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Review article

The study on the spatiotemporal changes in tradeoffs and synergies of ecosystem services and response to land use/land cover changes in the region around Taihu Lake

Jinglong Du [a], Yao Gong [a], Xu Xi [a,*], Changchang Liu [a], Chengyang Qian [b], Bao Ye [b]

[a] School of Geography Science and Geomatics Engineering, Suzhou University of Science and Technology, Suzhou, 215000, China
[b] Suzhou Industrial Park Surveying Mapping and Geoinformation Co. Ltd, Suzhou, 215000, China

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ABSTRACT

Interactions among ecosystem services (ESs) involve tradeoffs and synergies. Quantitatively studying the trade-off and synergistic relationships between land use/land cover change (LULC) and ESs enables the precise identification of the quality status and driving factors of ESs within the region, which is crucial for rational resource allocation and environmental protection. In this study, the spatial and temporal change characteristics of the three ESs of carbon storage (CS), soil retention (SR) and habitat quality (HQ) are explored by using the InVEST model and GIS technology in the region around Taihu Lake, and the tradeoffs and synergies among the three are determined based on the difference comparison. The results indicate that: (1) The study area has a downward trajectory in CS and HQ from 1990 to 2020, while SR experiences some fluctuations. The spatial distribution of the three ESs exhibits high levels in the southwest and low levels in the northeast. (2) The most sensitive regions where tradeoffs and synergies are most pronounced occur primarily in the newly construction land regions and the southwestern mountainous and hilly areas. In newly construction land regions, there are often tradeoffs relationships observed between CS and SR, as well as between HQ and SR. Conversely, a predominantly negative synergy is mainly observed between CS and HQ. In the southwestern hilly terrain, due to changes in landscape patterns, HQ and SR exhibit higher levels of negative synergistic relationships. (3) LULC is a significant driver of spatial and temporal changes in ESs, as well as changes in tradeoffs and synergies in the study area, necessitating integrated research from economic, social and climate change perspectives.

1. Introduction

Ecosystem services (ESs) refer to the various production and living resources and benefits that humans can obtain from natural systems [1]. Interactions among ecosystem services involve tradeoffs and synergies. Tradeoffs occur when boosting one service decreases others, while synergies involve simultaneous increases or decreases in multiple services [2]. In recent years, the degradation of ecosystem function has emerged as one of the major challenges for humanity [3]. Urbanization-induced land use and land cover change (LULC) is a crucial factor that contributes to this phenomenon [4,5], driving changes in ESs and altering trade-off and synergy

* Corresponding author.
E-mail addresses: jwuyue@163.com (J. Du), 2113021105@post.usts.edu.cn (Y. Gong), xixu@mail.usts.edu.cn (X. Xi), liuchangchang1025@163.com (C. Liu), qiancy@dpark.com.cn (C. Qian), yeb@dpark.com.cn (B. Ye).

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relationships among different ESs [6,7]. Therefore, research on the evaluation of ESs and tradeoffs and synergies among ESs based on LULC is highly necessary.

Current methods for assessing ecosystem services primarily include the Energy Analysis, the Value Assessment and the Material Quality [8]. The Energy Analysis assesses the value of ecosystem services by converting different types of energy into solar energy equivalents, though there is no standardized method for this conversion. The Value Assessment uses monetary values as a common metric to aggregate various indicators, yielding a comprehensive benefit assessment, but it struggles to capture the intrinsic mechanisms and ecological processes of ecosystem services. The Material Quality which relies on "3 S″ technology and mathematical models, is currently the most popular approach for ecosystem service research. Over 20 models have emerged, with common ones including the InVEST model, Solve model, and ARIES model. Among these, the InVEST model, which considers multiple indicators, can simulate changes in ESs and assess the tradeoffs/synergies among them at different spatial and temporal scales [9]. When using the InVEST model, methods such as map comparison, scenario analysis, simulation models, and difference comparison method. Among these, the difference comparison method is advantageous for spatial visualization of the relationships between ecosystem services and is widely used [10–15]. This paper also employs the difference comparison method to achieve spatial visualization of the tradeoffs and synergies among ecosystem services. Under the influence of factors such as climate change, land use patterns, social preferences, and incentive policies, there are significant regional differences in the tradeoffs and synergies of ecosystem services [16,17]. Moreover, these relationships continually evolve with changes in time, environment, and human activities. Complicating matters further, tradeoffs and synergies exhibit scale dependence [18], meaning conclusions may vary across different research scales. To address this issue, some researchers have quantified the distribution characteristics of the tradeoffs and synergies of ESs at different spatial scales, deepening our understanding of the interactions among ESs and providing scientifically effective governance approaches for regional ecological management [19,20]. Building on previous research, this paper will explore the temporal and spatial changes in the tradeoffs and synergies of ESs across three different spatial scales: city, county, and grid.

The area around Taihu Lake is the study area situated in the Yangtze River Delta in the eastern part of China, stands out as one of the focal regions characterized by significant conflicts between developmental pursuits and the provisioning of ecosystem services (ESs) in China [21]. Serving as the core region of the Yangtze River Delta Economic Circle, the study area has experienced extremely rapid socioeconomic development over the past 30 years, as well as dramatic changes in land use, which have had profound impacts on the structure and function of ESs. Relevant studies indicate that in recent years, SR and CS in the region around Taihu Lake have increased [22]. However, the imbalance between supply and demand in urbanized areas is prominent [23], and the spatial pattern of habitat quality has consistently been higher in the west and lower in the east [24]. Most research on the areas around Taihu Lake has focused

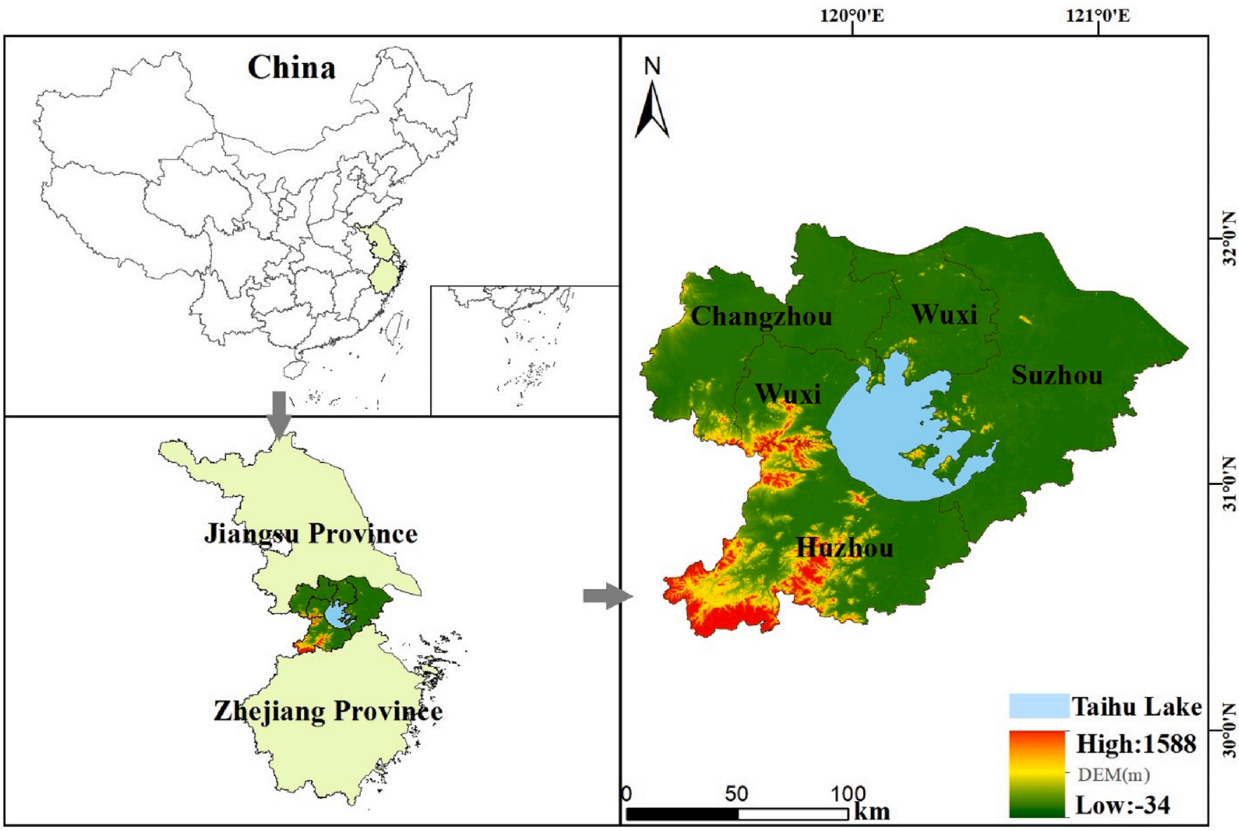

Fig. 1. Location of study area.

on the temporal and spatial changes and driving factors of individual ESs, lacking a deep analysis of the regional ecosystems and their spatial-temporal differences. Studies on tradeoffs and synergies have overlooked their spatial heterogeneity [25,26]. The spatial distribution characteristics of tradeoffs and synergies of ESs remain unclear. During the rapid urbanization process, how is the change and stability of various ESs, and what is the trade-off/synergy between ESs and whether ESs degradation occurs in any areas. These questions should be further investigation.

Considering data availability, the study selected three indicators, namely, Carbon Storage (CS), Soil Retention (SR) and Habitat Quality (HQ), and used the InVEST model to quantitatively evaluate the ESs and its trade-off/synergy relationships in the region around Taihu Lake. The study aims to explore how LULC impact ESs and their tradeoffs and synergies, and to provide valuable insights for ecological planning and environmental protection in the Taihu Lake region.

2. Materials and methods

2.1. Study area

The area around Taihu Lake, situated in eastern China with Taihu Lake at its center, encompasses cities such as Changzhou, Wuxi, and Suzhou in Jiangsu Province, as well as Huzhou in Zhejiang Province, totaling an area of approximately 23,500 km^2 (Fig. 1). The area boasts significant geographic diversity, characterized by hilly mountains predominantly in the southwest, while the northern and eastern parts are primarily composed of plains and water networks. Situated in the subtropics, characterized by a mild and humid climate, the region harbors diverse natural ecosystems such as forests, lakes and wetlands. These ecosystems provide a variety of ecosystem services, including carbon storage (CS), soil retention (SR), and habitat quality (HQ). As one of the regions with the highest population density, most advanced economic development, and densest road network in the country, striking a delicate balance between regional economic growth and ecological preservation is of paramount importance. Therefore, understanding the tradeoffs and synergies among ecosystem services (ESs) is instrumental in offering rational and practical recommendations for the ecological sustainable development of these rapidly urbanizing areas.

2.2. Data source

The data used in this paper include land use data [27] for four periods in 1990, 2000, 2010 and 2020, as well as precipitation data [28], soil data [29] and digital elevation data for the study area. Land use data utilized for calculating land use change and values of various ESs were obtained from China Land Cover Dataset (https://zenodo.org/), derived from Landsat TM images of 30 m × 30 m. Precipitation data used to calculate rainfall erosion was sourced from the National Tibetan Plateau (http://data.tpdc.ac.cn) with a spatial resolution of 1 km. Soil data employed to calculate soil erosion was derived from the Harmonized World Soil Database on FAO Soils porta (https://www.fao.org/soils-portal/en/), with a spatial resolution of 1 km. The digital elevation data was obtained from Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (https://www.gscloud.cn), with a spatial resolution of 30 m. Based on the above data, the InVEST model was employed to calculate and assess the ESs (CS, SR, and HQ), to analyze the tradeoffs and synergies among these three ESs, and to identify the complexity of the ESs in the area around Taihu Lake from 1990 to 2020.

2.3. Methods

2.3.1. Assessment of ESs

1. Method for Carbon Storage (CS)

The InVEST model utilizes the land use data and factors such as carbon densities of aboveground biomass, belowground biomass, soil and dead organic matter to determine the total carbon storage. The calculation is shown in Equation (1).

$$CS = \sum\nolimits_{i=0}^{n} A_i \times (C_{above} + C_{below} + C_{soil} + C_{dead}) \tag{1}$$

where i represents different land use type, including six types of cropland, forest, grassland, water, construction land and barren; A_i is the area of land use type i (ha), which can be obtained from TM images of the study area; C_{above}、 C_{below}、 C_{soil}、 C_{dead} are carbon densities for aboveground biomass, subsurface biomass, soil and dead organic matter, respectively (t /ha); using carbon density for model calculation and carbon density data from Sun [30], Zhang [31] and other research used.

2. Method for Soil Retention (SR)

The InVEST model effectively characterizes the spatial processes of soil erosion on slopes and sand transport within watersheds using land use data, soil attribute data, precipitation data and digital elevation data. The calculation is shown in Equation (2).

$$\begin{cases} RKLS = R \times K \times LS \\ USLE = R \times K \times LS \times C \times P \\ SR = RKLS - USLE \end{cases} \tag{2}$$

where *RKLS* and *USLE* respectively represent potential soil erosion and actual soil erosion; *R* represents rainfall erosivity factor, as described in Equation (3); *K* represents soil erodibility factor, as described in Equation (4); *LS* represents slope length-gradient factor (unitless); which automatically calculated by the InVEST model based on the two-dimensional surface method accounting for different slope conditions; *C* represents cover-management factor (unitless); *P* represents support practice factor (unitless). The values of *C* and *P* are between 0 and 1, and used in this paper referring to the studies conducted by Guo [32] and Xie [33].

$$R = \sum_{i=1}^{12} \left[1.735 \times 10^{\left(1.5\, lg \frac{p_i^2}{p} - 0.8188\right)} \right] \times 17.02 \tag{3}$$

where R represents rainfall erosivity factor $\{\mathrm{MJ} \bullet \mathrm{mm} / (\mathrm{hm}^2 \bullet \mathrm{h} \bullet \mathrm{a})\}$, p_i represents the monthly average precipitation (mm), and p represents annual average precipitation (mm).

$$K = \left[0.2 + 0.3 e^{-0.0256 S_a \left(1 - \frac{S_i}{100}\right)} \right] \times \left[\frac{S_i}{S_c + S_i} \right]^{0.3} \times \left(1.0 - \frac{0.25C}{C + e^{3.72 - 2.95C}} \right) \times \frac{\left[1.0 - 0.7 \left(1 - \frac{S_a}{100} \right) \right]}{\left[1 - \frac{S_a}{100} + e^{-5.51 + 22.9 \left(1 - \frac{S_a}{100}\right)} \right]} \times 0.1317 \tag{4}$$

where K is soil erodibility factor ($\mathrm{k} \bullet \mathrm{hm}^2 \bullet \mathrm{h} \bullet \mathrm{hm}^{-2} \bullet \mathrm{MJ}^{-1} \bullet \mathrm{mm}^{-1}$) , S_a is content of sand (%), S_i is the content of silt (%), S_c is the content of clay (%) , and C is the content of organic matter (%).

3. Method for Habitat Quality (HQ)

The InVEST model uses land use data and data on habitat threat density to assess the level of biodiversity in the region. The calculation is shown in Equation (5).

$$HQ = H \times \left[1 - \left(\frac{D}{D + K} \right) \right] \tag{5}$$

where *H* represents habitat suitability, and *D* represents degree of habitat degradation. *K* is the half-saturation constant, which is usually half of the highest value of habitat degradation. Cropland and construction land were selected as threat factors based on the specific situation of the region around Taihu Lake. The weight, maximum impact distance, decay type and the sensitivity of threat factors are set with reference to the relevant research [34–38].

4. Quantitative measure of tradeoffs and synergies between ESs

The relationships between ESs encompass various effects, including trade-off (negative correlation), synergy (positive correlation), and compatibility (no significant relationship) [39]. Tradeoffs refer to the increase or decrease in certain types of ESs, resulting in the decrease or increase of other types of ESs, while synergies refer to the simultaneous increase or decrease of two or more ESs [40]. The common methods for studying tradeoffs and synergies among ESs include map comparison, scenario analysis, simulation models, and difference comparison [12,41]. Among these, the difference comparison method holds an advantage in spatial visualization of the relationships between ESs and is more popular. The calculation is shown in Equation (6).

$$\begin{cases} A_{T_2} - A_{T_1} = \Delta A \\ B_{T_2} - B_{T_1} = \Delta B \\ \Delta A \times \Delta B = C \end{cases} \tag{6}$$

where T_1 and T_2 refer to two different time periods; A_{T_1} and A_{T_2} refer to the value of ecosystem service for type A in T_1 and T_2 period; B_{T_1} and B_{T_2} refer to the value of ecosystem service for type B in T_1 and T_2 period; ΔA and ΔB refer to the changes in ecosystem services A and B from T_1 period to T_2 period, respectively. If $C = 0$, then the relationship between ecosystem service A and B are compatible, meaning that neither type of ESs changed significantly during the time period; if $C < 0$, then they are tradeoffs, meaning that an increase in one type of ESs is accompanied by a decrease in the other type of ESs; if $C > 0$, $\Delta A > 0$ and $\Delta B > 0$, they are positive synergy, with both ESs increasing in tandem, meaning that the ecosystem as a whole is moving in a positive direction; if $C > 0$, $\Delta A < 0$ and $\Delta B < 0$, they are negative synergy, with both ESs decreasing in tandem, indicating an overall deterioration of the ecosystem.

3. Results

3.1. Land use change characteristics

With the support of GIS software, the land use changes in the study region were estimated for the four time periods of 1990 (Fig. 2a), 2000 (Fig. 2b), 2010 (Fig. 2c), and 2020 (Fig. 2d). The land use changes in the study area have four significant characteristics: (1) There has been a noticeable decrease in the amount of land used for cropland and a clear in-crease in the amount of land used for construction land, both of which have similar in-tensities. From 1990 to 2020, the area of cropland decreased by about 26 %, from 149.13×10^4 ha to 110.15×10^4 ha, while the area used for construction land increased by about 4.1 times, from 9.61×10^4 ha to 49.34×10^4 ha (Table 1). (2) Forest and water underwent some alteration as well; the area of the former decreased by around 10 % while the latter in-creased by about 6 %. (3) Grassland and barren made up a small percentage of the study area, and while they altered significantly as well, they had less of an effect on the land use pattern. (4) Spatially, cropland and construction land are mainly distributed in the eastern and northern plains; forest is mainly distributed in the western and south-western hills and mountains; the water is dominated by Taihu Lake, which is relatively stable; and grassland and barren are sporadically distributed.

3.2. Temporal and spatial change characteristics of ESs

3.2.1. Carbon storage

The annual average carbon storage in the study area was 10.94 t/ha, 10.83 t/ha, 10.46 t/ha, and 10.24 t/ha in 1990, 2000, 2010

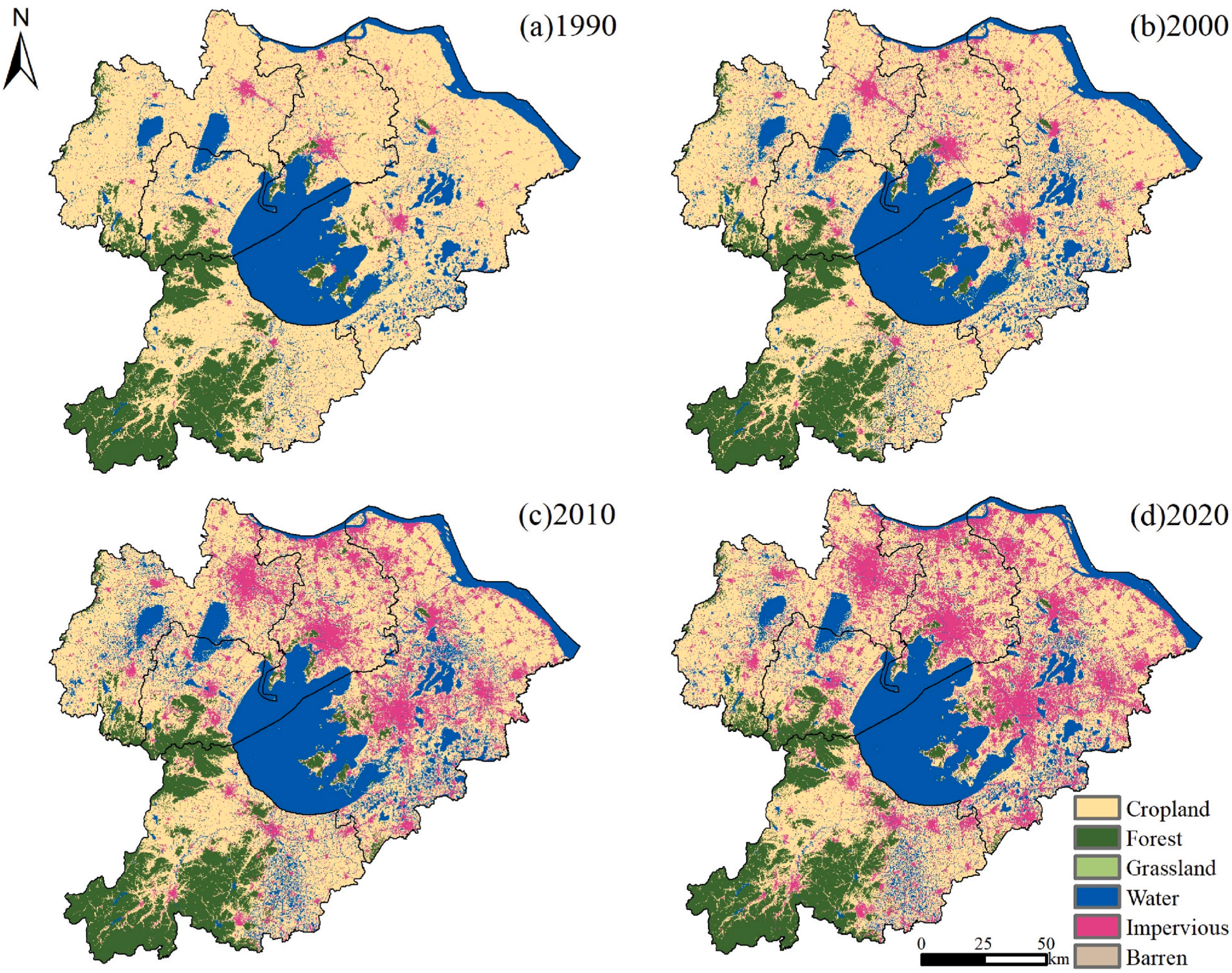

Fig. 2. Land use types in 1990 (a), 2000 (b), 2010 (c) and 2020 (d).

Table 1
Changes in land use in the region around Taihu Lake (unit: ha).

Year	Cropland	Frost	Grassland	Water	Construction Land	Barren
1990	1491343	338146	382	426811	96056	18
2000	1360064	343535	106	465297	183777	6.7
2010	1156056	323635	1105	502259	369670	31
2020	1101531	304216	42	453501	493424	42
1990–2020	−389812	−33930	−339	26690	397368	24
	−26.14 %	−10.03 %	−88.7 %	6.25 %	413.68 %	133.33 %

and 2020 (Table 2), respectively, with a decreasing trend over the years. In terms of spatial distribution, the study area exhibits an overall pattern of higher carbon storage in the southwest and lower in the northeast. Huzhou City has the highest value of carbon storage, notably surpassing the Suzhou-Wuxi-Changzhou area. The differences between the three cities in the Suzhou-Wuxi-Changzhou region are relatively minor, with Wuxi having the highest value and Suzhou the lowest value of carbon storage. It can be seen from Fig. 3a-d that there are three high-value and three low-value concentration areas of carbon storage. The high-value areas include Anji District, Deqing district, and Wuxing District at the southwest end of Taihu Lake, Liyang City and Yixing City on the western shore of Taihu Lake, and the Dong Island and Xi Islands in the middle of Taihu Lake. Conversely, three low-value areas are Suzhou-Wuxi-Changzhou urban agglomeration. With the advancement of urbanization progresses, there is a propensity for the low-value areas to continue growing.

3.2.2. Habitat quality

In 1990, 2000, 2010 and 2020, the habitat quality index in the study area was 0.57, 0.56, 0.52 and 0.48 (Table 2), respectively, with a consistent decreasing trend year by year. Spatially, the distribution of HQ showed in Fig. 3e-h is more consistent with the distribution of CS, characterized by “high in the southwest and low in the northeast”. The value of HQ in Huzhou is significantly higher than the value in Suzhou-Wuxi-Changzhou, with little difference within Suzhou-Wuxi-Changzhou. The high-value concentration areas are mainly located in Anji District, Deqing District, Changxing District and Wuxing District of Huzhou and Yixing of Wuxi, while the low-value concentration areas are primarily found in the urban areas of Suzhou, Wuxi and Changzhou.

3.2.3. Soil retention

Soil retention in the study area was 1.99 t/ha, 1.87 t/ha, 2.23 t/ha, and 2.07 t/ha in 1990, 2000, 2010, and 2020 (Table 2), respectively, showing some volatility. Spatially, it followed a pattern consistent with the distribution of CS and HQ showed in Fig. 3i-m, which were high in the southwest and low in the northeast. Huzhou exhibits the strongest SR capacity, with an average exceeding 5 t/ha, followed by Wuxi and Changzhou, while Suzhou has the weakest SR, with an average of less than 0.5 t/ha.

3.3. Tradeoffs and synergies of ESs

According to Eq. (6), the tradeoffs and synergies among CS, SR and HQ of ESs in the study region from 1990 to 2020 were calculated by image analyst with the support of GIS software. The *C* value calculated by Eq. (6) can only be infinitely close to zero, and referring to

Table 2
The average of ESs in the Study Region during 1990 and 2020.

Region	Year	CS (t/ha)	HQ	SR (t/ha)
Suzhou	1990	9.29	0.52	0.35
	2000	9.10	0.51	0.33
	2010	8.76	0.44	0.39
	2020	8.53	0.38	0.59
Changzhou	1990	9.81	0.51	0.46
	2000	9.68	0.51	0.49
	2010	9.37	0.48	0.73
	2020	9.25	0.44	0.70
Wuxi	1990	10.25	0.53	1.23
	2000	10.10	0.51	1.20
	2010	9.64	0.45	1.55
	2020	9.48	0.41	1.59
Huzhou	1990	13.98	0.71	5.38
	2000	14.00	0.70	4.97
	2010	13.63	0.69	5.75
	2020	13.30	0.65	4.97
Study Region	1990	10.94	0.57	1.99
	2000	10.83	0.56	1.87
	2010	10.46	0.52	2.23
	2020	10.24	0.48	2.07

Note: habitat quality (HQ); soil retention (SR); carbon storage (CS).

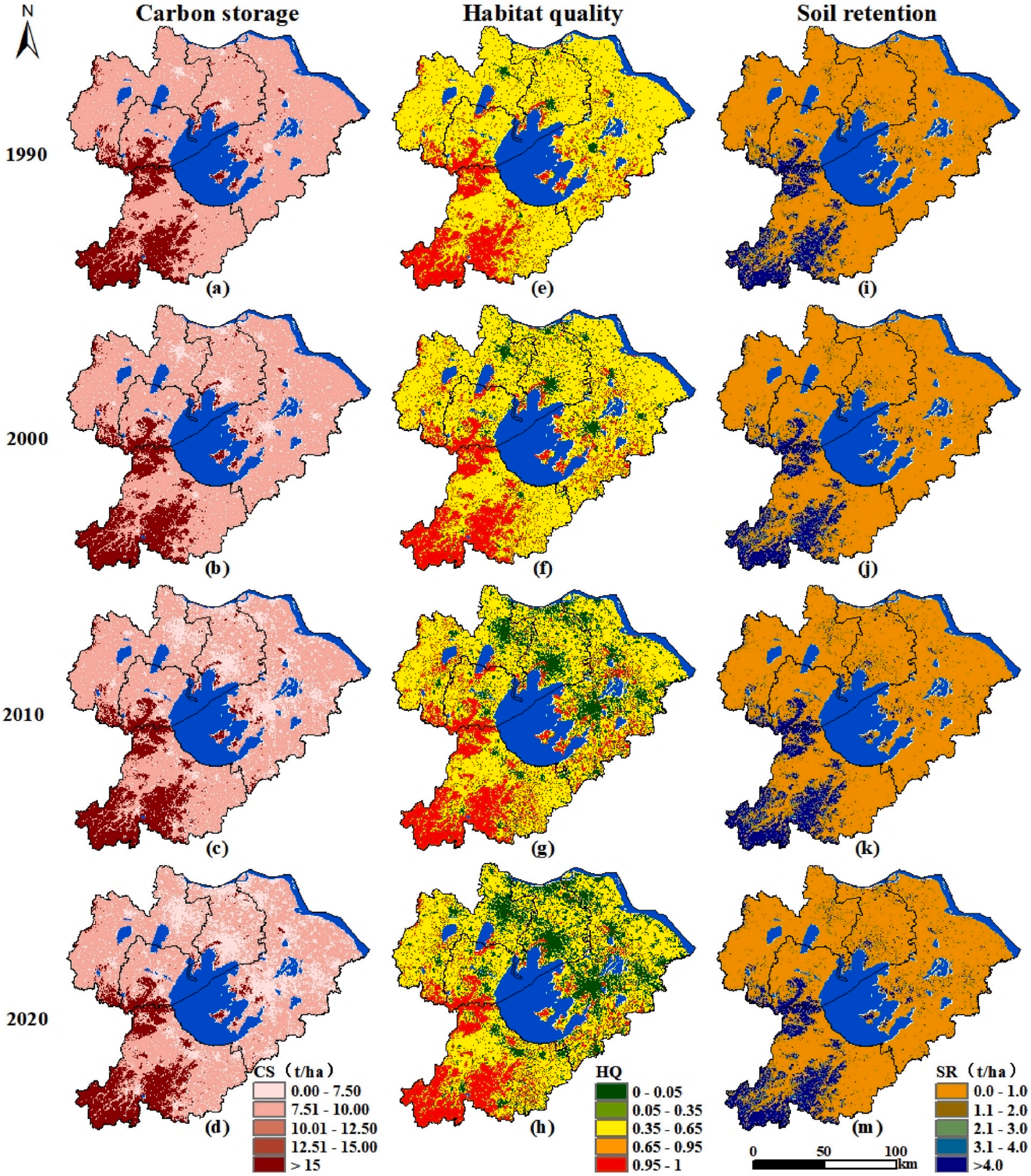

Fig. 3. Spatial pattern of three ESs in the region around Taihu Lake during 1990 and 2020 (CS: carbon storage, a-d; HQ: habitat quality, e-h; SC: soil retention, i-m).

the previous study [42], this paper determines that $-1\times10^{-8} < C < 1\times10^{-8}$ is compatibility, $C < -1\times10^{-8}$ is regarded as tradeoff, and $C > 1\times10^{-8}$ is synergy.

Approximately 75.09 % of the elements in the study area showed a compatible relationship between CS and SR from 1990 to 2020 (Table 3), suggesting that in these areas neither CS nor SR changed significantly over the course of the thirty-year period. Additionally, about 21.45 % of the elements indicated a trade-off relationship, meaning that CS and SR displayed opposite trends. As shown in Fig. 4a, these areas were primarily located in newly urbanized regions. This phenomenon can be attributed to urbanization leading to a

Table 3
The tradeoffs and synergies of ecosystem services in study area from 1990 to 2020.

Types of ESs	Region	Compatibility (%)	Tradeoff (%)	Positive Synergy (%)	Negative Synergy (%)
CS_SR	Suzhou	21.19	9.63	0.32	0.16
	Changzhou	15.91	3.98	0.25	0.22
	Wuxi	14.07	4.99	0.21	0.24
	Huzhou	23.91	2.84	0.28	1.78
	Study Region	75.09	21.45	1.07	2.40
CS_HQ	Suzhou	20.31	1.63	0.16	9.21
	Changzhou	15.53	0.94	0.19	3.71
	Wuxi	13.63	0.68	0.16	5.04
	Huzhou	23.40	1.20	0.40	3.82
	Study Region	72.87	4.44	0.91	21.78
HQ_SR	Suzhou	8.91	20.49	1.26	0.64
	Changzhou	7.18	11.68	1.12	0.38
	Wuxi	6.25	11.94	0.86	0.46
	Huzhou	6.57	9.64	1.52	11.09
	Study Region	28.92	53.76	4.75	12.57

Note: habitat quality (HQ); soil retention (SR); carbon storage (CS).

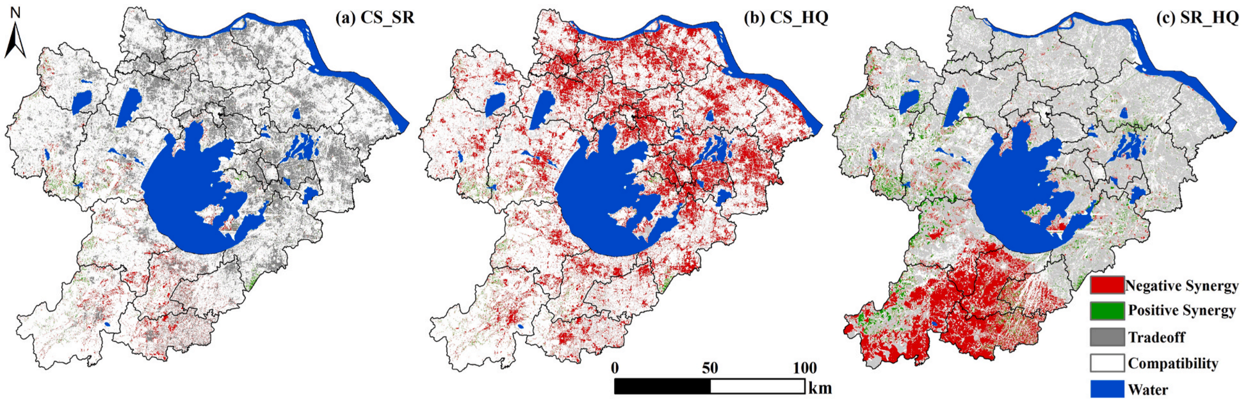

Fig. 4. The tradeoffs and synergies of ESs in the region around Lake Taihu from 1990 to 2020 (CS: carbon storage; HQ: habitat quality; SC: soil retention).

significant reduction in CS, while the hardening of the ground in urbanized areas reduced soil erosion, thus enhancing SR capabilities [43,44]. Conversely, the proportion of elements exhibiting a synergistic relationship was relatively low, accounting for only about 3.5 % of the total. Within this category, 1.07 % of regions exhibited the positive synergy, where both CS and SR increased simultaneously, which is beneficial for improving the ecological improvement. In contrast, 2.4 % of regions showed the negative synergy, indicating a degradation trend in the ecological environment. These regions were mainly located in the southwestern and western hilly areas, as well as some islands in Taihu Lake with relatively high forest cover. The decline in forest cover has resulted in a simultaneous decrease in CS and SR.

During the same period, approximately 72.87 % of the elements CS in the study area was found to be compatible with HQ, while only 4.44 % of the elements exhibited the trade-off relationship (Table 3). Additionally, 22.69 % of the elements displayed a synergistic relationship. Within this category, 0.91 % of regions exhibited positive synergy, indicating simultaneous increases in CS and HQ, which is highly favorable for improving the ecological environment. Conversely, both CS and HQ decreased simultaneously in 21.78 % of the region, primarily in newly urbanized areas and in some hilly and mountainous regions in the southwest, implying that the ecological environment in these areas is gradually deteriorating (Fig. 4b).

From 1990 to 2020, approximately 28.92 % of the elements exhibited the compatible relationship between SR and HQ in the study region, which observed in the pre-existing urbanized areas (Table 3). About 53.76 % of the elements showed the trade-off relationship, mainly occurring in newly urbanized areas (Fig. 4c). This was due to the conversion of other land into construction land, resulting in a decrease in HQ but an increase in SR. Around 17.32 % of the elements exhibited the synergistic relationship, with 4.75 % showing positive synergy and 12.57 % showing negative synergy and the areas of negative synergy were primarily found in the southwestern hilly regions.

4. Discussion

4.1. The impact of LULC on ESs

According to research, CS, HQ and SR are closely related to the types of land use [45]: construction land has the least CS, while cropland and forest have the most [46,47]. Forest and grassland have strong anti-disturbance and stability, maintaining high HQ, while cropland is less stable, while cropland, due to frequent human activities, has moderate HQ. The increase of construction land intensifies the threat to neighboring habitats, and break the ecosystem leading to a sharp decline in regional HQ [48]. SR is relatively good in places with extensive vegetation cover, so forest has the best soil retention capacity, followed by grassland and cropland. Due to the hardening of the ground construction land also has strong soil retention capacity [49].

Table 4 presents the studies of land use data and partly indication of ESs for four representative regions in China. Compared to the other regions and cities in China, the average CS in the region around Taihu Lake is 10.62 t/ha, lower than that of Wuhan city [50] (81.25 t/ha) and the Yangtze River Delta urban agglomeration [51] (23.6 t/ha), but comparable to that of Huining, Gansu Province [52] (12.3 t/ha). The average HQ in the study area is 0.53, lower than that of Wuhan city [53] (0.76) but similar to that of the Yangtze River Delta urban agglomeration [54] (0.56). The average SR in the study area is 2.04 t/ha, which is similar to that of the Weihe River Basin [55] (2.09 t/ha). These research results indicate that due to different land use patterns, there are differences in indicators of ESs among different regions. Regions with a higher proportion of forest and cropland tend to have better ESs compared to those with a higher proportion of construction land. As shown in Table 4, Wuhan city has a higher proportion of cropland than the region around Taihu Lake, while the proportion of construction land is lower, resulting in significantly higher CS and HQ than in the Taihu Lake area. Similar characteristics are observed in Huining County, the Yangtze River Delta urban agglomeration, and the Weihe River Basin.

Over the past three decades, the rapid economic development in the region around Taihu Lake, driven by the swift urbanization process, has led to a year-by-year increase in construction land. As a consequence, cropland and forest areas have correspondingly decreased. From 1990 to 2020, the area of cropland and forest decreased by 26.14 % and 10.03 %, respectively, while the construction land increased by roughly fourfold, resulting in a continuous decline in both CS and HQ. These findings are consistent with research conclusions from Wuhan city and the Yangtze River Delta urban agglomeration: from 2000 to 2015, due to the conversion of cropland and forest land to construction land, CS in Wuhan city decreased from 70.32 Tg to 67.71 Tg [50]; and due to the deepening urbanization, HQ in the Yangtze River Delta urban agglomeration showed a significant downward trend [54]. SR is significantly affected by LULC. Changes in land use affect soil properties, structure, and surface runoff, directly impacting soil erosion. Regions with high vegetation cover tend to have better soil retention capacity, with forest land exhibiting the best SR The SR in the study area fluctuated from 1990 to 2020. On the one hand, the decrease in forest land area weakened soil retention capacity. However, the substantial increase in construction land area (95 % of which originated from the conversion of cropland) led to an improvement in SR due to land hardening. On the other hand, SR is influenced by factors such as topography and precipitation. For example, in the Beisan River Basin, the low-value area for SR is only 1.87 t/ha, while the high-value area reaches 493.30 t/ha [56]. Compared to 2010, the study area experienced a significant increase in rainfall in 2020, leading to a decline in SR in Huzhou city, while in Suzhou city, the increase in construction land resulted in an improvement in SR.

Spatially, the capacities for SR, HQ, and CS generally follow a pattern of high value in the southwest and low value in the northeast, which essentially matches the pattern of land use in the study region. The western and southwestern hilly and mountainous regions, primarily encompassing Huzhou, Liyang in Changzhou, and Yixing in Wuxi, boast a forest cover of up to 30 %, resulting in higher CS, HQ, and SR. In contrast, the eastern plain areas are dominated by cropland and construction land, with forestland accounting for only 1.83 % and cropland and construction land covering 44.98 % and 27.55 % in 2020, leading to weaker ESs.

4.2. The response of tradeoffs and synergies to LULC

From 1990 to 2020, the LULC in the study area exhibited two significant characteristics. Firstly, there was rapid urbanization in the eastern region, with a nearly 30 % reduction in cropland and a more than four times increase in construction land over the course of 30 years. Secondly, there were significant changes in the landscape pattern in the western and southwestern mountainous and hilly areas. The area of forest decreased by approximately 10 %, with about 84 % of it converting to cropland and around 14 % transforming into construction land. Changes in land use have led to corresponding changes in ecosystem services. In the study area, 3783.89 km^2 of cropland was converted to construction land with lower carbon storage capacity, resulting in a decrease in CS by 2.48 t/ha.

Table 4
The indications of ESs in representative areas.

Area	Proportion of cropland area (%)	Proportion of frost area (%)	Proportion of construction land area (%)	CS(t/ha)	HQ	SR (t/ha)	Year
Study area	46.82	12.93	20.97	10.62	0.53	2.04	1990–2020
Wuhan city	56.79	10.50	12.64	81.25	0.76		2005–2015
Huining County	38.90	13.9	1.90	12.3			2000–2016
Yangtze River Delta urban agglomeration	47.63	27.04	12.75	23.6	0.56		2005–2019
Weihe River Basin	42.27	14.00	3.93			2.09	2000–22018

Note: habitat quality (HQ); soil retention (SR); carbon storage (CS).

Additionally, urbanization has disrupted biodiversity, causing the average HQ to decline by 0.49. Table 5 calculates the tradeoffs and synergies of ESs in sensitive areas (new construction land areas and mountainous and hilly areas) around Taihu Lake. The results show that in the new construction land areas, CS, SR, and HQ exhibit high tradeoffs and synergies (negative synergies): 83.8 % of new construction land areas shows a tradeoff between CS and SR, 91 % shows a negative synergy between CS and HQ, and 88.6 % shows a tradeoff between HQ and SR. In the mountainous and hilly areas, CS and SR, as well as CS and HQ, exhibit significant compatibility, with compatible areas accounting for about 95 % of the total area. However, due to changes in landscape patterns, 41.2 % of these areas show a tradeoff between HQ and SR, and 42.9 % show a negative synergy between HQ and SR. It is important to note that negative synergies reflect a simultaneous decline in various ESs, indicating that land use changes lead to an overall reduction in the region's ecosystem service capacity. These areas and the underlying causes of this phenomenon warrant further attention.

By comparing the distribution of tradeoffs and synergies between LULC and ESs, it becomes evident that the conversion of cropland significantly drives the tradeoffs and synergies between CS and other ESs. Xue et al. [20] studied the ESs in Bairin Left Banner. Without considering compatible relationships, from 2000 to 2020, CS and SR primarily exhibited the tradeoffs, mainly occurring in urban construction areas in Bairin Left Banner, with a smaller extent of synergy, primarily in certain forest areas. This finding aligns with the conclusions of the present study. In Bairin Left Banner, CS and HQ mainly showed a synergistic relationship, with the synergistic areas primarily located in forested regions. Similarly, land reclamation in the coastal wetlands of the Yellow River Delta [57] from 1989 to 2015 led to a significant negative synergy between CS and HQ. This phenomenon also occurred in the Beijing-Tianjin-Hebei urban agglomeration [58] and the Pingshuo mining area [15].

From 1990 to 2020, the tradeoffs between SR and HQ in the study area primarily occurred in new construction land areas, while synergies were mainly observed in the mountainous and hilly areas. This finding is consistent with studies conducted in Bairin Left Banner and Lanzhou City [59]. In Bairin Left Banner, SR and HQ generally exhibited tradeoff relationships, with synergies mainly found in forest areas. In Lanzhou City (2000–2020), synergies between SR and HQ were primarily seen in vast grasslands and small forested areas, while tradeoffs were prevalent in urbanized regions. These studies also confirm the sensitivity of forest and grassland ecosystems, which are prone to generating synergistic effects, particularly in mountainous and hilly areas. Due to topographic factors, soil erosion intensifies during rainy seasons, severely threatening SR and HQ. Consequently, the probability of negative synergies significantly increases.

4.3. Recommendations

(1) The Taihu Lake and its surrounding areas, known as the "green lungs" of the Yangtze River Delta, play a vital role in regional ecological conservation. Guided by the principles of "green, development, and low-carbon," measures such as biodiversity conservation, green countryside construction, wetland conservation around Taihu Lake, organic agriculture promotion, and deepening of ecological compensation mechanisms should be implemented to achieve a dual enhancement of ecological environmental quality and green development.
(2) The study indicates a significant degradation in the ecosystem service capacity of construction land, especially with CS and HQ exhibiting significant negative synergies. Financial support for urban greening should be increased, and effective measures such as the promotion of ecological engineering technologies, green roof technologies, vertical greening technologies, wetland restoration technologies, and the construction of artificial wetland systems should be adopted to enhance the ecosystem service capacity of urban construction land.
(3) By 2020, cropland accounted for about 47 % of the total area, remaining one of the most important land use types in the region around Taihu Lake. Effective measures should be implemented to protect cultivated land, such as promoting green agricultural technologies, developing circular agriculture, cultivating green agricultural brands, constructing high-standard farmland, and protecting both the quantity and quality of cultivated land, to achieve a dual enhancement of agricultural development and ecosystem protection.
(4) Ecosystem service management in the region around Taihu Lake should transcend administrative boundaries and implement joint management and protection across city clusters. Different ecological management zones should be delineated based on the distribution characteristics of ecosystem service tradeoffs/synergies, focusing on improving the structure of ecosystem services, macro-control, and enhancing the overall level of regional ecological service and management capacity.

5. Conclusions

This study examines the spatiotemporal changes in three ecosystem service values, namely CS, HQ, and SR, in the region around Taihu Lake from 1990 to 2020. The assessment of the tradeoffs and synergies among these ecosystem services reveals an overall decline in ecosystem functionality in the study area. CS and HQ show a downward trend over the years, while SR exhibits some fluctuations. Significant negative synergies between certain ecosystem services are observed, leading to an overall decrease in ecosystem service capacity. This paper still has several limitations: Firstly, it only explores the tradeoffs and synergies between land use/land cover (LULC) and ecosystem services (ESs) from a spatiotemporal perspective, lacking a quantitative analysis of the intensity of changes in ecosystem service tradeoffs/synergies. Additionally, it fails to spatially map ecologically sensitive areas where ecosystem services simultaneously decline. Secondly, due to data limitations, this study lacks quantitative analysis of the driving factors behind changes in ecosystem service tradeoffs/synergies. Lastly, in the process of ecosystem service assessment, there is a lack of on-the-ground research for localizing model parameters, and the accuracy of the assessment results remains to be further verified.

Table 5
The tradeoffs and synergies of ESs in sensitive areas of the study region from 1990 to 2020 (unit: %).

Types of ESs	Relationship	New construction land areas	Mountainous and hilly areas
CS_SR	Compatibility	13.6	94.9
	Tradeoff	83.8	1.3
	Positive synergy	0.1	2.4
	Negative synergy	2.5	1.4
CS_HQ	Compatibility	8.6	95.8
	Tradeoff	0.4	0.1
	Positive synergy	0	0
	Negative synergy	91	4.1
HQ_SR	Compatibility	8.4	6.4
	Tradeoff	88.6	41.2
	Positive synergy	0.2	9.4
	Negative synergy	2.8	42.9

Note: habitat quality (HQ); soil retention (SR); carbon storage (CS).

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Data availability statement

All data are available in Supporting Information SI.

CRediT authorship contribution statement

Jinglong Du: Writing – original draft. **Yao Gong:** Writing – original draft. **Xu Xi:** Conceptualization. **Changchang Liu:** Conceptualization. **Chengyang Qian:** Data curation. **Bao Ye:** Data curation.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33375.

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