12.654	4.768	0.001	−1.493
2010 (%)	14.653	67.847	1.277	12.879	5.135	0.001	−1.792
2020 (%)	14.559	68.436	1.277	12.909	5.570	0.001	−2.752
2000–2010 (%)	−0.225	−0.012	−0.057	0.225	0.367	0.000	−0.298
2010–2020 (%)	−0.093	0.589	0.000	0.029	0.435	0.000	−0.960

**Table S3**    Changes in the structure of ESV in the Middle Reaches of the Yangtze River Urban Agglomeration

Type	Sub-type	2000 (×10 <sup>4</sup> ) (USD)	2010 (×10 <sup>4</sup> ) (USD)	2020 (×10 <sup>4</sup> ) (USD)	2000–2010 (%)	2010–2020 (%)	2000–2020 (%)
Supplying services	Food production	6216.652	6158.857	6036.583	−0.930	−1.985	−2.897
	Raw materials	17277.657	17244.980	17033.242	−0.189	−1.228	−1.415
Regulating services	Gas regulation	25650.091	25483.895	24792.947	−0.648	−2.711	−3.342
	Climate regulation	29021.262	29141.976	28954.806	0.416	−0.642	−0.229
	Hydrology regulation	36257.218	36163.411	34608.668	−0.259	−4.299	−4.547
	Waste treatment	25665.391	25784.236	25169.144	0.463	−2.386	−1.934
Supporting services	Soil conservation	27812.715	27714.673	27349.710	−0.353	−1.317	−1.665
	Biodiversity maintenance	30640.394	30644.914	30341.243	0.015	−0.991	−0.976
Cultural services	Aesthetic landscape provision	15145.224	15230.242	15105.186	0.561	−0.821	−0.264
	In total	213686.603	213567.183	209391.528	−0.056	−1.955	−2.010