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Modeling the distribution of cultural ecosystem services based on future climate variables under different scenarios

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With the far-reaching consequences of worldwide climate variationon ecosystems and human societies, understanding and predicting changes in cultural ecosystem services (CES) is essential for sustainable development policy and resource planning. Past studies have focused on changes and impacts on natural ecosystems, while relatively few studies have been conducted on predictions of CES. This study combines POI datasets with future climate variables under different scenarios into the Maxent model for forecasting the spatial and temporal distribution of CES, which provides strong support for future decision-making. The results indicate that: (1) Under the SSP126 and SSP585 scenarios, the CES values in the northern, western, central, and northeastern parts of the study area are relatively high, while those in the southwestern, southern, and southeastern parts are relatively low. (2) Under the SSP126 scenario, the total CES shows an increasing trend from 2021 to 2040, but slightly declines from 2061 to 2080. In contrast, under the SSP585 scenario, the total CES significantly decreases from 2021 to 2040, especially in the provinces of Guizhou, Hunan, Zhejiang, and Anhui. (3) Temperature has a significant impact on CES predictions, with the annual mean temperature (Bio1) positively correlated with total CES, contributing between 0.75 and 0.78 to the distribution of CES across different years and scenarios. Additionally, the maximum temperature of the hottest month (Bio5) and the mean temperature of the wettest quarter (Bio8) also significantly influence CES under different scenarios and years. These findings reveal the regional characteristics and variations in CES distribution under different climate scenarios, providing crucial scientific evidence for future policy-making, resource management, and climate adaptation strategies. They also offer important insights into the impact of global climate change on ecosystems and human society, serving as a valuable reference for future national decision-making.

Keywords Climate change, Cultural ecosystem services, Prediction

In recent years, global climate change has posed significant environmental challenges, greatly impacting human society and natural ecosystems. As part of the ecosystem, cultural ecosystem services (CES) have become particularly important in this context[1]. CES differ from other ecosystem services as they encompass intangible and non-material benefits, primarily manifested in cultural identity, aesthetic value, education and research, and community interaction[2]. CES help people construct cultural identities through language, customs, beliefs, and lifestyles, which, though intangible, are crucial components of personal and collective identity. Natural landscapes and biodiversity, serving as aesthetic values, provide humans with non-material aesthetic experiences and cultural enlightenment[3]. Ecosystems offer extensive opportunities for education and research, enabling people to engage in non-material education and research through field investigations, scientific studies, and the establishment of nature reserves[4]. CES can also enhance social interaction; beautiful natural landscapes and traditional cultural festivals attract tourists, fostering recreational tourism activities and promoting local economic development, which is another manifestation of non-material cultural services[5]. Most studies have focused on the assessment of material ecosystem services such as water resources and agricultural output, while quantitative research on non-material benefits such as cultural identity, aesthetic value, and community interaction is relatively scarce. Additionally, there is a shortage of studies regarding the spatiotemporal evolution

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characteristics of CES under multiple future climate scenarios. Therefore, this paper aims to fill this research gap and provide a more comprehensive reference for future policy-making and resource management.

A number of scholars have undertaken a range of explorations of CES with corresponding results in both theory and practice[6,7]. Fish et al. explored the theoretical challenges posed by understanding ecosystems as cultural objects and understood CES and associated benefits in terms of environmental spaces and cultural practices resulting from human-ecosystem interactions[8]. Tugjamba et al. interview group discussions and household surveys to understand what are the main CESs that Mongolian pastoral nomads rely on, and explored the local impacts of CES by combining historical and cultural heritage, religion, and landscape values relevant to the well-being of residents[9]. Ryfield et al. examined the sense of place as a category of CES, emphasizing that the sense of place is a material phenomenon, which contrasts with CES's immateriality and intangibility, calling for the conceptualization of CES to form a more practical approach to assessing CES[10]. Roldan et al. provide an economic valuation of the CES of the Bay of Matanzas, arguing that the bay is an economically productive system that is also capable of generating CES, which provides estimable benefits to its inhabitants[11]. Lee et al. used text mining as a tool to quantify the characteristics of local CES expressed by local residents during a workshop. The most frequently used keywords in the text were selected and factors analyzed for each ecological resource to explain the characteristics of the CES provided by each ecological resource[12]. Görmüs et al. developed a cultural route in the study area using corridor and network analysis in GIS software, aiming to establish good links between ecosystem services and cultural routes, and evaluated the developed cultural route[13]. Thiele et al. developed a 'CESs of River Landscapes' framework for the spatial assessment of CES in German river landscapes and suggested that the framework is suitable across multiple levels and is capable of replicated[14]. In summary, current research on CES has covered theoretical exploration and practical application. However, there is still an important research gap, i.e., relatively few research concerning the effects of climate change on CES under different future scenarios. As climate change has far-reaching impacts on ecosystems and human activities, it is crucial to understand and predict the evolution and response of CES under different climate scenarios.

Only a few scholars have explored the impact of climate change on CES. Mucioki et al. examined the relationship between plants and indigenous peoples, identifying the CES benefits derived from indigenous management and the collection of important cultural plants, and further investigated how CES changes according to climate variations[15]. Manley et al. discussed what innovative tools and information can surmount the limitations of CES charting and simulating, using crowdsourced data and artificial intelligence methodologies to chart and represent leisure activities birdwatching to assess potential socio-ecological relationships and the consequences of impending climate and ecological alterations[16]. Markkula et al. explored the repercussions of climatic shifts on habitats, provisioning, and CES, showing that climate warming primarily has negative impacts on ecosystems and traditional livelihoods, with the most profound negative impacts on bogs and degraded ecosystems[17]. Additionally, more scholars have focused on the interactions between climate change and ecosystem services (ES). Bremer et al. developed a process to assess the trade-offs and synergies of ES under different land-use scenarios and climate change, considering water, fire, biodiversity, and cultural values as key factors in decision-making[18]. Watson et al. simulated 20 climate scenarios using general circulation models under four IPCC Representative Concentration Pathways, combining the mapped global ES with these scenarios to determine the locations and proportions of global ES in the transition of climate classes[19]. Hua et al. revealed the complex spatial associations between ES and climate drivers, providing a basis for optimizing local response strategies in the context of global warming[20]. Gutsch et al. simulated forest growth, carbon, and water cycles across Germany's forest regions until 2045, driven by national forest inventory data, under natural conservation, biomass production, and baseline management strategies combined with a series of climate scenarios[21]. Although previous studies have explored the impacts of climate change on ES and CES at various levels, most of the existing research has focused on natural ecosystems or used traditional methods for analysis. However, systematic studies on the spatiotemporal distribution predictions of CES and their relationship with future climate variables, especially under different scenarios, are still lacking.

Given the intangible and immaterial nature of CES, researchers are endeavoring to explore more effective assessment methods. This study introduces POI as a data source for revealing the relationship between CES and human well-being and predicting the future distribution of CES through Maxent modeling. The benefits of POI data in showing the relationship in between CES and human well-being are made it possible for to be highlighted[22]. POI information can provide beneficial info that reflects the straight influence of CES on human wellness. These POI information consist of historic and social heritage, places of worship, landscape worths, and so on, which are necessary aspects covered by CES. By assessing and incorporating these POI data, we can better understand the favorable influences of CES on the every day lives and physical and psychological wellness of area residents[23]. Additionally, POI data can likewise assist us evaluate the function of CES in the community economy to make sure that we can better comprehend the economic value of CES and give details plan recommendations for decision-makers[24]. the Maxent version is uniquely suited to combine POI data with environment variables to predict the future circulation of CES. Compared to other conventional ecological versions, the Maxent version has the ability to leverage a big amount of geographic distribution data and ecological variables, which enables it to offer more precise and reputable forecasts. By integrating POI data and climate variables, the Maxent model has the ability to trace the main vehicle drivers of CES distribution and visualize and predict the prospective distribution of CES in the future. This provides an essential recommendation point for decision-makers to develop techniques for CES defense and administration under different environment circumstances. The POI information and Maxent model made use of in this study have distinct advantages over various other information and versions[25]. Firstly, making use of POI data allows us to evaluate the impacts of CES on human well-being in a more user-friendly and comprehensive means, resulting in a better understanding of the social and economic value of CES. Second, the use of the maxent version makes full use of massive geographical information and environmental variables, enhancing the precision and confidence of the predictions[26]. This mix of information resources and approaches will offer new viewpoints and devices for CES conservation, management, and planning.

This paper assesses the circulation of CES in the southern sloping area under various future circumstances of climate modification and analyzes the influence of climate variables on CES. As one of the vital eco-friendly practical locations in China, the southern uneven region is abundant in natural and human resources, and at the same time faces significant population pressure and environmental challenges. An extensive research of CES in the southern hilly area can a lot more precisely comprehend the environmental and cultural values of the area and give scientific support for its lasting development. In addition, with the aggravation of global climate adjustment, the preservation and monitoring of CES has progressively ended up being a warm issue worldwide. With the results of this research study, we can better recognize the vulnerability and flexible ability of CES under different climate scenarios, and offer recommendations for the solution of plans and measures to resolve climate modification. Meanwhile, this research likewise offers methods and ideas for CES study in other areas, and supplies experience and referral for CES protection and monitoring on a global range.

Materials and methods

Overview of the study area

The southern hilly region is primarily located in the southern part of China (Fig. 1). This area boasts not only rich natural landscapes but also unique cultural landscapes and social systems. The cultural landscape of this region includes centuries-old historical relics, ancient villages, and traditional architecture. Interwoven with natural and cultural landscapes, there are numerous reserves and parks that not only showcase natural beauty but also reflect cultural and aesthetic values. Various forest parks and nature reserves in the area are rich in vegetation, including primitive forests, bamboo groves, and pine forests, forming unique ecosystems. In terms of traditional

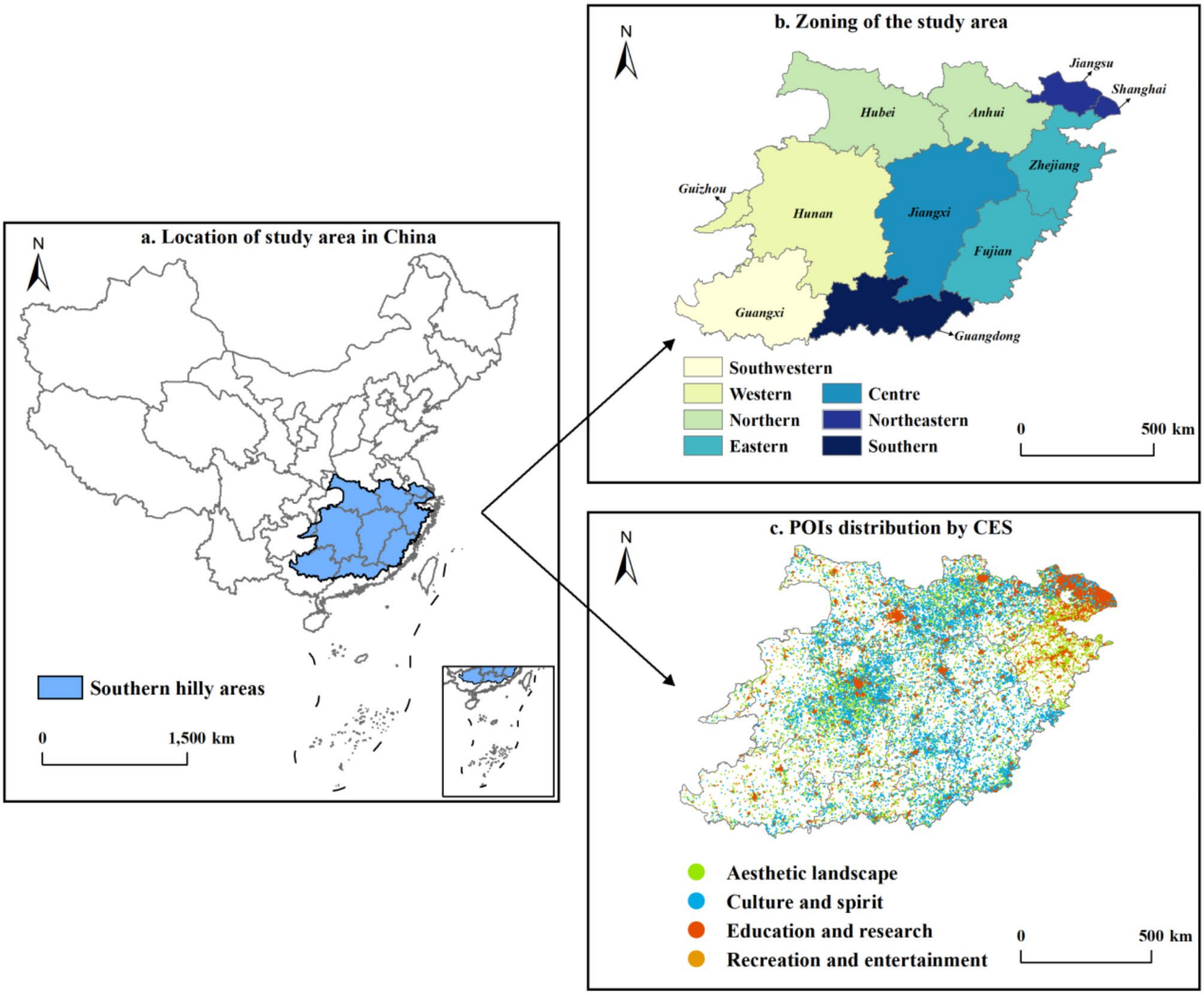

Fig. 1. Overview of the study area. *Note*: Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

culture, the ancient villages and rural landscapes, such as Yao villages, still retain their ancient lifestyles and architectural styles, attracting many tourists and researchers to explore. Numerous temples and religious sites are scattered throughout the southern hilly region. For instance, the Taoist sacred site of Mount Longhu and various Buddhist temples have become important destinations for tourists and believers alike. Additionally, many historical relics such as tombs and ancient burial sites are not only key focuses of cultural preservation but also serve as resources for research and education. The region also offers abundant opportunities for tourism and outdoor activities, such as hiking, camping, and water sightseeing. Numerous attractions, such as highly rated scenic spots, gardens, and lakes, provide aesthetic and spiritual enjoyment. For example, distinctive grasslands and alpine meadows, wetlands, and artistic lawns have become popular spots for sightseeing and photography. Educational and research-oriented CES are also widely present in the region. Several renowned universities and research institutions conduct extensive cultural and ecological studies here, encompassing topics such as ethnic culture, traditional architectural conservation and restoration, and ecological agriculture. Museums, science centers, and planetariums offer the public rich learning resources.

Moreover, the social system of the southern hilly region is distinctive. It is home to several ethnic minorities, including the Dong, Yao, Tujia, and Miao peoples. Their folk cultures, traditional festivals, and handicrafts not only enrich local culture but also provide important resources for CES. For example, annual traditional festival activities, ethnic music, and dance performances are not only integral parts of local residents' cultural life but also major attractions for tourists. In this multicultural context, studying the impact of climate change on the cultural ecosystem services of the region holds significant importance. This not only helps protect and inherit the unique cultural heritage but also provides scientific basis for future cultural tourism and sustainable development. This is of great reference value for the cultural preservation and planning of the region, as well as the sustainable development of China CES.

Data sources

The location of the CES is derived from the Gaode Maps POI dataset (Fig. 1), which is publicly accessible. Each POI has its own keywords. Considering CES types in the southern hilly regions and incorporating previous studies[26–29]. Various CES types were shown using the keywords in Table 1 (More detailed keywords are shown in Table A1), and the relevant POIs with their longitude, latitude, description, and annotation were extracted through the Gaode application programming interface. The dataset required coordinate transformation and data cleaning to ensure compatibility and consistency. In this process, 47,578 POIs representing the total CES for December 2022 were obtained, including 12,880 POIs in the aesthetic landscape category, 15,920 POIs in the cultural and spiritual category, 10,381 POIs in the education and research category, and 8,397 POIs in the recreation and entertainment category. The climate variable data used in this study, as shown in Table 2, are accurate to 1000 m. Climate variable data for all years (2021–2040, 2041–2060, 2061–2080) and all scenarios (SSP126 and SSP585) are derived from WorldClim (https://worldclim.org/data/cmip6/cmip6_clim30s.html). Specifically, the climate variable data are provided at a spatial resolution of 30 arc-seconds (approximately 1 km). We utilized the shared socioeconomic pathways (SSP) scenarios from the IPCC's sixth assessment report (AR6), namely SSP126: a low-carbon sustainable development pathway assuming significant global emission reductions, with greenhouse gas concentrations beginning to decline by the mid-21st century, and SSP585: a high-carbon fossil fuel dependency pathway assuming continued global reliance on fossil fuels, with increasing greenhouse gas concentrations. Using RStudio, we conducted a correlation analysis of 19 climate variables and selected environmental variables with a correlation greater than 0.7. Excluding highly correlated variables when the correlation between environmental variables exceeds 0.7 helps to reduce model complexity, minimize the effects of multicollinearity, and enhance model stability and explanatory power. Based on the contribution of these climate variables to predictions in CES and the correlations among these factors, this study excluded factors with low contributions and correlations greater than 0.7, ultimately retaining six climate factors (Bio1, Bio2, Bio5, Bio8, Bio10, Bio15).

Calculation of spatio-temporal prediction maps for various types of CES

The Maxent model was used to predict the CES distribution and the response curve of the model output was used to reflect the effect of each climate variable on the CES distribution. Maxentropy is a mathematical model for inferring the probability distribution of unknown information based on known incomplete information based on the theory of maximum entropy. Assuming that the probability distribution of the unknown region x is P(x) and the finite set of x in the study region is x, the entropy in the maximum entropy calculation is[30]:

Item 1	Item 2	Explanation	Keywords
Cultural ecosystem services	Aesthetic landscape	Through the display of natural and humanistic landscapes, it provides services for people's aesthetic enjoyment and spiritual nourishment	Scenic spots, gardens, grass, forest, pine, bamboo, apricot, plum; water, pools, mountains, fields, zoos
	Culture and spirit	To fulfill people's spiritual needs through transmitting and preserving cultural heritage and providing activities such as education and art	Traditional culture, religious beliefs, worship
	Education and research	To provide opportunities for people to learn and research, and to promote the transmission of knowledge, innovative development, and intellectual growth	Popularization of science, nature education, birdwatching, and research institutes
	Recreation and entertainment	To provide a diversity of recreational activities and leisure facilities to promote physical and mental well-being and social interaction	Mountain climbing, campsites, water sightseeing, underwater activities, horse racing, ice sports

Table 1. Categorisation of CES and keywords.

Code	Data name	Data sources
Bio1	Annual Mean Temperature/℃	WorldClim(https://worldclim.org/data/worldclim21.html)
Bio2	Mean Diurnal Range (Mean of monthly (max temp - min temp)) /℃	
Bio3	Isothermality (BIO2/BIO7) (×100)	
Bio4	Temperature Seasonality (standard deviation ×100)	
Bio5	Max Temperature of Warmest Month/℃	
Bio6	Min Temperature of Coldest Month/℃	
Bio7	Temperature Annual Range (BIO5-BIO6)/℃	
Bio8	Mean Temperature of Wettest Quarter/℃	
Bio9	Mean Temperature of Driest Quarter/℃	
Bio10	Mean Temperature of Warmest Quarter/℃	
Bio11	Mean Temperature of Coldest Quarter/℃	
Bio12	Annual Precipitation/mm	
Bio13	Precipitation of Wettest Month/mm	
Bio14	Precipitation of Driest Month/mm	
Bio15	Precipitation Seasonality (Coefficient of Variation)/mm	
Bio16	Precipitation of Wettest Quarter/mm	
Bio17	Precipitation of Driest Quarter/mm	
Bio18	Precipitation of Warmest Quarter/mm	
Bio19	Precipitation of Coldest Quarter/mm	

Table 2. Data sources for climatic variables.

Year	Type	Function combinations (FC)	Regularised multipliers (RM)	AICc	Average training AUC
2022	Default	LQPH	1	240.356	0.857
	Optimized	LH	4	0	0.936

Table 3. Parameter settings for model optimization.

$$H(P) = -\sum_{x \in X} P(x) \ln P(x) \quad (1)$$

The area under the curve (AUC) can be used as an indicator of simulation accuracy to judge the validity of the simulation. To maximize the model specifications, this study utilizes RStudio's ENMeval bundle, which gauges the goodness-of-fit of an analytical design by prioritizing parameters with smaller AIC worth[31]. In our examinations, the parameter combination chosen for the version is LH, and the regularisation multiplier (RM) value is 4. The variety of iterations in the criteria is readied to 10, the optimum number of repeatings is readied to 5,000, the output technique is chosen to be Cloglog, the outcome type of the data is "asc", and 25% of the distribution factors are chosen as the test readied to decrease the mistake brought on by the tasting variety. The location under the contour (AUC) values created by the design (Table 3) are all above 0.90, indicating that the CES distribution simulated by the Maxent version has high accuracy and accuracy.

Research ideas

This study selected the SSP126 (low carbon emission sustainable development pathway) and SSP585 (high carbon emission fossil fuel-dependent pathway) shared socioeconomic pathways and representative concentration pathways as two different climate scenarios. It utilized climate data from different future periods (2021–2040, 2041–2060, 2061–2080) as environmental variables. By combining these environmental variables with POI data classified by keywords (aesthetic landscape, education and research, culture and spirituality, recreation, and entertainment) and inputting both into the Maxent model, spatial prediction distribution maps for various types of CES are generated (Fig. 2). Furthermore, by merging the POI data representing the four types of CES (aesthetic landscape, education and research, culture and spirituality, recreation, and entertainment), and inputting the combined POI data along with the environmental variables into the Maxent model, a spatiotemporal distribution map of total CES is calculated and generated.

Results

Screening of climate variables prior to CES projections

In this study, the climate data for the period 2021–2040 under the SSP126 scenario was selected as the basis for analysis because its climatic characteristics align with the current climate conditions in China. Therefore, the CES distribution for 2021–2040 under the SSP126 scenario can be regarded as representative of the current CES status in China. This setting provides us with a reasonable baseline for comparing and evaluating the projected outcomes under different scenarios in subsequent sections. The contribution of the five filtered climate variables

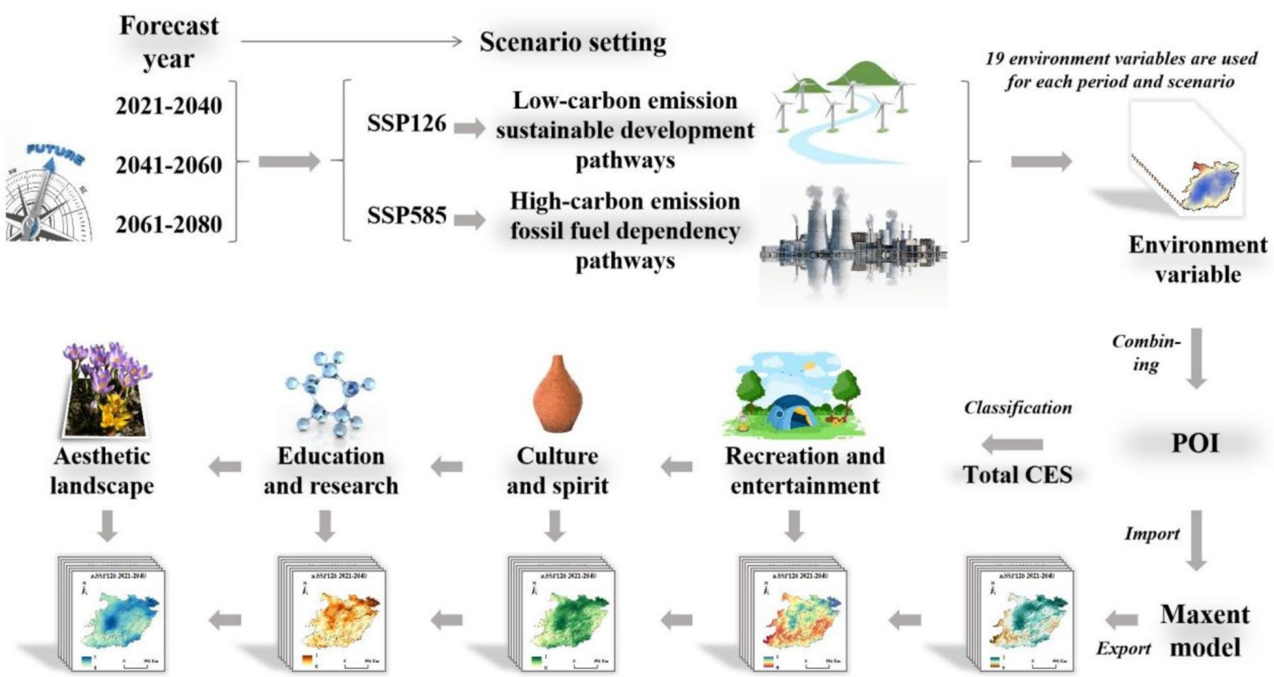

Fig. 2. Research idea chart.

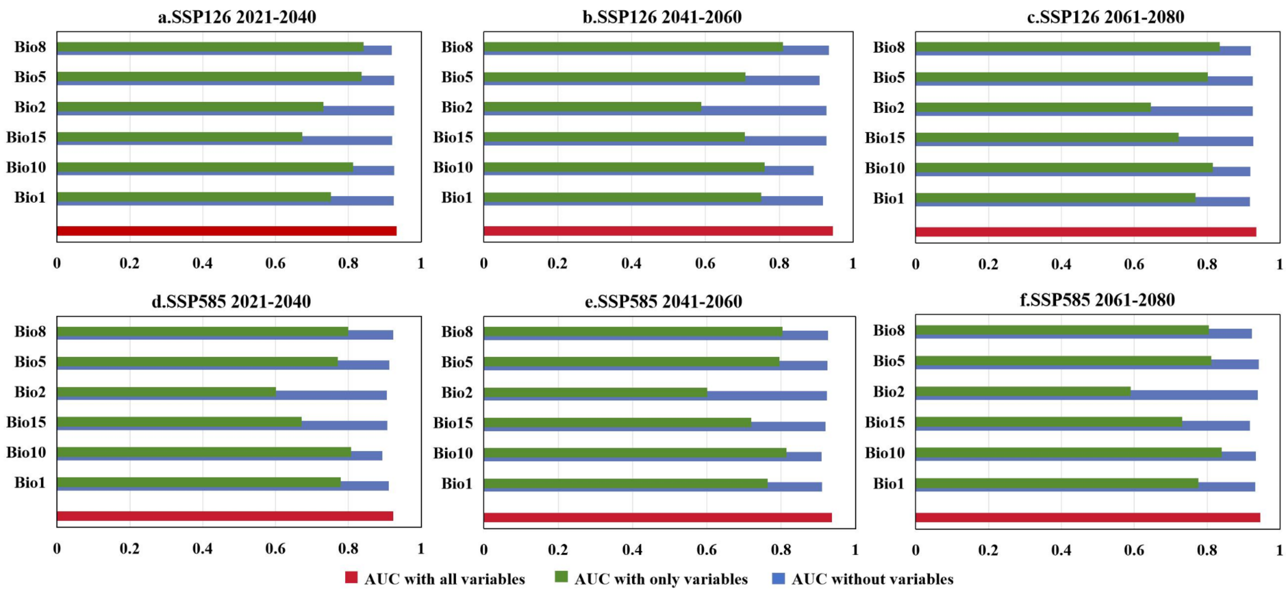

Fig. 3. Contribution of screened climate variables to total CES.

to the CES predictions is shown in Fig. 3. Overall, the prediction accuracies for all years and scenarios were higher than 0.9, indicating that the model predictions were accurate. Moreover, Bio8 (mean temperature of the wettest season), Bio10 (mean temperature of the hottest season), and Bio5 (maximum temperature of the hottest month) had the highest contribution to the CES prediction for all years and scenarios, whereas Bio2 (mean diurnal range) and Bio15 (seasonality of precipitation (coefficient of variation) had the lowest contribution to the CES prediction. This indicates that temperature has a significant effect on CES prediction.

Changes in aesthetic landscape CES

Under the SSP126 scenario (Fig. 4), the areas of high values for the aesthetic landscape category of CES are all concentrated in the western and northern parts of the research area in 2021–2080. From 2021 to 2040, there will be a few high-value areas of aesthetic landscapes CES to the east of Guangdong and south of Fujian, which will

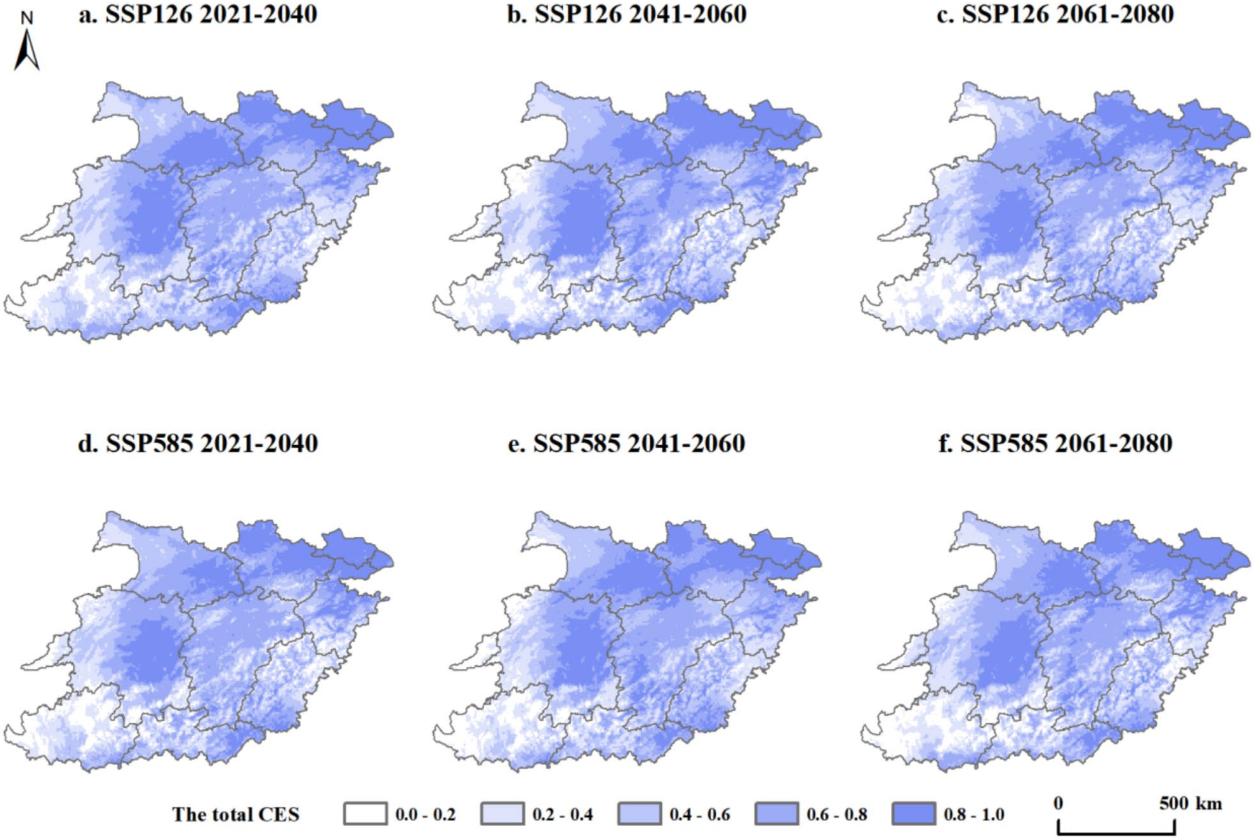

Fig. 4. Spatial distribution of CES in the aesthetic landscape category under different future scenarios. *Note*: The range of 0–1 indicates the distribution probability of various CES categories. A value closer to 0 indicates a lower distribution of CES, while a value closer to 1 indicates a higher distribution. The same applies to the following. Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

decrease from 2041 to 2060. The same type of CES will also decrease in Hunan, Anhui, and Hubei provinces. Compared to 2041–2060, the aesthetic landscape CES across the entire study area will show an increasing trend from 2061 to 2080. Under the SSP126 scenario, the aesthetic landscape CES in Hunan and Zhejiang provinces will significantly decrease from 2021 to 2040. In contrast, under the SSP585 scenario, the aesthetic landscape CES in Jiangxi, Hunan, and Zhejiang provinces will increase from 2041 to 2060. From 2061 to 2080, under the SSP585 scenario, the aesthetic landscape CES in Hunan, Hubei, and Anhui provinces will decrease, while it will increase in Jiangxi and Zhejiang provinces.

Changes in the CES category of culture and spirituality

Under the SSP126 scenario, the cultural-spiritual CES has a large distribution of high values in the western, northern, northeastern, central, and eastern parts of the research area, with less distribution of this category in the southwestern and eastern parts of the research area (Fig. 5). From 2041 to 2060, the cultural and spiritual CES in the Guangxi Zhuang Autonomous Region further decreased, while that in Zhejiang Province increased. From 2061 to 2080, the cultural and spiritual CES in provinces such as Guangxi, Jiangxi, and Zhejiang increased, with no significant trends observed in other regions. Compared to the SSP126 scenario, in the SSP585 scenario, the cultural and spiritual CES in southwestern regions such as Guangxi and Guangdong increased from 2021 to 2040, while changes in other areas were not significant, indicating that cultural and spiritual CES are less affected by rising carbon dioxide concentrations. Under the SSP585 scenario, from 2041 to 2060, the high-value areas of cultural and spiritual CES in provinces such as Guizhou, western Hunan, and Hubei showed a trend of eastward contraction. By 2061 to 2080, the CES in Guizhou, western Hunan, northern Hubei, and northern Jiangxi further decreased.

Changes in the education and research CES category

The SSP126 scenario has an overall distribution of high values for the education and research category of CES in the west, north, center, and northeast of the research area (Fig. 6). Compared to the period from 2021 to 2040, the education and research-related CES in regions west of Hunan and in Anhui Province decreased between 2041 and 2060. In contrast, there was a further decline in education and research CES in Guangxi and Guangdong Provinces from 2061 to 2080 compared to the 2041–2060 period. Other regions did not show any significant

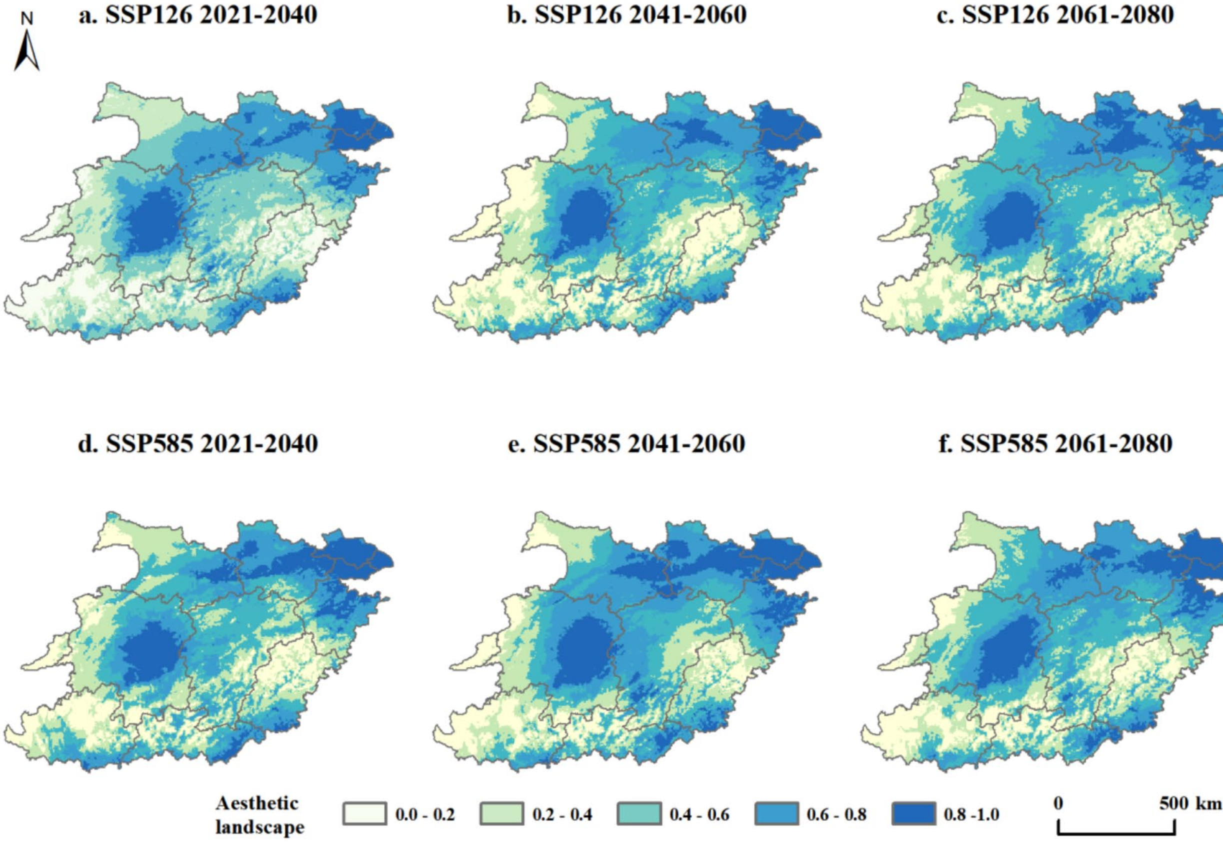

Fig. 5. Spatial distribution of cultural and spiritual CES under different future scenarios. *Note*: Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

trends. Compared to the SSP126 scenario, in the SSP585 scenario during 2021–2040, the education and research CES in Hubei and Anhui Provinces decreased, while it increased in Guizhou, Hunan, and Jiangxi Provinces. By 2041–2060, the education and research CES decreased in Hunan and Jiangxi Provinces and increased in Hubei and Anhui Provinces. From 2061 to 2080, the education and research CES in Hunan, Jiangxi, and Hubei Provinces exhibited a shrinking trend, decreasing towards the east.

Changes in the recreation and entertainment CES category

Under the SSP126 scenario, the recreation and entertainment category CES as a whole exhibits high values east of the west, center, north, and north-east of the research area, and low values in the south-west, south, and east of the research area (Fig. 7). Compared with the period from 2021 to 2040, the recreational and entertainment CES in provinces such as Guizhou, Jiangxi, Hubei, Guangdong, and Fujian shows a decreasing trend from 2041 to 2060. By 2061 to 2080, provinces like Guizhou, Hunan, and Zhejiang experience a slight increase in recreational and entertainment CES. Under the SSP585 scenario, compared to the SSP126 scenario, the recreational and entertainment CES across the entire study area from 2021 to 2040 exhibits varying degrees of decline, indicating that increased carbon dioxide concentrations significantly reduce recreational and entertainment CES. Under the SSP585 scenario, from 2041 to 2060, this type of CES increases in provinces such as Guizhou, Hunan, Jiangxi, Hubei, and Anhui, but decreases in Zhejiang. By 2061 to 2080, the recreational and entertainment CES across the entire study area will further decline.

Spatio-temporal evolution of total CES in different scenarios

Overall, under the SSP126 and SSP585 scenarios, the high total CES value areas are primarily distributed in the northern, western, central, and northeastern parts of the study area, while the low-value areas are mainly located in the southwestern, southern, and southeastern parts of the study area (Fig. 8). Compared to the period of 2021–2040, under the SSP126 scenario from 2041 to 2060, there is a significant increasing trend in the total CES value in the northern parts of Jiangxi, Zhejiang, and Anhui provinces, as well as in the southeastern part of Guangdong province. Conversely, the total CES in Guangxi and the western part of Guangdong province shows a decreasing trend. By 2061–2080, the total CES in the southern parts of Guizhou, Jiangxi, Anhui, and Zhejiang will decrease again. Under the SSP585 scenario, compared to the SSP126 scenario, the total CES in the entire study area decreases to varying degrees from 2021 to 2040. During 2041–2060, the total CES in Hubei, Anhui,

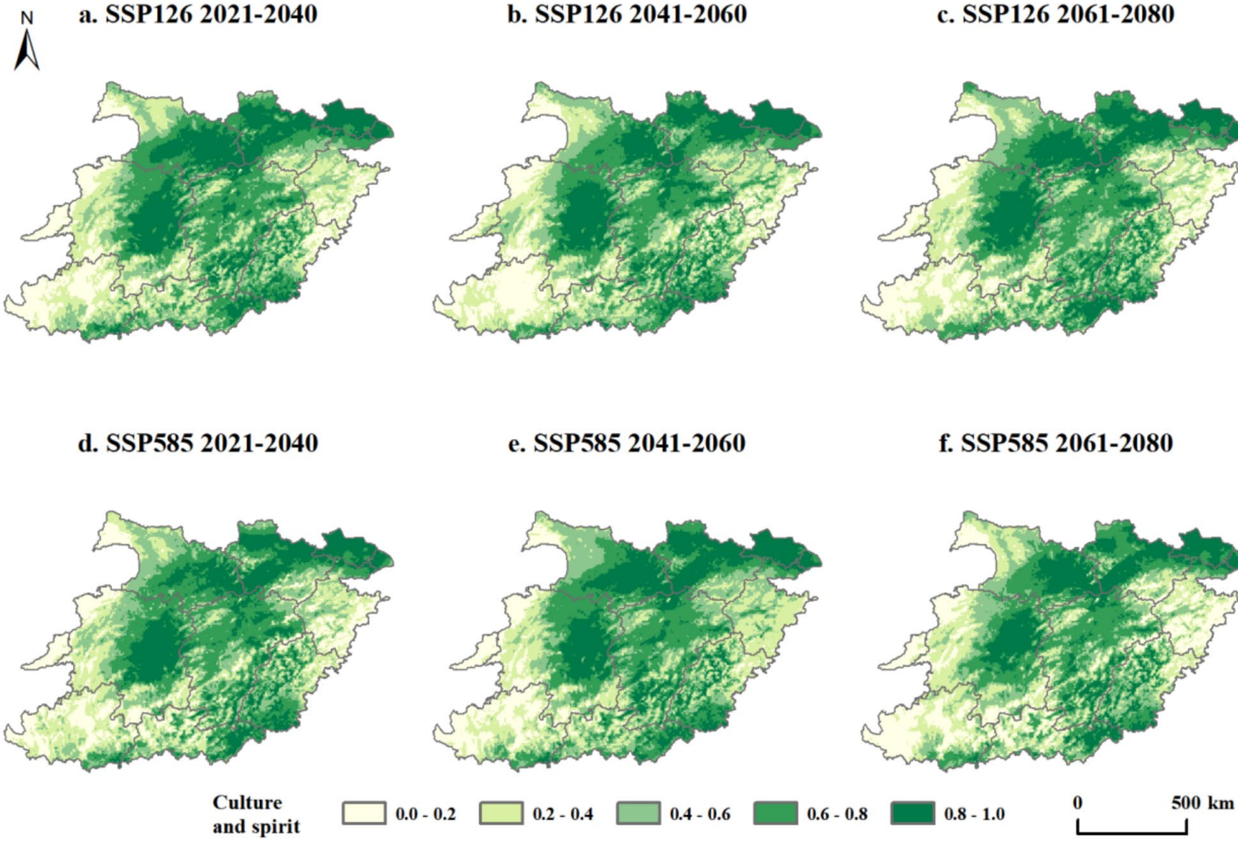

Fig. 6. Spatial distribution of CES in the category of educational research under different future scenarios. *Note*: Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

and Jiangxi provinces shows an increasing trend. By 2061–2080, the total CES in the northern parts of Guizhou, Hunan, and Zhejiang, as well as in Anhui province, will decrease once more.

Impact of climate variables on CES

Overall, total CES also tends to increase under different scenarios and years as Bio1 (mean annual temperature) increases, but at different rates (Fig. 9). It is important to note that in the SSP585 scenario, the initial value of Bio1 on CES is higher and constant from 2021 to 2040, and as Bio1 increases when Bio1 > 20.35 °C, total CES increases. As Bio2 (mean diurnal range) increases, total CES shows an overall trend of increasing and then decreasing across scenarios and years, with the first small peak of Bio2 occurring between 6.75 and 8.10, the second small peak between 9.45 and 10.80, and the SSP585 scenario having significantly higher peaks than the SSP126 scenario across years. At Bio5 (maximum temperature of the hottest month) < 32.85 °C, the effect on CES is relatively smooth across scenarios and years, and when Bio5 > 32.85 °C, CES first increases sharply to reach a peak and then decreases sharply. In 2021–2040, Bio8 (the average temperature of the wettest quarter) has a similar effect on CES in the SSP585 and SSP126 scenarios, whereas, in 2041–2080, CES consistently increases with the increase of Bio8 in the SSP126 scenario, but shows a decreasing and then an increasing trend of CES with the increase of Bio8 in the SSP585 scenario. For Bio10 (the average temperature of the hottest quarter), CES shows a similar trend with increasing Bio10 for different scenarios from 2021 to 2060, decreasing and then increasing in both 2021–2040 and gradually increasing in 2041–2060. In 2061–2080, the initial value of Bio10 for the SSP126 scenario was significantly higher than that of the SSP585 scenario and showed different trends of influence on CES. With the increase of Bio15 (precipitation seasonality (coefficient of variation)), the total CES all showed an increasing and then decreasing trend, but the nodes at which the changes occurred varied across years and scenarios.

Discussion

Spatio-temporal evolution of CESs based on POI data and future climate scenarios

We utilized the open digital mapping service platform "Gaode Map" to search for keywords and obtain POI data for various CESs. This approach is more reflective of public sentiments and preferences compared to traditional remote sensing methods[32]. Existing research predominantly uses remote sensing imagery for CES assessment. For instance, Thiele et al. (2020) developed the "River Landscape CESs" framework[14], which, while highly

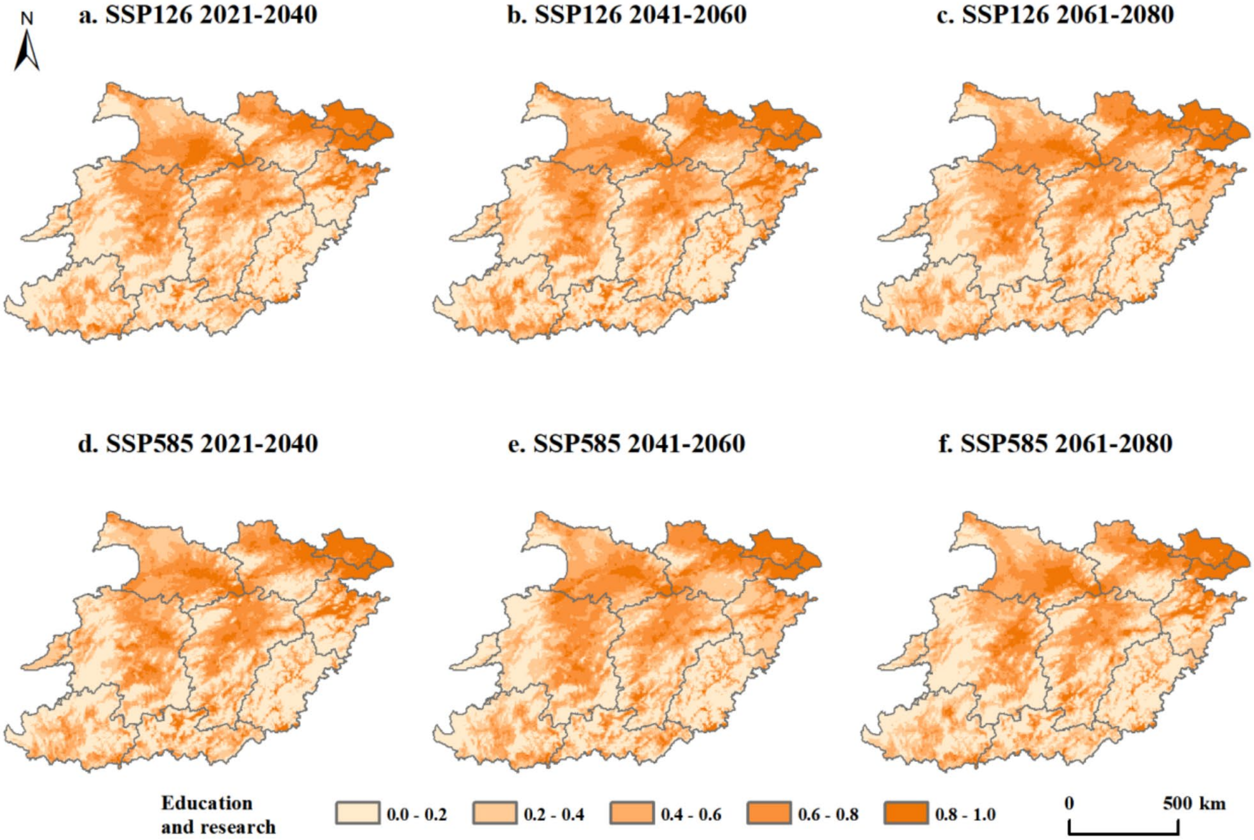

Fig. 7. Spatial distribution of future recreation and entertainment CES under different scenarios. *Note*: Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

accurate in spatial assessments, falls short of capturing human subjective perceptions. Hence, our method has a certain advantage in data quality. However, it also has limitations, such as the inability of Gaode Map to cover some POI information in certain regions and the instability of network connections that may reduce the number of queries[33]. To address these issues, future efforts could consider combining field survey data and machine learning techniques to extract more features from multiple data sources, thereby improving the accuracy of prediction results.

In terms of the spatial distribution of different types of CES, this study found that the western and northern parts of the southern hilly areas are more suitable for the development of aesthetic landscapes, while the central and northeastern parts exhibit high-value clusters for education and research. This is consistent with Ryfield et al., who emphasized that a 'sense of place' is a material phenomenon, contrasting with the immaterial and intangible nature of CES[10]. Additionally, the assessment process developed by Bremer et al. indicates that the trade-offs and synergies of ecosystem services under different land use scenarios and climate change are significant[18], which aligns with this study's findings on the spatial distribution changes of CES under different scenarios. In the SSP126 scenario, cultural and spiritual CES in provinces such as Guangxi, Jiangxi, and Zhejiang show an upward trend from 2061 to 2080, likely due to increased environmental awareness and government policy guidance, leading to greater emphasis on cultural preservation and ecological construction in these areas.

In terms of education and research CES, the western, northern, central, and northeastern regions of the southern hilly area have higher educational resources and research investments, which are beneficial for the advancement of education and research fields. However, it is anticipated that in the coming decades, the educational and research CES in the western and northern regions will experience a certain degree of decline. This could be related to changes in economic and social development paths, adjustments in resource allocation, and population movements. Similar to the changes in CES benefits brought by indigenous management and the collection of important cultural plants studied by Mucioki et al. (2021), we also found significant variations in CES across different regions and scenarios[15]. In terms of recreational and entertainment CES, this study found that the more developed areas in the central, northern, and western parts of the study area possess high-quality tourism resources and related hubs, which can promote the development of recreational and entertainment CES. However, under the SSP585 scenario, recreational CES is projected to decrease to varying degrees from 2021 to 2040, indicating that the increase in CO_2 concentration significantly reduces recreational CES. This may be attributed to the adverse effects of climate change on the tourism industry, such as high temperatures and

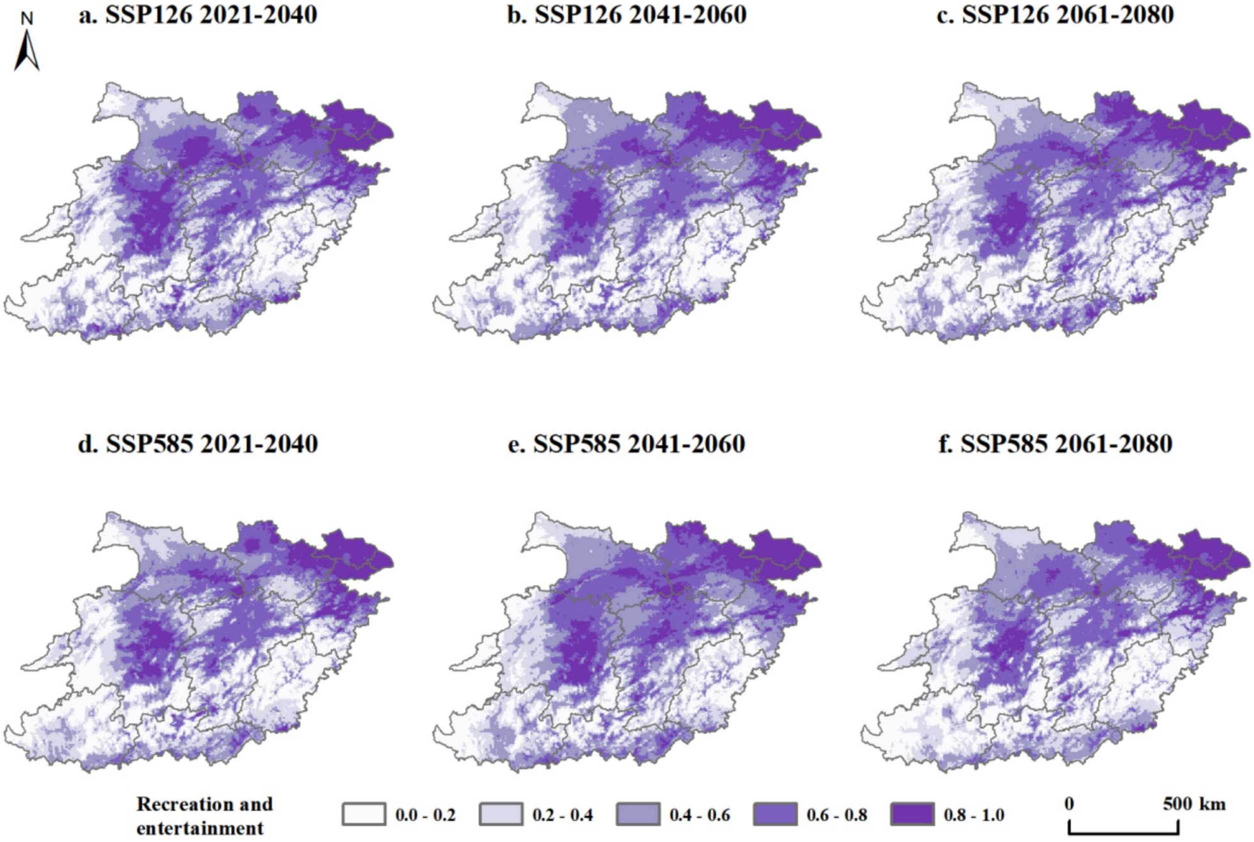

Fig. 8. Spatial distribution of total CES under different future scenarios. *Note*: Figure was generated using ArcGIS 10.8 (Esri, URL: https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview).

extreme weather conditions, as well as increased environmental management requirements, which reduce the occurrence of recreational activities.

Climate change has a substantial impact on the total CES circulation in the southern hilly regions. Under the SSP126 low GHG emissions scenario, the extent of warming is smaller, leading to lesser adverse effects on sensitive environments. On the other hand, in the SSP585 high GHG emissions scenario, the total CES in the entire study area shows varying degrees of decline, indicating a greater impact of climate change on sensitive environments. The circulation of total CES in various fields within the study area is also influenced by the processes of economic and social development. For example, in the SSP126 scenario, the total CES in the eastern, western, northeastern, and southeastern regions shows an upward trend, similar to the method used by Lee et al. in quantifying local CES characteristics through text mining, indicating that these regions have undertaken more environmental protection actions to achieve sustainable growth under this scenario[12]. This study provides a new perspective by using POI data and the Maxent model to predict the spatial distribution of CES under different future climate scenarios, differing from existing research in both theory and practice. This not only fills the gap in current research but also provides a significant reference for future policy-making and resource management.

Multiple factors affecting spatio-temporal variation in CES

The fluctuations in CES across different time periods under the same scenarios may involve multiple complex factors. Temperature and precipitation are the primary climatic factors, with the annual mean temperature (Bio1) being found to have a significant impact on total CES. Under the SSP126 and SSP585 scenarios, the patterns of temperature change vary across different periods. Specifically, the temperature conditions during 2041–2060 may be favorable for the northern parts of Jiangxi, Zhejiang, and Anhui provinces, as well as the southeastern part of Guangdong province, leading to an increase in CES in these areas. However, during 2061–2080, temperatures may exceed a certain threshold, causing CES to decline once again in these regions. This aligns with the findings of Mucioki et al. (2021), which indicate that climate change has a significant impact on ecosystem services during specific periods[15]. Additionally, changes in precipitation will also affect the spatial distribution and temporal evolution of CES. Changes in land use types, such as urban expansion[34], shifts in agricultural land[12], and the establishment of nature reserves[14], directly influence CES supply. For example, during 2041–2060, Hubei, Anhui, and Jiangxi provinces may experience less urban expansion and more ecological protection, leading to an increase in CES. However, by 2061–2080, changes in land use patterns in these regions may result in a decrease in CES. During 2041–2060, economic development may boost tourism

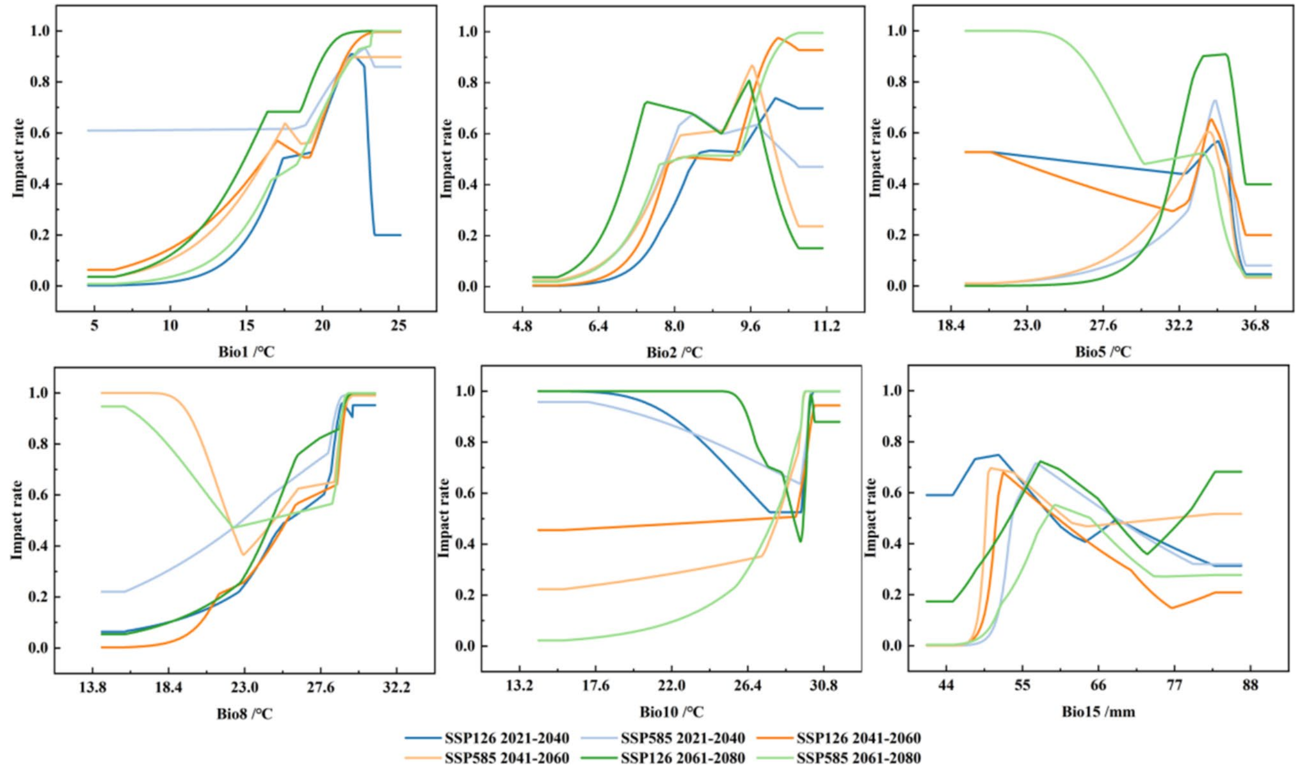

Fig. 9. Impact of changes in climate variables on total CES.

and cultural activities, particularly in Hubei, Anhui, and Jiangxi provinces, leading to an increase in CES. By 2061–2080, prioritizing economic development could result in the overexploitation of natural resources and increased environmental pressures, leading to a decline in CES.

The total CES is influenced by various climatic variables. There is a positive correlation between the total CES and Bio1 (annual mean temperature), as higher temperatures may favor vegetation growth and ecosystem functions, thereby providing more CES. Bio2 (mean diurnal range), Bio5 (max temperature of the warmest month), and Bio8 (mean temperature of the wettest quarter) show a certain trend in their impact on the total CES, where their influence first increases and then decreases with the rise in climatic factors. This may be because moderate temperatures and humidity can enhance the provision of ecosystem services, but values that are too high or too low could adversely affect the ecosystem. The study by Markkula et al. also indicated that there is a threshold value concerning the impact of climate change on ecosystem services[17]. Under different circumstances, the extent to which these climatic variables affect the total CES varies. Temperature changes and temperature thresholds under different scenarios might lead to this variation. As moderate seasonality in precipitation favors ecosystem stability, too much or too little variability can lead to a decline in the functionality of ecosystem services. Therefore, the coefficient of variation of precipitation seasonality (Bio15) shows a trend of first increasing and then decreasing under different years and situations. Considering the impact of temperature on CES, the government should take measures to reduce GHG emissions, especially under the SSP585 scenario. This might include strengthening energy transition, promoting renewable resources, and efficiently utilizing energy. This study enhances our understanding of the vulnerability and resilience of CES under different climate scenarios and provides recommendations for measures to address climate change.

Recommendations and prospects

In the western, northern, and northeastern parts of the study area, efforts should be made to enhance the protection and development of aesthetic landscapes. These regions should be developed into tourist attractions, providing aesthetic experiences that integrate with the natural environment to attract visitors and boost the local economy. The central and eastern parts of the study area can meet people's expectations and spiritual needs for cultural heritage through the construction of cultural facilities and the organization of cultural activities. Future CES research should focus on the development of various CES, increasing people's awareness and appreciation of nature, culture, education, and learning[35]. The southern hilly areas, with their unique ecological and social value, hold significant importance for CES research both nationally and globally. The rich social heritage and ethnic customs of this region are essential foundations for the exchange of cultural diversity at both the national and global levels. In future CES planning, special attention should be given to the protection and circulation of social heritage, promoting social exchange and collaboration, and enhancing the understanding and appreciation of culture[36].

When planning for the southern hilly regions, it is necessary to consider the impact of rising temperatures and changes in precipitation and to take appropriate management measures to address precipitation changes under different scenarios to protect water resources and ecosystems and promote sustainable development. Compared to other types of ecosystem services, CES are intangible, subjective, and difficult to quantify. Using POI as the basis for CES mapping provides new opportunities for CES research. These POIs have wide coverage, fast data updates, and rich varieties, deeply reflecting human preference information and holding significant research value. The Maxent model we used incorporates POI quality that reflects human preferences and appropriately considers the impact of climate variables on CES demand, making the predicted CES scientifically valid. However, we have also identified some issues, such as the relative abundance of POI data in urban areas and the scarcity of data collection resources in remote rural areas, leading to difficulties in POI data collection. Additionally, POIs cannot completely replace field surveys to reflect actual CES demand, which remains a potential need. In the distribution prediction of CES, considering only climate factors as environmental impact factors is not comprehensive enough. In fact, CES is influenced by a broader range of integrated factors. In future research, we will further incorporate more factors into our analysis and promote the development of CES research methodologies. We can also improve the Maxent model to enhance the accuracy and completeness of predictions. Despite some problems and challenges, the POI-based CES research methodology provides new possibilities and concepts. Through continuous improvement and innovation, we believe that we can better understand and assess CES, providing scientific support for global ecological environment protection and sustainable development.

Conclusion
This paper utilizes the Maxent model to analyze the spatial and temporal distribution of CES under different future climate scenarios, as well as the impact of climate variables on the overall CES. The results indicate that under the SSP126 and SSP585 scenarios, the overall CES is higher in the northern, western, central, and northeastern regions of the study area, and lower in the southwestern, southern, and southeastern regions. Under the SSP126 scenario, from 2021 to 2080, the total CES in the western, eastern, northern, and southern parts of the study area increases, while it decreases in the southwestern and southern parts. The SSP585 scenario shows a decrease in the total CES in the western and northern parts. Among the climate variables, temperature-related factors have the greatest impact on overall CES across different forecast years and scenarios, with the annual mean temperature (Bio1) showing an overall positive correlation with total CES. As the maximum temperature of the warmest month (Bio5) and the mean temperature of the wettest quarter (Bio8) increase, their impact on total CES also grows. The future development of CES in the hilly areas of the south and across the nation will face challenges such as climate change. Flexible strategies, enhanced monitoring, and protection measures are needed to ensure the sustainable development of CES.

Data availability
Some data for this study are not published due to [non-publication of data], but may be obtained from the corresponding authors upon reasonable request. Publicly available data Code Data name Data sources Bio1 Annual Mean Temperature/℃ WorldClim(https://worldclim.org/data/worldclim21.html) Bio2 Mean Diurnal Range (Mean of monthly (max temp - min temp)) /℃ Bio3 Isothermality (BIO2/BIO7) (×100) Bio4 Temperature Seasonality (standard deviation ×100) Bio5 Max Temperature of Warmest Month/℃ Bio6 Min Temperature of Coldest Month/℃ Bio7 Temperature Annual Range (BIO5-BIO6)/℃ Bio8 Mean Temperature of Wettest Quarter/℃ Bio9 Mean Temperature of Driest Quarter/℃ Bio10 Mean Temperature of Warmest Quarter/℃ Bio11 Mean Temperature of Coldest Quarter/℃ Bio12 Annual Precipitation/mm Bio13 Precipitation of Wettest Month/mm Bio14 Precipitation of Driest Month/mm Bio15 Precipitation Seasonality (Coefficient of Variation)/mm Bio16 Precipitation of Wettest Quarter/mm Bio17 Precipitation of Driest Quarter/mm Bio18 Precipitation of Warmest Quarter/mm Bio19 Precipitation of Coldest Quarter/mm Other data Obtaining other data could contact corresponding author with E-mail: guoluo@muc.edu.cn.

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Author contributions
Chang You: Supervision, Writing – review & editing, Investigation, Resources. Hongjiao Qu: Formal analysis. Lun Yin: Formal analysis. Luo Guo: Resources, Validation, Supervision, Writing – review & editing.

Declarations

Competing interests
The authors declare no competing interests.

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